Optimisation of the value chain of the existing free potentials of wood resources for power generation in Baden-Württemberg

Zur Erlangung des akademischen Grades eines

Doktors der *Ingenieurwissenschaften*
(Dr.-Ing.)

von der KIT-Fakultät für Wirtschaftswissenschaften

des Karlsruher Instituts für Technologie (KIT)

genehmigte

DISSERTATION

von

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Tag der mündlichen Prüfung:	30. Oktober 2018
Referent:	Professor Dr. Wolf Fichtner
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Dedicated to all my family, especially my parents Julián and Rosario – the indirect cause of this dissertation – as well as my sister Raquel and my brother Carlos in gratitude for their firm and decisive support

Acknowledgement

I would like to express my absolute gratitude to the following persons, who have made this doctoral thesis possible. Regardless of the magnitude of their contributions, I wish to acknowledge all of them for their valuable support and advice.

Professor Dr Wolf Fichtner

Professor Dr Frank Schultmann

Professor Dr Otto Rentz

Professor Dr Ute Karl

Professor Dr Stefan Nickel

Professor Dr J. Philipp Reiss

Professor Dr Dominik Möst

Professor Dr Russell McKenna

Dr Kai Mainzer

Dr Dogan Keles

Professor Dr Patrick Jochem

Dr David Balussou

Dr Marcus Wiens

Wolfram Neidhardt

Thomas Dengiz

Dr Sonja Babrowski

Dr Anke Bekk (née Eßer)

Dr Christian Bidart

Fritz Braeuer

Dr Patrick Breun

Dr Andreas Bublitz

Sylvain Cail

Dr Martina Comes

Florian Diehlmann

Ana María Fernández

Daniel Fett

Christoph Fraunholz

Dr Jonathan Gómez Vílchez

Dr Ingmar Gehrke

Dr Massimo Genoese

Dr Martina Haase

Rupert Hartel

Dr Heidi Heinrichs (née Gerbracht)

Dr Tobias Heffels

Dr Anne Held

Dr Felix Hübner

Tobias Jäger

Dr Gunnar Kappler

Dr Thomas Kaschub

Phuong Minh Khuong

Yvonne Koch (née Röming)

Emil Kraft

Dr Robert Kunze

Niko Lehmann

Dr Ana López-Cortón Facal

Dr Erik Merkel

Dr Ann-Kathrin Müller

Elias Naber

Christoph Nolden

Alexandra-Gwyn Paetz

Dr René Pforte

Dr Sophia Radloff (née Laure)

Andreas Rudi

Dr Carmen Schiel (née Mayer)

Hanns-Maximilian Schmidt

Dr Frank Schwaderer

Dr Hannes Schwarz

Dr Katrin Seddig

Kilian Seitz

Viktor Slednev

Dr Julian Stengel

Dr Felix Teufel

Marjorie Vannieuwenhuyse

Dr Rebekka Volk

Jann Michael Weinand

Dr Marius Wunder

Hasan Ümitcan Yilmaz

Tobias Zimmer

Nico Belezis

Sofia Belezis

Liana Blecker

Egon Fehr

Corinna Feiler

Josiane Folk

Michaela Gantner-Müller

Katrin Grauer

Karin Simianer

Ralf Stegmüller

Eve-Marion Weiss

Abstract

The energy mix of Baden-Württemberg – one of the most wooded regions of Germany – could be diversified through the optimal valorisation of the existing free potentials of wood resources. Circa 17 PJ of forest residues and landscape wood raw material grow annually over the territory of this federal state. For this reason, an optimisation of the corresponding value chain for power purposes is accomplished in order to identify the most cost-efficient utilisation pathways. Firstly, each unexploited potential of wood resources for up to ten different types of wood chips is estimated at district level. Next, the stages of felling, extraction, debranching, moving and chipping of wood resources are modelled into four specific logistic chains on the basis of the size of forest ownership, the steepness of slope and the variety of tree. Moreover, specific unit costs based on different cost allocation procedures are assigned to the ten identified types of chipped wood resources. Besides the modelling of the transport sector, an array of all feasible technologies for conversion of wood resources into bio-based power are compared to each other in terms of costs. A singular conclusion is drawn according to which, for each particular capacity under the same operation conditions, gasification is more cost-efficient than combustion – except for co-firing. Hence, the fluidised bed gasification coupled to a gas engine or a combined cycle as well as the direct co-firing of wood resources at a 10% co-fire rate are preselected for the intended analysis on account of their higher cost-effectiveness. Lastly, a new MILP model called BIOSPHERE (Bioenergy Optimisation Software for Production Pathways at High Energy and Resource Efficiency) is created for the optimisation of the value chain of wood resources. This optimising tool includes a unique mathematical constraint aiming at assuring profitability of investments within each utilisation pathway.

A scenario-based analysis is first developed for remunerations modelled with a high enough value above the breakeven point. Thereby, a combined heat and power cogeneration process consisting of a fluidised bed gasifier coupled to a gas engine of 20 MW_e renders electricity production costs of 10.1-13.8 €cent/kWh_e for an annual amount of 7,500 full load hours. The co-firing option for the existing coal-fired power plants with bio-based capacities up to 84.3 MW_e generates lower electricity production costs of 6.6-11.7 €cent/kWh_e, when the facilities are yearly operated for 3,000 full load hours. If a fluidised bed gasifier is connected to a combined cycle of 210/340 MW_e (7,500 full load hours per year), this technology turns out to be the most cost-efficient with electricity production costs in the order of 5.6-7.1 €cent/kWh_e. These costs ranges can be reduced by progressively decreasing remunerations below each resulting breakeven point. As for the option of co-firing, cheaper bioenergy configurations arise on the basis of cheaper wood resources that enable lower production costs of up to 5.6 €cent/kWh_e for 4,000 hours per year at full load. In conclusion, the low incremental capital costs of co-firing as well as the high efficiencies of fluidised bed gasification-based combined cycles together with the valorisation of the more economical deciduous fractions of wood resources might reduce electricity production costs to a rather low range between 4.5 and 9.5 €cent/kWh_e. Leveraging such cost reductions, the introduction of appropriate energy policy instruments for the promotion of carbon-neutral baseload power generation is strongly recommended in view of restrictions induced by Germany's nuclear and coal phase-outs.

Although the quality of the results of this study is mainly conditioned by uncertainty and the high spatial aggregation level of the spatial unit, the implemented methodology as well as the performed optimisation analysis represents an interesting breakthrough that may contribute to the initiated energy transition in Baden-Württemberg and the whole of Germany.

Index

Abbreviations

ESA	Energy System Analysis
BIGCC	Biomass integrated gasification combined cycle
BIOSPHERE	Bioenergy Optimisation Software for Production Pathways at High Energy and Resource Efficiency
BP	By-product
CHP	Combined heat and power
CHPA	Combined heat and power act
DBH	Diameter at breast height
DW	Dry weight
DSEPC	District-specific electricity production cost
DSTC	Distance-specific transport costs
EPC	Electricity production cost
FBC	Fluidised bed combustion
FBG	Fluidised bed gasification
FBG+E	Fluidised bed gasifier coupled to a gas engine
FIP	Feed-in premiums
FIT	Feed-in tariffs
FW	Fresh weight
GAMS	General Algebraic Modelling System
GIS	Geographic Information Systems
GREA	German Renewable Energy Act
HRSG	Heat recovery steam generator
IPCC	Intergovernmental Panel on Climate Change
JP	Joint product
LP	Linear programming
LFO	Large (private or public) forest owners

m^3 s	Cubic metre solid volume (wood)
m^3 l	Cubic metre loose volume (wood chips)
MILP	Mixed integer linear programming
MC	Moisture content
NLP	Nonlinear programming
O&M	Operation and maintenance
ORC	Organic Rankine cycle
OPTCR	Relative Optimality Criterion
PERSEUS	Program Package for Emission Reduction Strategies in Energy Use and Supply
RAM	Random-access memory
RMILP	Relaxed mixed linear integer programming
S<50F	Steepness of slope lower than 50% in forest areas
S>50F	Steepness of slope higher than 50% in forest areas
S<50L	Steepness of slope lower than 50% in landscape areas
S>50L	Steepness of slope higher than 50% in landscape areas
SPFO	Small private forest owners
TGC	Tradable green certificates

Nomenclature

Indices

ec	Energy carrier
exp	Sink of bioenergy (power or heat) and non-biogenic energy (fuel *F*) as an export of the energy system
F	Fuel as energy from non-biogenic resources
hc	Harvesting costs
i, j, k	Upstream processes within the supply chain of a bioenergy generation process *p*
imp	Source of (biogenic) energy and material imports of the energy system
jc	Joint costs
n	Number of spatial units (regions)
p	Bioenergy generation process
proc	Process
prod	Producer
reg	Region (administrative unit)
t	Period of years
u	Bioenergy generation unit (power plant)
unit	Unit

Sets of indices

BIOPROD	Set of producers within the bioenergy value chain
BIOGENUNIT	Set of bioenergy generation units
C	Set of bioenergy processes within the conversion sector
C_i	Set of bioenergy processes within the conversion sector *C*, which are sinks of energy and material contributions $PL_{i,p}$ originating from upstream processes *i*

D	Set of upstream processes within the densification sector
D_p	Set of upstream processes *i* of the densification sector *D*, which are sources of energy and material contributions $PL_{i,p}$ to a bioenergy process *p* of the conversion sector *C*
EC	Set of energy carriers
EXP	Set of export producers (sinks)
$GENPROC$	Set of energy generation processes
$GENUNIT$	Set of energy generation units
H	Set of upstream processes within the harvesting sector
H_p	Set of upstream processes *i* within the harvesting sector *H*, which are sources of energy and material contributions $PL_{i,p}$ to a bioenergy process *p* of the conversion sector *C*
IMP	Set of import producers (sources)
$IMP_{prod,ec}$	Set of producers acting as sinks that collect the energy carrier *ec* from the import producer *imp*
$INVPER_u$	Set of periods of time constituting the economic life of an investment in a unit *u*
$P_{prod,ec}$	Set of processes that are contained in producer *prod* and convert the energy carrier *ec* into another one
$P'_{prod,ec}$	Set of processes that are contained in producer *prod* and generate the energy carrier *ec*
$PROC$	Set of processes
$PROD$	Set of producers
$PROD_{exp,ec}$	Set of export producers acting as a sink of the energy carrier *ec*
$PROD'_{prod,ec}$	Set of producers acting as sources that provide the producer *prod* with the energy carrier *ec*
$PROD_{prod',ec}$	Set of producers acting as sinks that collect the energy carrier *ec* from the producer *prod'*
REG	Set of regions
PER	Set of time periods

SUPPROC	Set of upstream processes within the supply chain of the bioenergy generation processes
$SUPPROC_p$	Set of upstream processes within the supply chain of a bioenergy generation process *p*
T	Set of upstream processes within the transport sector
T_p	Set of upstream processes *i* of the transport sector *T* that are sources of energy and material contributions $PL_{i,p}$ to a bioenergy process *p* of the conversion sector *C*
UNIT	Set of units containing energy generation processes

Parameters

α	Discount factor
η	Efficiency of a process
a	Fixed costs of transport means
b	Distance-specific variable costs of transport means
CAPACITY	Block size of discretely modelled units
Cfix	Specific fixed operation and maintenance costs of a process
Cfuel	Specific costs of fuel
Cinv	Specific investment or capital costs of a unit
Cvar	Specific variable operation and maintenance costs of a process
Dem	Power demand of a spatial unit
EC_LIFE	Economic life of a bioenergy generation unit *u*
FLH_MAX	Upper limit of the annual full load hours
FLH_MIN	Lower limit of the annual full load hours
HP	Heat price
HP_o	Heat price in the case of zero remuneration for power
LIFE_TEC	Technical life or time period in which a unit is available as of its commissioning
Pot	Potential of biogenic resources for each spatial unit

R	Specific remuneration granted to the generation of bio-based power
R_o	Specific remuneration granted to the generation of bio-based power provided that heat is not remunerated
R^2	Coefficient of determination
TotMaxCap	Total maximum capacity expansion per year for a territory

Variables

φ	Virtual flow
Cap	Capacity of a unit *u*
Com	Number of units commissioned in each period of time *t*
DSTC	Distance-specific transport costs
FL	Activity level of a flow (flow level)
Fuel	Activity level of non-biogenic energy imports
PL	Activity level of a process (process level)
$PL_{i,p}$	Energy and material contributions of upstream processes *i* from the *H*, *D* and *T* sectors to a bioenergy process *p*
TC	Transport costs
x	Distance covered between sources (forest/landscape) and sinks (demand)

1. Introduction

1.1. Motivation

The federal state of Baden-Württemberg, like the whole of Germany, is currently facing the challenge of decarbonising its energy system while diversifying it by implementing new sources of renewable energies in the framework of the so called "Energiewende" – the energy transition. The last reform of the German Renewable Energy Act (GREA) [EEG 2017] established the target of reaching a share of renewable energies of at least 80% in total gross power consumption until 2050 with the suggestion of achieving a portion comprised between 55% and 60% by the year 2035. Although this energy transition into a decarbonised energy system is already initiated and an encouraging contribution of 31.6% from renewable power to total gross consumption was announced by [UBA 2016] for the German energy system in 2016, a huge amount of energy is still required in order to meet the objectives pursued in the aforementioned act.

Among all sources of renewable energy, biomass is the energy resource that presents a comparatively higher potential for exploitation than others such as e.g. hydro, photovoltaic, solar thermal, wind, geothermal or ocean energy. Whereas solar or wind energy have been actively promoted during the last two decades, others such as hydro generation already began to get established since the onset of the industrial age and, on the other hand, geothermal or ocean energies noticeably exhibit a more reduced potentiality on account of either their lesser resource availability or even the corresponding technological immaturity. Similarly, several techniques of bioenergy production based on diverse types of solid (e.g. forest residues, energy crops) and liquid (e.g. sewage sludge, animal manure) biomass have been fostered in the last years. All these resources with the exception of forest residues are generated and systematically depleted by converting them into bioenergy. Nevertheless, the particularity of wood resources lies in the fact that there exist considerable free potentials of underused wood material resulting predominantly from dispersed areas in forests and landscape. Consequently, these potentials might constitute an interesting unconsumed resource for conversion into bio-based power and heat, thereby contributing to facilitating the fulfilment of the targets set up for the middle of this century.

Apart from more costly biofuels and bio-based chemical production, conversion of wood resources into bioenergy can be performed via either a heat or a power production process or even through combined heat and power cogeneration. In any case, whether techno-economically analysing the generation of heat or that of power or even both depends more on the intended focus of the study as well as the data availability concerning the targeted bioenergy system than on other aspects, as both sustainable energy carriers are equally demanded in a modern society. However, although a conversion process into heat is assigned a higher efficiency than in the case of power (or combined heat and power cogeneration), the analysis of a wood resources-based bioenergy subsystem for power production entails a greater complexity and hence can yield a more interesting solution. This is due to the fact that heat production must be implemented according to a decentralised generation pattern by transporting wood resources over short distances – provided that expensive, medium and large-sized thermal energy storage systems are not employed thereby avoiding higher levels of centralisation. Instead, power generation is feasible for both decentralised and centralised power plants with the latter option being even more cost-efficient owing to the implementation of economies of scale. Anyhow, heat and power generation – as it is also the case of biofuels and bio-based chemicals – represents unalike bioenergy carriers with completely different costs per unit of energy produced (cheaper for heat). Therefore, a separate and hence smaller analysis for each bioenergy output is recommended in order to specifically focus on each utilisation pathway independently of which might become the most cost-effective.

In keeping with [BMEL 2014], Baden-Württemberg presents the second biggest forest area (1,371,847 ha) in Germany after the federal state of Bavaria (2,605,563 ha) with both federal states showing a share of approximately 37-38% of the respective total surface. These figures allow gaining insight into the great potential of wood resources within the boundaries of this region. On this basis, Baden-Württemberg is expected to produce a considerable unconsumed technical potential, which is currently not being utilised for either material or energy purposes and that can be estimated at circa 17 PJ/a of primary energy according to both official sources [BMVBS 2010] and [WMBW 2010]. This bioenergy potential in form of power might introduce the possibility of diversifying the energy mix of the federal state of Baden-Württemberg, whilst simultaneously reducing greenhouse gas emissions by means of substituting wood resources for fossil fuels.

The rationale behind the existence of this free potential in Baden-Württemberg points to several factors, which ultimately relate to the increased costs incurred throughout the value chain of wood resources. In the first place, this resource usually has no or just a reduced market value associated with it – albeit considerably high costs – due to its extremely low quality as a raw material. Furthermore, wood resources are generated predominantly on stands subject to high dispersion rates. This unavoidably brings about higher costs for collecting and concentrating this material. Besides, not only the spatial distribution but – although to a lesser extent – the appropriate space of time for harvesting wood resources during the year also renders this material more complex. In essence, as a bioenergy source, wood resources are an abundant but costly and low-level energy carrier largely due to their special intrinsic characteristics. Utilisation pathways within the value chain of wood resources are in general made up of a series of quite expensive processes, precisely on account of the technical measures introduced for counterbalancing the previously reported features. In this regard, high hourly rates and predominantly low productivities and efficiencies characterise and determine in term of costs the processes within each stage.

Wood resources largely arise from forests and landscape areas as well as urban and rural settlements situated all over the region of Baden-Württemberg. The value chain of wood resources gathered in these areas for power production encompasses a number of utilisation pathways that comprise a long sequence of different processes ranging from resource harvesting to conversion into bioenergy. However, some stages such as collection or conversion show much more technical complexity than others – and therefore also higher costs. In this respect, whereas harvesting depends on certain features such as ownership structure, slope type or tree size, the stage of conversion into power exhibits a wide spectrum of combustion and gasification technologies as illustrated in Figure 1.1. This fact connects with a multiplicity of possible technology options for each arbitrary stage within a given utilisation pathway, each presenting dissimilar techno-economic parameters (e.g. efficiency, scale, specific costs, remunerations, lifetime, full-load hours), which even might vary over space and time. Furthermore, some processes (e.g. collection, drying, densification, storage) may be operated in a location far away from the place where conversion is carried out. Thereby, the stage of transport or even others such as loading/unloading and transhipment are accomplished between the harvesting and the conversion locations through a certain stretch of transport infrastructure (road, railway or waterway). All in all, the consideration of all possible combinations of successive processes with a particular location, technology and scale over a given time frame results in a large mathematical problem that may be solved – the real scientific motivation – so as to identify the most techno-economically optimal utilisation pathways for transforming wood resources into bio-based power (see Figure 1.1).

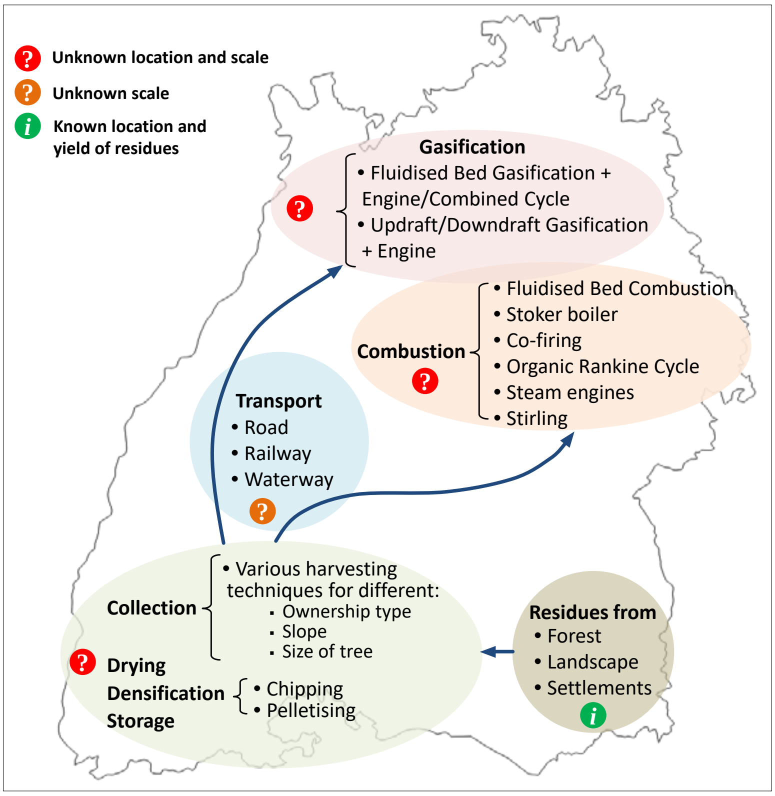


Figure 1.1: Value chain of wood resources for power generation in Baden-Württemberg including all the utilisation pathways as a combination of consecutive processes with different location, technology and scale

1.2. Objective and methodological approach

The objective of this study is the identification of the free potentials of wood resources growing in each spatial unit of Baden-Württemberg as well as their optimal utilisation for electricity production by allocating these free technical potentials to one or more power plants with a specific location, technology and scale. Knowing the spatial distribution of all processes within each utilisation pathway as well as the incurred expenses throughout the whole production chain allows the dimension, composition and spatial variation of the electricity production costs for each of the chosen conversion units for two different approaches based on the modelling of remunerations above and below the original breakeven point to be determined. Beyond the spatial dimension, the temporal evolution of the system will not be included in this dissertation due to lack of data availability concerning the cost projection of different bio-based conversion technologies as well as the time development of potentials and harvesting expenses of all different types of wood resources over the next decades[1]. The answers to these open questions against the backdrop of the points introduced in section 1.1 concerning the motivation of this study should shed enough light on how to proceed with respect to achieving a cost-efficient and sustainable conversion of wood resources into power.

Wood resources are harvested, densified into chips, transported and finally converted into bio-based power. In this manner, they take the form of bioenergy flows that constitute a network of interconnected processes laid down along the entire bio-based subsystem. The dimension and configuration of these bioenergy flows depend upon the free potentials of wood resources as well as the electricity demand of each spatial unit but also on the geographic characteristics of Baden-Württemberg. Together with the determination of this network of energy flows shaping the value chain of wood resources, different distribution patterns of both resources and bioenergy over the entire territory of the federal state – from highly centralized via intermediate levels of centralization through to completely decentralized – will be ascertained.

The proposed methodological approach consists in accomplishing a series of steps, which are explained throughout the following chapters with the aim of attaining the objectives previously fixed.

Chapter 2 addresses the existing free potentials of wood resources in the bioenergy system of Baden-Württemberg. Specifically, the unconsumed portion of both real technical potentials of forest residues and landscape wood raw material within each spatial unit of the federal state is identified and put forward for the first time. The spatial distribution of the free potentials for wood resources introduces a significant limitation when it comes to selecting the appropriate spatial aggregation level for the analysis of the targeted bioenergy system. The lack of adequate data describing the potential of wood resources at a lower aggregation level than that of districts (e.g. communities) prevents a higher spatial resolution and, in consequence, better accuracy for the optimisation-based analysis from being achieved.

[1] One option might have been to use a series of assumptions involving the corresponding temporal evolution of such data. Nevertheless, as predictions about techno-economic data of bioenergy technologies are scarce and quite unreliable, the intended analysis is carried out exclusively for the year of initial operation on the assumption that no substantial variation should occur in succeeding years. The same can be stated for potentials and harvesting costs despite the supposedly not insignificant effect of climate change on generation and hence cost formation of wood resources.

In **chapter 3**, six different logistic chains for harvesting wood resources as well as the dependence of distance-specific transport costs on the route length are identified as a unique integral methodology. On the other hand, a set including the most cost-efficient technologies for conversion of wood resources into bio-based power is techno-economically described for the first time and presented as an interim conclusion in **chapter 4**. The different utilisation pathways of wood resources are structured as a succession of stages, which the different processes of the system are allocated to. Such steps are sequentially arranged on the basis of a scheme consisting of four specific sectors as illustrated in Figure 1.2: harvesting, densification, transport and conversion. The intended assessment contemplates all techno-economic parameters (e.g. efficiency, capacity, specific costs[2], remunerations, lifetime, full load hours) of all processes involved along these four sectors. These techno-economic data are collected, statistically harmonised and conveniently compiled in a database for the proposed analysis.

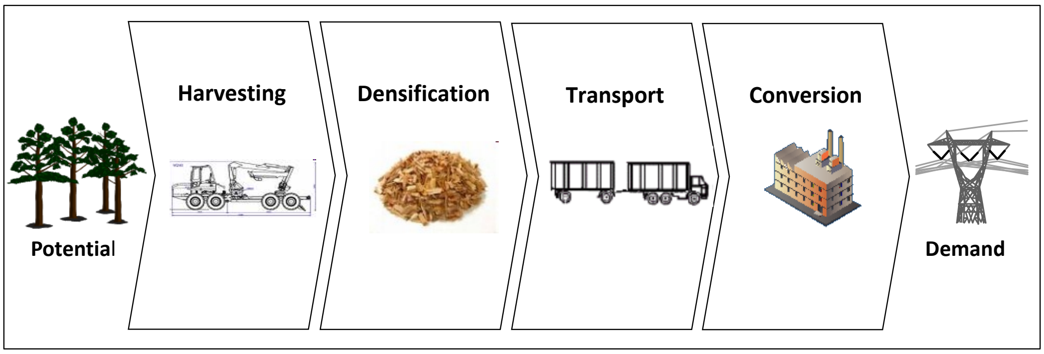


Figure 1.2: Sector structure of the wood resources-based bioenergy system for power generation

Essentially, one of the most relevant issues is carried out in **chapter 5**, in which an existing energy and material flow optimising model derived from the PERSEUS[3] family is utilised. The selection of this tool relies on leveraging the already existing structures of this energy system optimisation model for reproducing a bioenergy subsystem. This model serves as a basis for a further methodological development so as to construct a unique and more sophisticated optimisation tool called Bioenergy Optimisation Software for Production Pathways at High Energy and Resource Efficiency (BIOSPHERE) for the exclusive analysis of bioenergy subsystems. The improvement of the basic PERSEUS model refers to the modification of its source code by introducing a set of new constraints. These are linked to the fulfilment of the profitability of discrete investments – i.e. those only concerning each bio-based utilisation pathway as the sum of a conversion plant and its supply chain – as well as the description of the cost components of electricity production costs. This profitability is exclusively assessed from the point of view of the concerned plant operator in the sense that the sum of remunerations (subventions, wholesale prices, market premiums or even heat retail prices) received for bioenergy production has to at least cover the total costs originated

[2] All costs employed in the framework of this study refer to the base year 2017.

[3] Program Package for Emission Reduction Strategies in Energy Use and Supply (PERSEUS).

throughout the complete supply chain and the conversion plant. Methodologically, BIOSPHERE is configured as a multi-period mixed-integer linear programming model (MILP) and consists of a source code programmed in GAMS®[4]. This is coupled to a database compiled in Microsoft Access®, where data characterising the region under consideration and the entire value chain of biomass resources are stored. Specifically, the optimisation analysis is based on the minimisation of a declared objective function that includes the total expenditures of all processes involved.

The methodological steps aiming at the modelling of the wood resources-based bioenergy system in Baden-Württemberg is the subject of **chapter 6**. A unique period of time is activated because the time component is not considered in the present analysis. The selection of the district as a suitable spatial unit for this study represents the best possible spatial partition of the region in line with the available data. Different datasets resulting from the correlation of the free potentials and the logistic chains of chipped wood resources as well as those of transport and conversion technologies in addition to their specific spatial allocation are generated. Thus, a data base is created and integrated into the cost minimisation model BIOSPHERE.

Chapter 7 identifies a series of scenarios including diverse techno-economic settings in order to appropriately analyse the wood resources-based bioenergy system of Baden-Württemberg when the remunerations are modelled above and below the original breakeven point. Thereby, an optimisation-based analysis is carried out by generating scenarios on the basis of the most cost-effective technology options and all identified types of wood resources so that different bioenergy production patterns may arise and be assessed. Besides the determination of the optimal electricity production costs together with their spatial variation over the defined catchment area and their respective cost components for each selected bio-based power plant, the cost minimising model provides a total solution in the form of a matrix or array. This is made up of four process-related partial solutions – each in the form of a 3-tuple (location, technology, capacity) –, each linked to the respective four sectors of the entire system. By appropriately lessening remunerations below the breakeven point, certain level of cost reductions for some plant operators are identified on the basis of an example taken from a preselected technology option (co-firing). In addition, the resulting specific electricity production costs are accordingly treated with a sensitivity analysis that aims at assessing the effect caused by parameter uncertainty of input data on the solution.

In **chapter 8**, major conclusions of the entire dissertation are drawn. Insight is therefore gained into the mechanisms resulting in the formation of the optimal utilisation pathways by identifying the distribution patterns of wood resources and bioenergy throughout the districts of Baden-Württemberg. A critical reflection as well as a list of future research perspectives is included in the last part of this chapter.

The dissertation concludes with a summary in **chapter 9**.

[4] General Algebraic Modelling System (GAMS)

2. The potentials of wood resources in Baden-Württemberg

The federal state of Baden-Württemberg is located in the southwest of Germany and presents a total land area of 35,752 km^2 with a total population of 10.88 million inhabitants according to the last census published in the year 2016 [SLBW 2016]. Baden-Württemberg's state capital is Stuttgart. The federal state consists of four administrative regions, namely Stuttgart, Karlsruhe, Freiburg and Tübingen, which are divided into 44 administrative units: namely 35 districts and 9 urban districts in the form of conurbations or agglomeration areas. These districts encompass a total of 1,103 municipalities spread all over the federal state. The map in Figure 2.1 illustrates the administrative structure of Baden-Württemberg.

Figure 2.1: Administrative structure of Baden-Württemberg (based on [Wikimedia Commons 2012])

The region of Baden-Württemberg is according to [BMEL 2014] a highly wooded region presenting a forested area of 1,371,847 ha with a 38% share of the state's total surface. Only the federal states of Hesse and Rhineland-Palatinate with a share of 42% and the Saarland – accounting for 40% of its entire territory – have a larger forest portion referred to the total surface than Baden-Württemberg [BMEL 2014]. The same source also reports that Baden-Württemberg possesses the second largest forest area after the federal state of Bavaria, which registers 2,605,563 ha. The Black Forest and the mountainous zone of the Swabian Alb are some of the most important woodlands of Baden-Württemberg with a significant contribution to the generation of wood resources.

2.1. Identification of wood resources

According to [WMBW 2010], a number of different types of wood resources arise in Baden-Württemberg. They show diverse characteristics, which ultimately depend on their nature and origin. These kinds of wood-based biomass fractions may be employed for energy and material purposes, but only a part of these are currently utilised. They are identified and classified below into six categories as illustrated in Figure 2.2.

- Forest residues from logging by means of thinning and clearing activities
- Wood raw material from copses and groves dispersed within the countryside
- Woody agricultural wastes from vineyards and orchards (pruning, clearing)
- Wood material from urban and interurban areas (private spaces, public infrastructures)
- Wood wastes from households, trade, construction and demolition
- Industrial wood residues from sawmills as well as pulp and paper mills

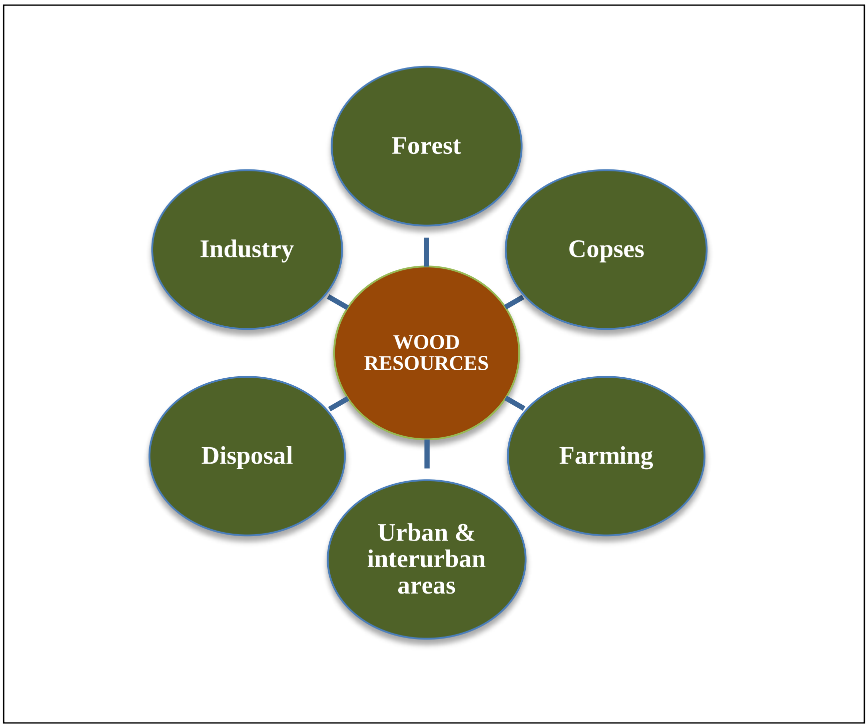


Figure 2.2: Origin of wood resources in Baden-Württemberg

Consistent with this classification, a relatively old although still valid study, [Leible et al. 2007], estimates around 4.4 million tonnes DW (dry weight) of different types of wood resources that were generated yearly across the entire territory of Baden-Württemberg. In quantitative terms, the addition of water at a rate of 35%[5] MC (moisture content) enables the

[5] Usual moisture content of wood after natural drying on a sunny site in the forests of Germany [FNR 2014]

presented amount of wood to be converted into nearly 7 million tonnes FW (fresh weight). The resultant quantity of wood resources is equivalent to 80 PJ of primary energy per year, which is absolutely consistent with the total technical potential of 78 PJ calculated in the cited study. This figure refers to the amount of resource produced in all sectors identified for the different origins according to the categorisation of Figure 2.2. These wood resources can be classified into forest residues from timber exploitations, woody green wastes (wood residues from urban and interurban areas including agricultural wastes), wood wastes (disposal of utilised solid wood products) and industrial wood residues from the processing of round wood into usable raw materials (paper, pulp and planks). Only the contribution of copses and groves to the total volume of wood resources is not included in the prior study, as they are considered separately as an additional type of wood material with a potential still to be estimated.

A further typology of wood resource is that derived from forest reserves and natural parks [WMBW 2010], which extend throughout the entire region, especially in the wildest areas of the Black Forest and the Swabian Alb. These spaces are also considered in the assessment of total wood resources for Baden-Württemberg even though they represent privileged natural areas where flora and fauna are to be protected and maintained for the next generations. This inclusion in the overall analysis precisely aims at combining conservation with rational exploitation of woodlands for better management and preservation of these special protected areas.

The identified five categories of wood resources are explained in detail in the following subsections.

2.1.1. Forest residues

Forest residues are a by-product of logging processes obtained in the stands of forests by means of thinnings and clearfells with the aim of producing timber as primary product [Kofman et al. 2007]. They are also called logging residues and include branches, crowns, tops, stumps and any wood material not appropriate for timber production or other final industrial use. The main source of forest residues is the weak thinning material or small timber. It comprises sick specimens as well as to low-quality trees with a diameter at breast height (DBH) between 7 and 20 cm [Kaltschmitt et al. 2001]; besides further woody species competing with other more favoured trees or stands.

According to [Kofman 2006], forest residues arising after logging activities present a moisture content of around 50%, which can be decreased to 20% by means of natural drying processes of several years of duration. However, rates of MC between 30% and 40% can be reached in shorter periods of time on the order of several months, for instance from spring to summer [Kofman et al. 2007]. But in any case, the moisture content of wood must be properly specified, as it has a major impact on the amount of energy liberated during wood combustion – to the extent that the lower the MC the higher the *lower heating value* of the fuel. As stated by [FNR 2014], seasonal drying takes place in the forests of Germany at the roadside usually until a moisture content of about 35% is achieved. From this point on, forest residues do not dry substantially anymore and then have to be loaded and transported after chipping. In consequence, this 35% moisture content is assumed for the forest residues arising in the woodlands of Baden-Württemberg.

[WMBW 2010] reports that an annual volume of 10.7 million m^3 *s* (cubic meter solid volume) of timber is produced in the forest areas of the federal state. About 70% of this raw material is sold to sawmills, another 15% goes to the paper, pulp and wood-based industry while the remaining 15% falls on final consumers of firewood with an amount of 36.4 PJ/a according to [BMVBS 2010]. By contrast, certain volumes of forest residues resulting from logging labours are, however, not completely collected for eventual energy or material purposes according to indications of both studies [WMBW 2010] and [BMVBS 2010]. An important and roughly quantified leftover remains in the forests of the region, albeit it could potentially offer a large amount of bioenergy. In terms of technical potential, forest residues in Baden-Wuerttemberg represent a promising energy carrier that is currently being underutilised by large industrial clients and small final consumers.

Table 2.1: Structure of forest areas in Baden-Württemberg on a surface basis (third Federal Forest Inventory BWI III [Kändler et al. 2014])

Forests in Baden-Württemberg		**BWI III**
Forest surface (1000 ha)		*1,402.3*
Ownership (%)	*Federation/State*	24.1 (0.5/23.6)
	Communal corporations	40
	Private owners	35.9
Species (%)	*Deciduous*	46.8
	Coniferous	53.2

The third Federal Forest Inventory (Bundeswaldinventur BWI III) gives insight into the structure of forests in Baden-Württemberg (see Table 2.1) with regard to their ownership and the type of harvested species (coniferous or deciduous). [Kändler et al. 2014] reveals that no essential change in the kind of property occurred in the 25 years since the first Federal Forest Inventory BWI I in 1987 until the publication of the third BWI in 2014. In this respect, 40% of the woodlands are corporate forests in the hands of public entities from municipalities, cities, towns or urban districts; around 36% are in private ownership and circa 24% of the forests are owned by either the federal state of Baden-Württemberg or the Federal Republic of Germany. The ownership type has a great influence on the forest management and consequently also on the economics of the generation process of timber and wood residues. On the other hand, while some statistical information regarding federation, state and corporate forests are well known and published, this is not completely the case for private owned woodlands due to their right of non-disclosure of private information [ForstBW 2013]. As regards the classification of trees in species, the around 1.37 million ha of forest areas are covered by 53.2% of coniferous trees as well as 46.8% of deciduous specimens. But the share of each type of species has really experienced a major change since the first inventory of 1987. From this year onwards, the percentage of deciduous trees grew continuously from 36.1% to 42.9% in 2002 (BWI II) and definitely to 46.8% of the total forest surface due to the decline of spruce and pine trees [Kändler et al. 2014].

2.1.2. Landscape wood raw material

Landscape wood raw material is not a residue in itself but a natural resource, which can be obtained by harvesting trees and bushes growing in wooded formations such as copses and groves scattered all over the landscape. These small-sized woodlands arise dispersedly within the open country (e.g. hedge banks), mostly on succession areas[6] within abandoned farmland and underexploited grasslands and pasturelands. To this extent, [LEADER 2012] additionally points out the possibility that certain terrains at forest boundaries between agricultural fields and woodlands might also provide a contribution to this resource. Specifically, this category involves wood raw material derived from small wooded areas that does not require any maintenance labour as a whole, but that they might be partially trimmed off with a given periodicity. A completely different resource – consequently not included as landscape wood raw material – is the case of certain disturbing parts belonging to wooded formations, which are next to some infrastructures such as roads, railways and waterways and need to be regularly maintained in order to facilitate the viability (see next subsection about woody green wastes). As a result, landscape-based resources currently present the particularity that they are being hardly exploited for either material or energy purposes, so that most wood raw material remains unharvested on copses and groves [Johst et al. 2014]. Therefore, this resource represents a substantial free potential of bioenergy, which is to a large extent still untapped. On the downside, copses and groves and in general all kind of small wooded structures from the countryside are unfortunately not quantified and hence not inventoried due to the complex nature of implementing such a task and despite the increasing interest in this raw material.

A further relevant point concerns the ownership structure of those terrains producing landscape wood raw material. The property of succession areas as well as that of copses and

[6] According to the UNESCO Encyclopaedia of Life Support Systems [EOLSS], succession as a concept concerning a temporal dimension of biodiversity dynamics was introduced in 1806 in its present meaning. Two main types of succession can be distinguished: (i) primary succession, which starts when some vegetation arise in uncolonised bare substrates (e.g. sand dunes, alluvial and volcanic deposits or glacial retreat zones), and (ii) secondary succession, which begins on sites where the former vegetation cover has previously been destroyed or severely disturbed, but soil formation processes have already taken place and soil seed banks are still present. In line with this definition, succession areas in Baden-Württemberg exclusively refer to the second case of secondary succession, as these terrains previously undergone agricultural or livestock exploitation before being abandoned to the current underused state, from which copses and small wooded structures have grown. On the other hand, the study [NYSDEC 2006], which was commissioned by the New York State Department of Environmental Conservation, also provides a good definition of succession as a series of gradual replacements of a plant community (and the associated fauna) by another over time and in the absence of disturbance. Each intermediate phase of this process is denominated successional stage.

small wooded areas resides in public and private hands, with the former registering a more active utilisation of this wood resource [LEADER 2012]. An additional aspect, equally indicated by the same study, is the large amount of land owners, which possess the different plots making up such succession areas. In contrast to forest residues, the ownership type does not have a major impact on the management of these surfaces. It is rather the number of potential landlords within a specific succession area, which more significantly conditions the corresponding harvesting process.

Another issue, which was introduced by [FNR 2014], is that the composition of landscape wood raw material is highly heterogeneous. This is in general owing to the large diversity of wood species, which in turn may also exhibit a variable quality from one specimen (tree or bush) to another. [Johst et al. 2014] affirms in this sense that the quality of wood chips obtained from copses and groves might be affected and consequently be worse than that of forest residues because of this inhomogeneity. In relation to the wide variety of landscape-based wood resources, a project carried out on landscape reserves gave insight into this question by analysing 170 ha of mixed stands with respect to 50 ha of single-species based areas in the framework of a study directed by [Tischew et al. 2009]. As a synthesis of the above, the conclusion to be drawn is that landscape wood raw material can be considered as a mixture of coniferous and deciduous species according to a spatially varying ratio in contrast to forest residues, which are generated in relatively large forested areas with a prevailing type of species.

Regarding water content, landscape wood raw material shows a similar behaviour to forest residues, as both categories are constituted by the same species (coniferous or deciduous) with the common characteristic of reaching an equal rate of water content after drying on a sunny site. As a result, a moisture content of 35% is assigned to this resource as an assumption based on [FNR 2014], according to which natural drying within Germany's open land (and therefore within Baden-Württemberg's countryside) does not go beyond the referenced MC because of its relatively high environmental humidity.

2.1.3. Woody green wastes

Woody green wastes are made up of those wood resources that derive from two of the main sources described in Figure 2.2, namely wood residues from urban and interurban areas as well as agricultural wastes. The former are the result of the labours carried out for the maintenance of private ownerships and public infrastructures, whereas the latter arise as a residual product from farming activities. They both present the common characteristic of requiring costly disposal, because they cannot be easily removed as normal organic waste due to their large volume and low mass density [LUBW 2010]. For this reason, some usual procedures for elimination of these wood residues are their combustion in waste incineration plants with the subsequent conversion into power and heat [Abfallbilanz 2013], the simple process of comminution for production of compost by mulching on agricultural fields or even the burning of these wastes just in the place of collection [Johst et al. 2014].

The woody share of green wastes includes branches, crowns, stumps, tops, roots, whole small trees and bushes that originate in residential areas – e.g. in gardens and public spaces such as cemeteries, camping sites or parks – as well as in interurban zones along roads, railways and waterways. On the other hand, woody green wastes are additionally comprised of residues arising in those labours seasonally accomplished on both vineyards and orchards as a result of pruning, clearing or harvesting tasks (e.g. harvest wastes such as husks). According to [LUBW 2010] and [VRRN 2010], the woody fraction of green wastes roughly accounts for 25% of total green wastes, whereas the remaining 75% is exclusively of an herbaceous nature. Therefore, the latter portion can be fed into biologic processes consisting of either a unique phase of composting or a combination of fermentation (biogas production) and composting by undergoing a so called "cascade use" procedure only suitable for non-woody material.

As regards energy generation, an important aspect exhibited by woody green wastes as compared to forest or landscape-derived resources is that green wastes present slightly lower rates of heating value along with a higher emission potential and also more elevated levels of nutrients [LUBW 2010], which is usually associated with increased formation of ashes. In practice, the quality of woody green wastes such as pruning rests from farming is so low that they are usually not collected and left on the ground for a subsequent process of mulching.

2.1.4. Wood wastes

The first three previously analysed types of wood resources are actually materials directly gained from nature without having suffered any sort of transformation. In contrast, wood wastes are the final result of the elimination of residual wood by means of municipal waste disposal services. Wood wastes are generated by a number of sectors (households, commerce, industry, construction) and arise in different fractions as a used resource ranging from untreated to treated materials [DEFRA 2012]. In such a context, the German Act of wood wastes [AltholzV 2017] regulates what resources are categorised as wood wastes by taking into account the presence of other materials, substances or additives that could modify the original nature of this residues. In agreement with this law, wood wastes refer to the portion of wood remains including old timber, utilised articles of furniture, shipping pallets and wood debris. The concept of "cascade use" may also be identified within the value chain of wood wastes, since old or already used wood residues can be reutilised for energy or other material purposes after a previous utilisation for the original intended use.

2.1.5. Industrial wood residues

Similarly to wood wastes, industrial wood residues are not a resource arising in woodlands either. They are a by-product of wood transformation processes performed in the wood industry [AltholzV 2017]. This economic sector involves both the saw mill and pulp industry, which is disseminated throughout the whole territory, especially in most forested areas. As a highly wooded region, Baden-Württemberg presents a lot of production centres for the development of this industrial activity, which has become a significant economic sector in the federal state.

Wood processing in saw and pulp mills generates substantial amounts of secondary wood residues of industrial origin (e.g. sawn timber, sawdust, bark) that are mostly treated in further steps for energy or material purposes (e.g. fabrication of pellets or fibreboards). Thereby, this resource introduces an additional example of "cascade use"-based valorisation process, where a second use of the wood feedstock is implemented after generation of the main products timber and pulp.

2.2. Potential of wood resources

Before analysing the potential of the previously identified wood resources, an introduction concerning the different types of potential is to be conducted. The concept of potential, when applied to resources distributed over a surface, encompasses four possible restriction levels that may be arranged according to a pyramidal structure. Figure 2.3 below relates these four levels respectively to four different bounded potentials, namely the theoretical, technical, economic and market potential. In this regard, it is illustrated how every restriction level acts over the whole potential thus successively reducing the available quantity of resource on the basis of specific technical, economic and market constraints.

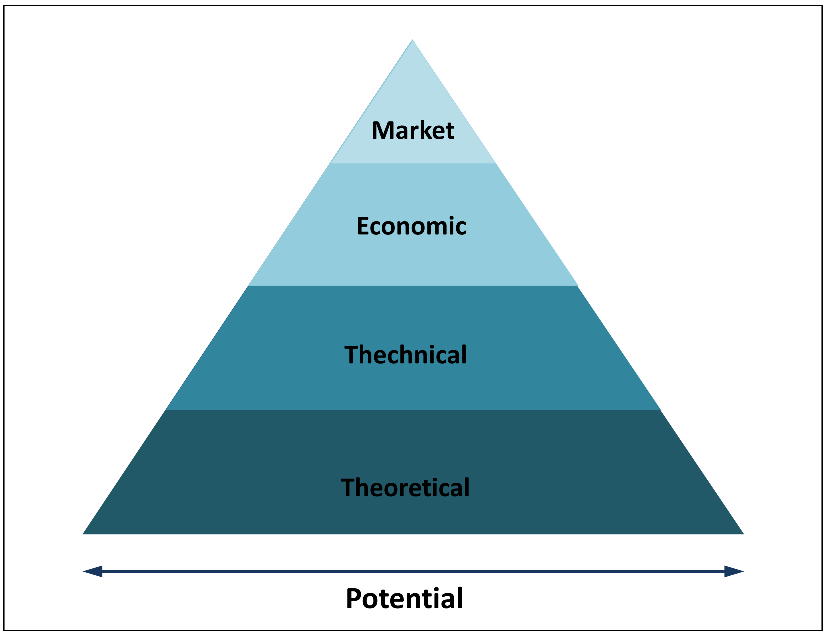


Figure 2.3: Different restriction levels of potential for a resource distributed over a surface (based on [Lopez et al 2012])

As stated by [Rentz et al. 2001], the theoretical potential is determined by the physically available amount of resource within a certain region, throughout a given period of time and regardless of any other kind of restriction of economic or technical nature. Likewise, [Bidart 2013] defines the theoretical limit of a potential as the upper limit of primary energy calculated without imposing any kind of constraint.

Secondly, [Rentz et al. 2001] designates the technical potential as a fraction of the theoretical potential that can only be utilised under the consideration of certain technical restrictions such as those related to certain topographic limitations (e.g. accessibility of resource exploitation areas) or the existence of administrative specifications (e.g. preservation of natural parks). In general, certain aspects such as structural, instrumental, administrative, social, land-use and ecologic characteristics are accepted as appropriate criteria to determine the available technical potential. Additionally, the definition of technical limit as presented by [Bidart 2013] takes into account all possible technological restrictions shaping the potential for a particular primary energy carrier within the surface of a targeted territory.

Thirdly, the economic potential comprises a share of the technical potential that becomes economically competitive as compared to other fractions of the same technical potential while exploited under identical conditions [Rentz et al. 2001]. In this sense, the variation of certain economic parameters such as costs, prices or remunerations as well as the introduction of more cost-effective and innovative processes may have a strong influence on the final dimension of the economically exploitable potential.

Finally, based on the interesting contribution of the technical report published by NREL [Lopez et al. 2012], the market potential is introduced and thus presented as a decisive constraint for determining the corresponding dimension under the existing market conditions. The market potential equals a subset of the economic potential that complies with all conditions and requirements imposed by the market – beyond the proven economic feasibility of the process in question. Aspects such as the regional market development over time, the investor’s response to commercial challenges as well as the consideration of resource-related policies may lead to significant variations in the market potential.

Knowing the dimension of these four potentials can help determine the economics of a bioenergy system when it comes to evaluating the viability of a wood resources-based energy vector in the power market of a region. Accordingly, the technical potentials of the different types of wood resources originating in Baden-Württemberg are to be estimated in the next subsections as input data for the optimisation-based analysis of the corresponding bioenergy subsystem. As a result, the fraction of the technical potential that is exploitable under profitability conditions is to be determined, thus giving insight into the dimension of the economic potential of wood resources.

2.2.1. Determination of the technical potentials of wood resources

As previously analysed, five different types of wood resources arise in the federal state of Baden-Württemberg, namely forest residues, landscape wood raw material, woody green wastes and both kinds of wood-based remains derived from either municipal disposal (wood wastes) or the wood industry (industrial wood residues). The following pie chart in Figure 2.4 displays the annual technical potential of the available wood resources that are generated in Baden-Württemberg.

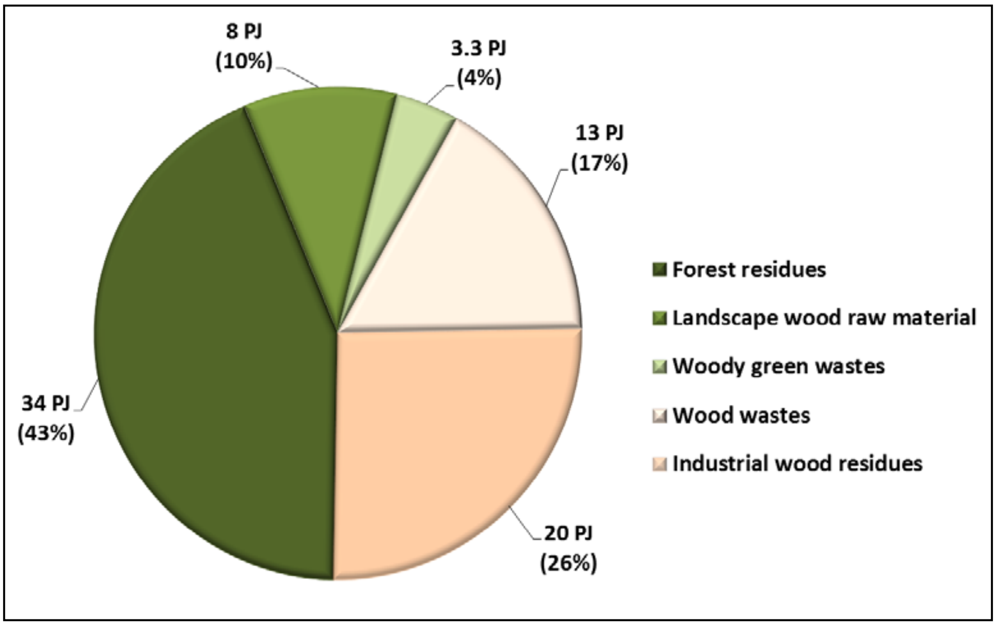


Figure 2.4: Annual technical potentials of wood resources in Baden-Württemberg for the year 2010 (based on [WMBW 2010], [Becker et al. 2007], [LEADER 2012], [Abfallbilanz 2013], [LUBW 2008] and [BMVBS 2010])

With respect to forest residues originating in the woodlands of Baden-Württemberg as a result of harvesting labours, [WMBW 2010] references the existence of a technical potential of 34 PJ/a, which nearly represents half of the whole wood resources in the federal state. This amount of bioenergy is also referred to by other studies such as [BMVBS 2010] and [Bunzel et al. 2011]. They are all based on the same database developed by the German research centre Deutsches Biomasseforschungszentrum (DBFZ), according to which around 35 PJ/a are accounted for by the technical potential of forest residues. On the contrary, a somewhat lower portion of forest residues estimated at 32 PJ was reported by [Leible et al. 2007] with 1,700,000 tonnes DW. In this sense, [Eltrop et al. 2006] provided even a much lower quantity of forest residues in the order of about 1,200,000 tonnes DW, which would be associated with a technical potential of not more than 21 PJ/a. In any case, the technical potential of forest residues in all previous studies is assessed separately from an already consumed portion of 36.4 PJ/a, which is dedicated to energy and material purposes but without any residual character. Moreover, the technical potential of forest residues published by [Leible et al. 2007], [BMVBS 2010], [WMBW 2010] and [Bunzel et al. 2011] appears to be in the order of magnitude of that reported by [Kappler 2008], which ranges between 1,600,000 and 2,200,000 tonnes DW for all Baden-Württemberg. In keeping with this last study, the technical potential of forest residues can be predetermined at 34 PJ per year, as circa 2,000,000 tonnes DW of forest residues may be assumed to be required for conversion into that volume of primary energy if a lower heating value of 11[7] GJ/t FW at 35% MC is taken into account. Thus, building on supply-cost curves also conducted by [Kappler 2008] for forest residues, a maximal production cost of this resource chipped at the forest roadside can be deduced and valued at circa 143.4 €/t DW (equivalently 93.2 €/t FW at 35% MC) if the production chain from felling to chipping is considered.

Another important source of wood resources is landscape wood raw material with an assessed technical potential of 8 PJ per year. It represents approximately 10% of the whole annual wood resources in Baden-Württemberg according to the estimations based on [WMBW 2010], [Becker et al. 2007] and [LEADER 2012]. This feedstock consists of harvested trees and bushes growing in copses and groves within succession areas and forest boundaries dispersed throughout the countryside. This potential represents an important contribution in Baden-Württemberg because it is extremely underused at present.

Woody green wastes, as a resource originating throughout the urban and interurban zones as well as in the agricultural areas of Baden-Württemberg, also show a significant technical potential that is to be allowed for despite its reduced dimension. According to [Abfallbilanz 2013], the total green wastes collected in the federal state during the year 2013 amounted to 906,000 tonnes FW, from which 238,000 tonnes FW were combusted in existing incineration plants thus generating power and heat. This latter quantity equates to the woody fraction of green wastes, which in fact corresponds approximately to 25% of total green wastes as reported by [LUBW 2010]. In line with this, the technical potential of woody green wastes can be estimated at a total of 3.3 PJ/a over the course of 2013. This is also in accordance with the percentage exhibited by the woody portion – namely 25% – of the annual generation volume of 13 PJ/a, which is referenced by [WMBW 2010] for the whole woody and herbaceous green wastes collected from private spaces and public infrastructures.

On the other hand, the annual amount of wood wastes generated in the federal state accounted for 864,817 tonnes DW according to [LUBW 2008]. As stated by [WMBW 2010], this quantity corresponds to a technical potential of 13 PJ/a distributed all over the region. As part of the municipal waste stream, this potential is managed by the disposal system of Baden-Württemberg. Lastly, the already cited study [BMVBS 2010] – conducted by the competent Ministry of the German Federal Republic – indicates a technical potential of industrial wood residues in Baden-Württemberg equal to 19.8 PJ per year. A quantity that differs noticeably from the amount of 15 PJ/a as stated by the report [WMBW 2010], published by the Ministry of Economy of the government of Baden-Württemberg. In this regard, the former potential for industrial wood residues is taken into consideration and thus illustrated in Figure 2.4 due to the broader scope of the corresponding study, in which all federal states are treated.

[7] Average value taken from [FNR 2014]

2.2.2. Consumed and free technical potentials of wood resources

The above determined technical potentials of the different types of wood resources arising in Baden-Württemberg are either partially or completely consumed for energy or material purposes. Depending on the technical and economic conditions in which these resources are gathered and valorised, a pair of specific amounts involving the free and consumed technical potentials for each resource is to be identified. The below depicted bar diagram of Figure 2.5 illustrates in which proportion each wood resource still presents an exploitable free potential for future utilisation or if otherwise it is almost or completely depleted.

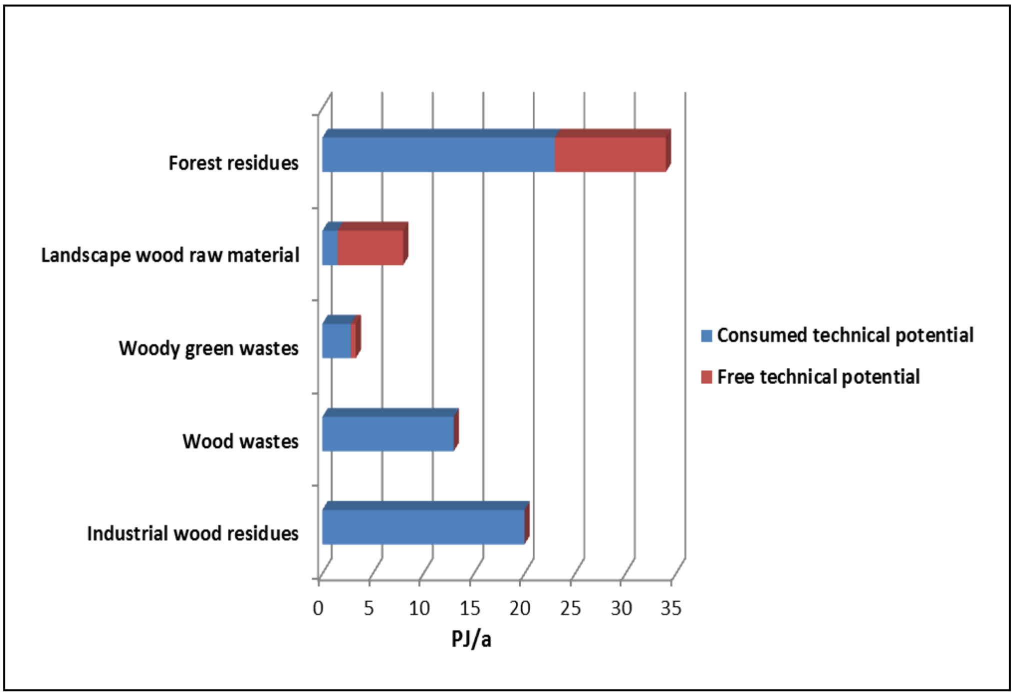


Figure 2.5: Annual consumed and free technical potentials of wood resources in Baden-Württemberg in the year 2010 (based on [WMBW 2010], [Abfallbilanz 2013], [LUBW 2008] and [BMVBS 2010])

According to this diagram, a consumed potential of 23 PJ/a is referenced by [WMBW 2010] as well as [Bunzel et al. 2011] and [BMVBS 2010] in relation to roughly 1,200,000 tonnes DW of forest residues already used up. This amount perfectly correlates with a free potential of 11 PJ/a that arises distributed all over Baden-Württemberg. On the other side, the determination of both consumed and free potentials for landscape wood raw material is also possible by means of data published by [WMBW 2010]: an amount of roughly 1.5 PJ/a is consumed in contrast to the remaining free potential valued at 6.5 PJ/a.

With regard to woody green wastes, [Abfallbilanz 2013] refers to 238,000 tonnes consumed and thermally valorised during the year 2013. This amount approximately equates to 2.8 PJ, which permits deducing an extremely tiny free potential of 0.5 PJ still available to be utilised in the districts of the federal state. In practice, this annual free potential might be supposed to be zero or negligible on account of the fact that the corresponding resources might already be consumed, although they are not registered as such. This assumption lies on the own nature of green wastes, which arise and then necessarily have to be disposed of, with certainty, by means of their utilization for energy conversion or material use.

According to [LUBW 2008] and [BMVBS 2010], both wood wastes and industrial wood residues exhibit no free potential since the entire generation of the former is already being reutilised for either energy or material purposes, whereas the latter are self-consumed by the processing factories themselves in the wood industry. In both cases, wood resources are completely depleted and thus transformed into material or energy-based final products.

2.2.3. Free technical potentials at district level

The geography and the spatial magnitude of Baden-Württemberg together with its administrative subdivision into 35 districts and 9 urban districts suggests analysing this bioenergy system by calculating the remaining free potentials of the previously presented wood resources at a simple district level. In reality, a further step down across the hierarchy of the administrative structure of the federal state would signify descending into the municipal or community level. Thus, a higher spatial resolution would be attained as a result of reaching a lower aggregation level for the spatial subdivision in question. This procedure would imply a more accurate potential allocation to the intended spatial units for each kind of wood resource. Nevertheless, data availability relating to the free and consumed technical potentials of wood resources at community level is found to be quite limited. The cconstruction of suitable data would have required conducting a harmonisation process for applying it to all communities due to possible inconsistencies among parameters of different spatial units. This way, producing such a databank without suitable research studies, appropriate methods (e.g. laser scan exploration system, remote sensing technique) and the necessary expertise would turn out to be quite complicated. Due to the above argumentations, it can be concluded that the spatial distribution of the free potentials for each formerly itemised type of wood resources can only be carried out on a mere district basis.

In keeping with this, the bar diagram in Figure 2.5 showing all types of wood resources at the level of the federal state uniquely indicates the existence of significant free potentials for forest residues and landscape wood raw material. To this extent, the remaining potential of woody green wastes becomes virtually negligible, whereas wood wastes and industrial wood residues directly exhibit a zero free potential in both cases. In consequence, only the potentials of forest residues and landscape wood raw material are to be appropriately analysed and illustrated in the next subdivisions as a spatial distribution at district level. Although the spatial aggregation level determined by the district – or that of the community – have already been employed for Baden-Württemberg in other research studies such as [Leible et al. 2007] and [Kappler 2008], the spatial distribution of the free portion of the technical potentials for forest residues and landscape wood raw material is ascertained at the spatial aggregation level of the district for the first time. Concerning the aforementioned publications, only the total technical potential of different types of biomass was referred to instead of the free or even the consumed fraction. Forest residues were effectively analysed at different spatial aggregation levels but without any reference to landscape-based resources. In this way, one of the intended objectives of this dissertation is the identification of the existing free potentials of wood resources growing in the districts of Baden-Württemberg. Subsequently, their optimal utilisation for electricity production – by allocating these free technical potentials to bio-based power plants – can already be ascertained. This analysis comprises a new data set that is never employed before for optimising the wood resources-based bioenergy subsystem of this federal state. For this purpose, the following subdivisions give insight into the fundamentals, methodology and assumptions taken into consideration for determining the spatial distribution of the free potentials for both forest residues and landscape wood raw material in the districts of the federal state of Baden-Württemberg.

2.2.3.1. Spatial distribution of forest residues

A series of fundamentals are described hereafter in relation to the determination of the spatial distribution of forest residues at district level within the region of Baden-Württemberg. These involve ascertaining the specific yield (tonne/hectare) of this wood resource as well as the forest areas inventoried for each district against the backdrop of the consideration of the total dimension of this residue in energy and material terms at federal state level.

As previously indicated, the free potential of forest residues amounts to 11 PJ per year in contrast to the already consumed potential of around 23 PJ/a. As a result, the sum of both quantities totals a technical potential of 34 PJ/a for the whole of Baden-Württemberg. In agreement with these figures, around 640,000 tonnes DW account for the aforementioned amount of 11 PJ/a as a free potential of forest residues distributed throughout all districts of the federal state. If 35% moisture content is taken into account, an equivalent quantity of 950,000 tonnes FW is to be registered.

On another level, the specific yield or throughput of forest residues on a surplus basis expressed as the annual free technical potential per unit area of woodlands in each district of Baden-Württemberg is depicted in Figure 2.6 based on appropriately processed data derived from the statistical source [ForstBW 2013] and the study [Leible et al. 2007]. The specific yield is calculated at 35% MC because this is the usual moisture content registered in the forest stands of the federal state [FNR 2014]. As s result, the average value of the specific yields for all districts of Baden-Württemberg, when including the water content and being exclusively referred to the inventoried forest areas, lies around 0.68 t FW/ha. This parameter reaches a maximum value at 1.92 t FW/ha for the urban district of Pforzheim and a minimum for Ulm on the order of 0.15 t FW/ha.

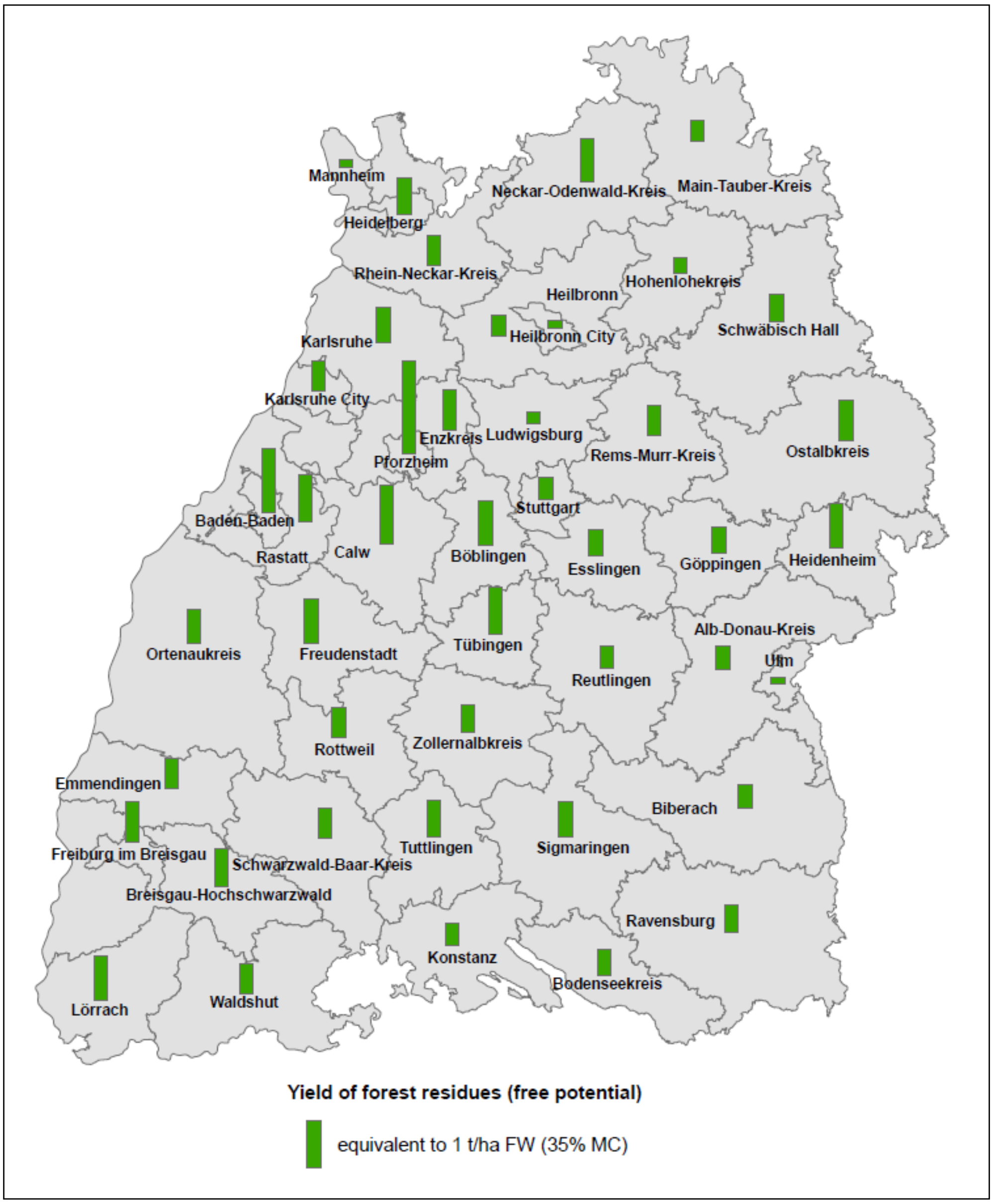


Figure 2.6: Free potential-based specific yield of forest residues in the districts of Baden-Württemberg

On the one hand, the specific yields resulting from unconsumed forest residues arising in each district of the federal state are determined and exhibited on the above represented map. On the other, the determination of the available forest areas in each district of Baden-Württemberg is of great importance for calculating the free potential of forest residues in each district. The study [ForstBW 2013] includes an inventory of the forest areas in Baden-Württemberg and refers to these surfaces (hectares) for each of the 44 districts as the sum of all public and private forest areas (see Figure 2.7). In this regard, mention should be made of particular data concerning the specific forest area of the urban district of Mannheim, which registers a significantly small wooded surface of only 226 ha. This area is considered to be extremely low in relation to the forest surfaces of other similarly sized urban districts such as Heilbronn City, Karlsruhe City, Heidelberg, Pforzheim or Ulm. In fact, [StaBund 2016] assigns to

Mannheim other more congruent forest area[8], around 1812 ha, which is equally consistent with the specific data generated for the third Federal Forest Inventory (Bundeswaldinventur BWI III) and definitely selected for this research study.

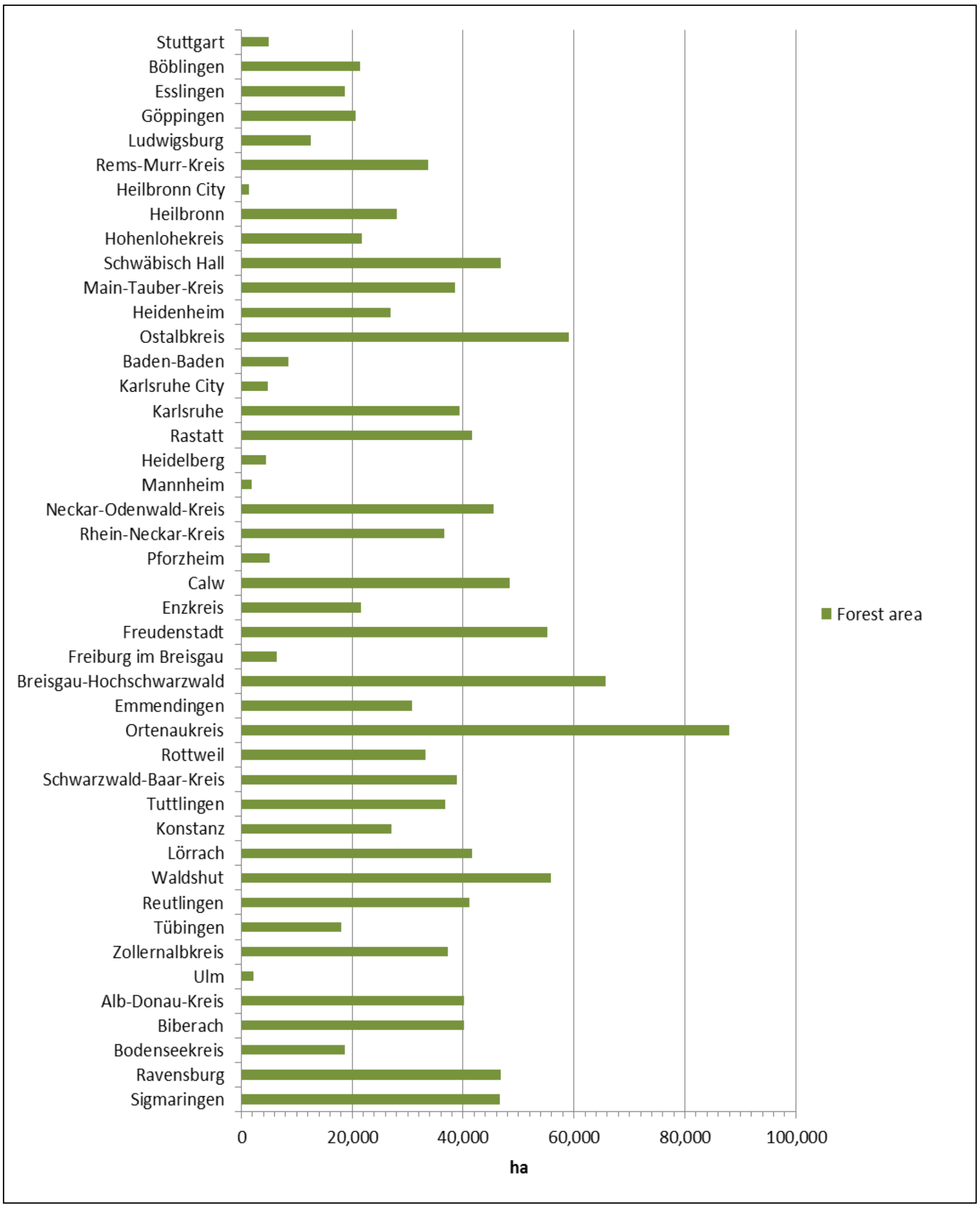


Figure 2.7: Total forest area for each district of Baden-Württemberg

The methodology underlying the determination of the spatial distribution of forest residues at district level is based on the calculation of the free technical potentials on the basis of the appropriate multiplication of the free potential-based specific yield of forest residues and the total forest area for each district. This permits generating the spatial distribution for the free potential of forest residues at district level in the region of Baden-Württemberg. These free

[8] According to [StaBund 2016], the rest of the districts show forest areas quite similar to the data exhibited by [ForstBW 2013]. Only the district of Mannheim gives such divergent information between both sources.

potentials are conceived as an annual free yield for each district and are represented in tonnes FW at 35% MC in Figure 2.8 below.

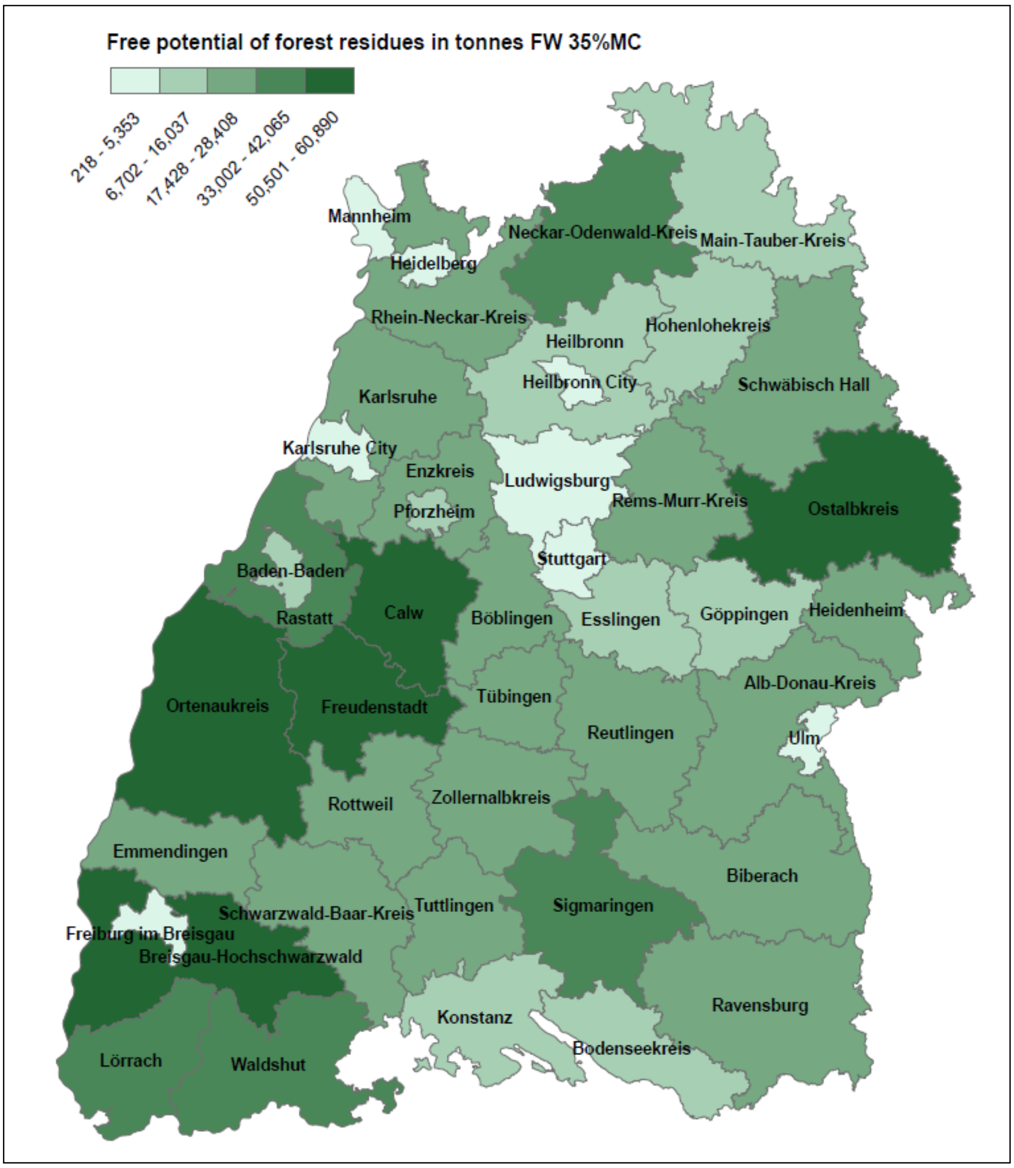


Figure 2.8: Annual free potential of forest residues for each district of Baden-Württemberg

2.2.3.2. Spatial distribution of landscape wood raw material

The determination of the spatial distribution of landscape wood raw material at district level rests upon a number of fundamentals that put a limit to the dimension of the free potential for each district. Landscape wood raw material as an indigenous resource derives from copses and groves growing in succession areas dispersed over the open country of the entire territory of the federal state. As formerly analysed, they represent a free potential of 6.5 PJ per year as against the already consumed potential of circa 1.5 PJ/a, thereby totalling approximately 8 PJ/a. According to this figures, circa 580,000 tonnes FW at 35% MC would make up the total free potential of landscape-based resources collected in the districts of Baden-Württemberg.

From a methodological point of view, the estimation of the district-specific free potentials for landscape wood raw material follows the same steps as those conducted for forest residues. In the first plane, the specific yield on a surplus basis (specific free potential) for each district is to be quantified and subsequently multiplied by the corresponding succession areas of copses and groves. The resulting amount equates to the free potentials of landscape wood raw material for each district. It is the objective of this subdivision and is therefore calculated on the basis of a series of fundamentals that are successively presented hereunder.

The first step of this process could not be successfully performed through a simple literature review due to the lack of data concerning the dimension of the specific yield. Instead, a number of studies exclusively refer to the annual rate of growth for trees and bushes harvested from copses and groves, which is expressed as the theoretical potential per unit area. In this sense, certain studies such as [Wolff 2005], [Straub 2010], [Becker et al. 2007] and [LEADER 2012] report a specific rate of growth per year of approximately 5 $t \cdot ha^{-1} \cdot a^{-1}$ FW; whereas [Kaltschmitt et al. 2009] indicates an amount varying between 3 and 6 $t \cdot ha^{-1} \cdot a^{-1}$ FW with MC between 40% to 60% (before natural drying); which on the other hand is in a similar range as that of [Johst et al. 2014] with 3.5-5.5 $t \cdot ha^{-1} \cdot a^{-1}$ FW. Other studies such as [Tischew et al. 2009], however, refers to a wide array of rates of generation ranging from 1 to 6 $t \cdot ha^{-1} \cdot a^{-1}$ FW. After a comprehensive analysis of all these publications, an annual rate of growth in the order of 5 $t \cdot ha^{-1} \cdot a^{-1}$ FW is assumed as an appropriate specific theoretical potential for landscape-based resources (see Table 2.2). Nevertheless, the corresponding technical potential of this resource is still to be assessed, namely by introducing a technically usable portion, which [Wolff 2005] and [Becker et al. 2007] specifies at around 70% for trees and bushes originating in copses from succession areas. Thereby, this percentage determines the specific technical potential (t/ha) or technical potential per unit area of landscape wood raw material generated during a year in every district of the federal state with a common value of 3.5 $t \cdot ha^{-1} \cdot a^{-1}$ FW 35% MC. But the estimation of the specific free potential or specific yield still requires the subtraction of the consumed fraction from the entire specific technical potential. As landscape-based resources register no consumed share[9], then the annual amount of the specific yield or specific free technical potential of landscape wood raw material is equal to the previously calculated specific technical potential, i.e. 3.5 $t \cdot ha^{-1} \cdot a^{-1}$ FW 35% MC (see Table 2.2), for every district of Baden-Württemberg. In short, the free portion of technical potential of landscape wood raw material equates to the technically usable portion of the yearly generated theoretical potential of landscape resources. For a better methodological understanding, the entire deduction process with the corresponding outcomes for each stage is accordingly represented in following Table 2.2.

[9] There is indeed no regular consumption of landscape-based wood resources with the exception of those areas where the consumed share (1.5 PJ/a for all Baden-Württemberg) are already being harvested like in certain specific cases such as the pilot project introduced by [LEADER 2012]. Obviously, if landscape wood raw material is consumed in a specific site, then there will be no free potential anymore on this area. Anyhow, most of the landscape-based resources, specifically 6.5 PJ/a, is still to be exploited in the remaining succession areas.

Table 2.2: Methodological steps for the determination of the specific free potential (specific yield) per year for landscape wood raw material in the districts of Baden-Württemberg

Specific theoretical potential (rate of growth)	**Technically usable portion**	**Specific technical potential**	**Consumed portion**	**Specific free potential (specific yield)**
t·ha⁻¹·a⁻¹ FW 35% MC	*%*	*t·ha⁻¹·a⁻¹ FW 35% MC*	*%*	*t·ha⁻¹·a⁻¹ FW 35% MC*
5	70	3.5	0	**3.5**

The specific free potential (specific yield) of landscape wood raw material is estimated at 3.5 $t \cdot ha^{-1} \cdot a^{-1}$ FW at 35% MC, which by comparison proves to be significantly higher than the average (0.68 $t \cdot ha^{-1} \cdot a^{-1}$ FW at 35% MC) of all free potentials of forest residues over all districts. The rationale behind this fact lies in the low degree of utilisation of wood material originating from landscape, in contrast to the high level of exploitation of forestry-based wood resources.

The second methodological step aiming at the identification of the free potentials of landscape-based resources consists in estimating the total surface of copses and groves within each district of Baden-Württemberg. Nevertheless, the calculation of the number of hectares of copses and other similar small wooded formations growing in the succession areas of each specific district is not an easy task. In fact, no study on this topic is still conducted for a complete federal state at the time of execution of this dissertation – not even for a smaller territory than Baden-Württemberg. The reason for this refers to the high complexity and elevated costs linked to either of the novel techniques based on remote sensing and laser scan exploration [Straub 2010].

On account of this lack of data availability, a new approach is to be implemented so as to address the estimation of the copse areas. An interesting solution seems to be the introduction of five fundamental district classes based on the gradation of the rate of forest density (see Table 2.3), namely the ratio of the forested area to the entire surface of each district. This array of district classes is based on a number of indications put forward by both studies [Becker et al. 2007] and [LEADER 2012], which permits introducing a pair of significant assumptions. The former study reports an analysis of a semi-urban zone (small town with surroundings) of 11 km^2, where the copse area accounts for 1.6% of the whole territory and roughly 5% of its farmland. If the prior analysis is extrapolated to a sparsely wooded district, then the portion of copses and groves could be assumed to be raised to around 8% of the total agricultural area due to the more reduced weight of urban zones in the total area of such a district if compared to the cited study. On the contrary, the latter research source refers to a highly wooded space (60 km^2) comprised of a few communities in the South of the Black Forest in Baden-Württemberg, for which 13% of the open country is declared to consist of copses. In line with this case, a maximum rate of 12% based on farmland can be assumed for highly forested districts. This percentage is ascribed to the fact that an entire, highly forested district should obviously present a somewhat lower rate owing to the inclusion of a higher proportion of agricultural areas as compared to the selected forested communities. Hence, a strong correlation between the forest density of a district and the corresponding percentage of copse areas – based on its farmland – can be identified under the premise that the more forested a region is the higher its portion of copses should be. Besides, a high rate of forest density in the region of Baden-Württemberg is typically related to uneven terrains, which favour the formation of copses and groves within the succession areas dispersed throughout the countryside. These facts together with the categorisation of the districts into five fundamental classes is synthesised in Table 2.3 in order to facilitate estimating the respective landscape areas formed by copses.

Table 2.3: Fundamental district classes on the basis of the correlation between forest density and formation of copse areas in the districts of Baden-Württemberg

District class	**Rate of forest density** *(-)*	**Percentage of copse areas** *(% of farmland)*
1	0.10 - 0.19	8
2	0.20 - 0.29	9
3	0.30 - 0.39	10
4	0.40 - 0.49	11
5	0.50 - 0.63	12

The first fundamental district class comprises those districts showing scarce forest zones. This is the case of some urban districts such as Mannheim, Heilbronn City and Ulm in addition to the district of Ludwigsburg, which is to a great extent part of the agglomeration area of Stuttgart. All of them are assigned a percentage of copse areas based on farmland in the order of around 8%. At the opposite end, the fifth fundamental district class encompasses all those substantially wooded districts characterised by high rates of forest density varying between 0.50 and the maximum value 0.63. The districts of Freudenstadt, Calw, Baden-Baden, Rastatt, Pforzheim, Lörrach and Tuttlingen belong to this fifth district category, which the highest share of copse areas referred to farmland – specifically 12% – is allocated to. Between both ends, a linear gradation of both the rate of forest density and the percentage of copse areas takes place in the form of three further district classes.

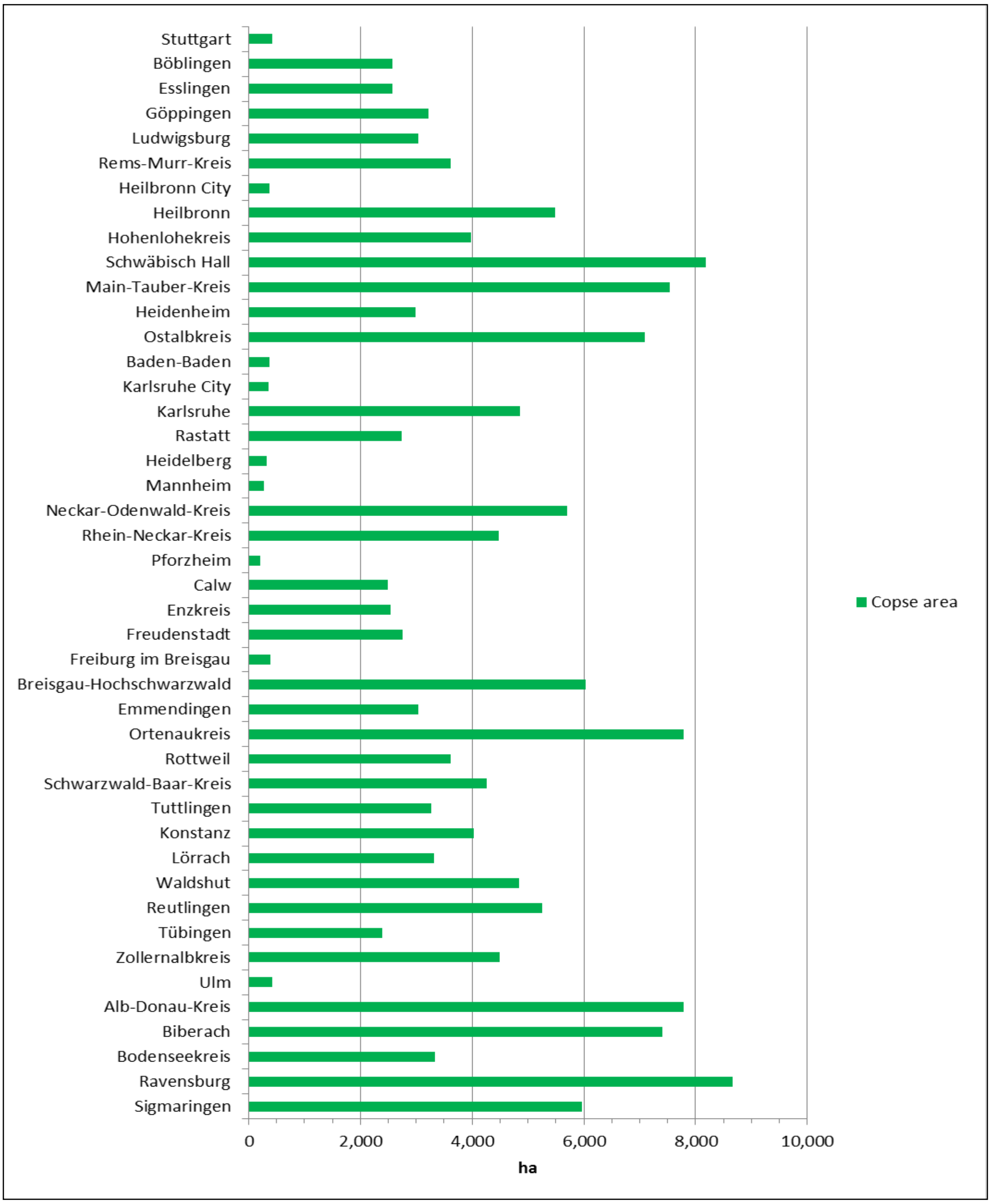


Figure 2.9: Total surface of copses in each district of Baden-Württemberg

The percentage of copse areas on district's farmland, which is illustrated in Table 2.3, along with the statistical data regarding the agricultural area of each district [SLBW 2016] allow as an acceptable estimate the district-specific surface of groves and copses to be assessed for the entire territory of Baden-Württemberg. Accordingly, Figure 2.9 summarizes for every district the corresponding total surface of all small wooded areas (copses and groves) that produce landscape wood raw material in succession areas located out of forests and within the farmland.

After having determined the free potential-based specific yield of landscape wood raw material as well as the total surface of copses – both at district level –, the spatial distribution of the free technical potentials for landscape-based resources derived from copses and groves at district level can be reproduced by appropriately multiplying both parameters for each specific administrative unit. These free potentials are accordingly depicted in tonnes FW at 35% MC in Figure 2.10 below.

Figure 2.10: Annual free potential of landscape wood raw material for all districts of Baden-Württemberg

2.2.4. Tabulation of the free technical potentials of wood resources

The free technical potentials of both forest residues and landscape wood raw material in each of the 44 districts of Baden-Württemberg are displayed in Table 2.4 below. The corresponding annual amounts are expressed in tonnes FW at 35% moisture content.

Table 2.4: Free potentials of forest residues and landscape wood raw material at district level

	Free technical potential *(t/a FW 35% MC)*	
	Forest residues	***Landscape wood raw material***
Stuttgart	2,292	1,498
Böblingen	19,750	9,000
Esslingen	10,060	9,008
Göppingen	11,110	11,276
Ludwigsburg	2,884	10,637
Rems-Murr-Kreis	20,716	12,659
Heilbronn City	218	1,326
Heilbronn	11,674	19,214
Hohenlohekreis	6,702	13,949
Schwäbisch Hall	26,653	28,645
Main-Tauber-Kreis	16,037	26,375
Heidenheim	25,318	10,471
Ostalbkreis	50,914	24,806
Baden-Baden	11,098	1,311
Karlsruhe City	2,982	1,241
Karlsruhe	28,408	16,990
Rastatt	40,286	9,566
Heidelberg	3,430	1,105
Mannheim	279	971
Neckar-Odenwald-Kreis	42,065	19,924
Rhein-Neckar-Kreis	22,532	15,647
Pforzheim	9,783	698
Calw	59,588	8,731
Enzkreis	18,312	8,894
Freudenstadt	50,912	9,645
Freiburg im Breisgau	5,353	1,391
Breisgau-Hochschwarzwald	50,501	21,103
Emmendingen	18,910	10,618
Ortenaukreis	60,890	27,248
Rottweil	20,478	12,639
Schwarzwald-Baar-Kreis	23,923	14,918
Tuttlingen	28,261	11,466
Konstanz	12,533	14,105
Lörrach	38,451	11,595
Waldshut	34,326	16,942
Reutlingen	19,021	18,363
Tübingen	17,428	8,347
Zollernalbkreis	21,233	15,741
Ulm	349	1,465
Alb-Donau-Kreis	19,179	27,225
Biberach	19,745	25,896
Bodenseekreis	10,318	11,652
Ravensburg	26,638	30,311
Sigmaringen	33,002	20,900

3. The supply chain of wood resources

The techno-economic description of the supply chain of wood resources requires an in-depth knowledge of all stages involved in the harvesting and transport of forest residues and landscape wood raw material. Such a holistic techno-economic analysis has never been performed before. It seeks to provide a unique integral methodology for the whole supply chain of any kind of wood resources. This chapter addresses the problem of cost allocation to the resulting products of a given manufacturing process on the basis of whether they behave as a by-product, a main or even a joint product. In this manner, a methodology for cost allocation to wood chips produced from forest residues collected at the forest roadside and landscape wood raw material at the chipping site is developed for the first time.

Subsequently, the most significant fundamentals on the different logistic chains for harvesting wood resources are introduced. In this regard, the types of forest ownership, the degrees of mechanisation, the steepness of slope of forest areas and the diameter at breast height together with the unit-mass law as well as the role of the chipping process determine to a large extent the logistic chains of forest residues harvested at the stand and carried to the forest road. Likewise, those logistic chains involving the harvesting of landscape wood raw material from wooded formations within landscape to a chipping site are also shaped by a number of aspects relating to the multiplicity of owners, a selected set of degrees of mechanisation, the effect of a lower diameter at breast height and the importance of the chosen location of chipping sites.

The introduction of the aforementioned basics enables developing an appropriate methodological approach for the techno-economic characterisation of each harvesting system. This approach is put forward for the first time with the aim of modelling any wood resources-based bioenergy system. According to this new approach, a list of logistic chains for the production of wood chips derived from forest residues includes the motor-manual harvesting system carried out by small private forest owners as well as the partly, highly and fully mechanised harvesting procedures being performed by large forest owners for different steepness of slope. Similarly, both the partly and highly mechanised harvesting techniques, which are managed by large forestry corporations for different terrain inclinations, are presented as the most representative logistic chains for harvesting and densifying landscape wood raw material.

Finally, the last stage within the complete supply chain of wood resources, namely the transport of wood chips to the corresponding conversion plant, is analysed on the basis of the existing bibliography. In addition, a novel method is developed for the purpose of choosing the most appropriate means of transport and hence determining its distance-specific transport costs as well as the corresponding loading and unloading costs.

3.1. The problem of production cost allocation to main or joint products and by-products

As stated by [Oenning 1997], the issue of cost allocation to the products of a manufacturing process is already mentioned in the economic literature of the eighteenth century, specifically in relation to the agricultural sector. According to this study, each targeted output is called *main product* while any other receives the name of *by-product* with the particularity that both types unavoidably arise if the purpose of the intended production process is to be fulfilled. In this respect, any manufacturing process is linked with the generation of a unique or several types of either a main or by-product with the objective clearly directed toward the production of a specific main product.

According to [Blocher et al. 2008], many manufacturing plants simultaneously yield one or more products apart from waste or defective units with the characteristic that neither of these outputs can be produced without the other. These output products start their manufacturing life as part of the same raw material until a certain point in the production process at which they can be easily distinguished from one another. In keeping with [Drury 1994], two or more output products can emerge either simultaneously or successively throughout the production processes from a number of different industries, namely chemicals, oil refining or food industry. As a result, these outputs are categorised either as a main product or as a by-product according to a specific cost allocation criterion to be determined. In this context, whereas the main product is intentionally produced, the by-product inevitably arises as an incidental output of the production process.

[Oenning 1997] and [Deevski 2016] separately introduce two different approaches in order to apportion production costs to both formerly mentioned kinds of products and, in turn, classify each output derived from a given manufacturing process. The first approach – which is not applied in this dissertation – distributes costs using physical measures such as weight, volume, quantity or energy content of the resulting main and by-products. The first step is to select the proper physical measure as the basis for the intended cost allocation procedure. As a disadvantage, the study [Blocher et al. 2008] reports that this method ignores the revenue-producing capability of individual products, which may have no relationship to any physical magnitude. Furthermore, each product can also show a different physical measure and then this criterion might end up not being applicable. Therefore, the following method is an alternative way that is clearly more preferable and widely used because it addresses these limitations. This second approach employs a benefits-received criterion, which suggests a cost allocation method conceived on the basis of the relative sales value (also reported as saleable value) of each generated output. The sales value of a product identifies its ability to yield sales when a manufactured article is marketed. As a result, the larger the sales of a product may become in the context of a commercial action, the higher its sales value will be, with the main product presenting a major sales value in comparison to a minor (or even zero) sales value in the case of the by-product[10]. Based on this allocation method, only the main products showing higher sales values are assigned some manufacturing process costs, whereas no costs are apportioned to the by-products featuring insignificant sales value[11]. For [Blocher et al. 2008], this methodology is superior to the physical measure method in terms of fairness because it allocates costs in proportion to the products' ability to absorb these expenses on the basis of the individual product's revenues. In contrast, a significant limitation affecting the sales value method points to the fact that market prices for some branches are extremely volatile and change steadily.

In the course of the production process, both the main and the by-product become separate and identifiable as different individual products at a specific stage called split-off point [Drury 1994], at which all the previously incurred costs are, as aforementioned in the preceding paragraph, exclusively ascribed to the main product or products (two or more). If only one main product arises throughout the entire manufacturing process, then it will continue to be treated as a main product. Nevertheless, if the latter is the case, two or more main products will consequently be termed as joint products, in clear reference to the jointly produced outputs. Due to the fact that costs arising during the joint production[12] process have a common, inseparable nature just until the split-off point or point of separation, they are accordingly considered as common costs and more frequently also designated as joint costs. Thereby, these joint costs can now be accounted for and consequently allocated to the respective joint products via the cost apportionment method based on sales value – as formerly introduced in previous paragraph.

On the other hand, joint and by-products may need further processing after the point of separation in order to bring them into a saleable form. The additional costs incurred in the enhancement of the joint and by-products beyond the split-off point are denominated as separable costs [Bailey 2009], and can therefore be easily traced and attributed to each particular product in contrast to joint/common costs [Drury 1994].

[10] Based on [Bailey 2009], products can evolve over time from being a by-product to a main product when the sales value of the former increases, and vice versa. The reason for this variation can rest on eventual technology or market changes that for instance may lead by-products to become main products as a consequence of a progressively increased sales value.

[11] [Deevski 2016] also reports the possibility of cost allocation to by-products by means of a further approach that contemplates assigning to by-products a varying part of costs in proportion to the respectively yielded revenues. Similarly, [Blocher et al. 2008] refers to two additional methodologies for by-product costing on the basis of allocating the resulting production costs to the by-products by considering two different criteria such as asset recognition and collected revenues. All these approaches are discarded for this dissertation.

[12] [Oenning 1997] introduces the concepts of simple, multiple and cyclic joint production depending on how many split-off points take place throughout the entire joint production process – one or several respectively for simple or multiple joint production – and whether any of the resulting outputs cyclically flow back to the stage prior to the split-off point – acting now as an input.

3.2. Methodology for cost allocation to chipped wood resources

3.2.1. Cost allocation to chipped forest residues at the forest roadside

As explained in chapter 2, forest residues are the result of logging processes carried out in the forest stands through thinning and clearing labours. They are made up of branches, crowns, tops, stumps and any other wood material not appropriate for timber production or other final industrial use such as pulp. Traditionally, forest residues have always presented a low or even null sales value as compared to that of timber, the product being the object of the harvesting process. In fact, forest residues were historically treated as a by-product of the main product obtained for industrial purposes (i.e. timber, pulp). However, the need to implement CO_2-neutral energy carriers to supply power and heat demand has caused an increasing interest in the valorisation of forest residues for bioenergy purposes. In consequence, the corresponding sales values have significantly grown as a result of their evolution from an original by-product to a final output as a joint product. In this regard, some forest residues-based research publications such as [Cremer 2008] or [Hepperle 2010] address the issue of cost allocation by considering this material as a by-product or also as a main product. In other consulted studies directly or indirectly concerning forest residues production such as [Kühmaier et al. 2007], forest residues are uniquely analysed as a main product, while timber also arises as a further main product. Thus, both main products with equal sales values evenly share the joint costs incurred before the split-off point as real joint products. By contrast, other studies such as [Wittkopf 2005] deal with the processing of the full tree, which is entirely chipped for energy purposes, thereby producing a sole product with the same cost apportionment as that carried out for jointly generated products. In a few cases such as in [Frutig et al. 2011], the costs incurred by felling, extraction and debranching of trees are systematically assigned to the main product (timber) according to the traditional approach, and not jointly to both the main product and the resulting forest residues that are indeed treated as a by-product. Although cost allocations are generally accomplished on the basis of contemplating forest residues as a by-product or a joint product, another different matter is that these residues may be straightaway chipped at the stand or from the rack – giving access to the stand – moved up to the roadside for being chipped. In these cases, costs originating in such activities are classified as separable costs occurring after the split-off point (debranching) and are therefore equally attributable to forest residues.

At any rate, [Bailey 2009] already reported that a by-product can evolve and transform itself into a main product, always provided that its sales value gains in importance at a given point in time just in consequence of technological, socio-political or even market-induced changes. Under this kind of circumstances, forest residues might be able to adopt a new behaviour as a main product at the same level as the original main product, timber, and thus both definitely act as real joint products. As a result, forest residues and timber might then be considered as jointly generated main products, i.e. joint products sharing the joint costs involving their common joint generation process until the split-off point at debranching.

Irrespective of the magnitude of the sales value of both joint products, whether they are equal or not, the fact is that forest residues and timber as joint products do not usually have insignificant sales values. Therefore, the resulting outputs can be assigned the incurred joint costs in a certain specific manner that is linked to the proportion between the respective joint products' sales values. As the evolution of the forest residues' sales value may range from zero or an extremely low amount to quite higher rates – i.e. from a behaviour as a by-product to that of a joint product –, a possible maximum sales value for forest residues might be assumed to be equal to that of timber. The aim should be attaching the same weight to both outputs in the framework of an eventual scenario where forest residues might be regarded as a joint product. This methodology will enable featuring forest residues as well as their final outcome, wood chips, as an output with two different cost assignments depending on how the forest residues' added value is subjectively perceived by the observer. This double behaviour will permit the techno-economic analysis of any forest residues-based harvesting system at the roadside on the basis of two different cost scenarios, specifically a minimal cost scenario with forest residues regarded as a by-product and a maximal cost setting according to the joint product approach. Any intermediate transfer stage between these scenarios would inevitably refer to a middle harvesting cost between both limits, with a substantially different economic significance. Naturally, the maximum forest residues' cost in the joint product based scenario could be higher if the cost allocation methodology is differently performed in the sense of (abnormally) increasing the sales value and hence the allocated costs of forest residues over those of timber. Anyhow, the proposed maximum scenario gives a good insight into the economic structure of the forest residues-based value chain, where wood chips are not worth more than but at least as much as timber – and this is already a rather high cost for such a resource (chipped forest residues) when assessed at the roadside.

According to the aforementioned approach based on ascribing the same sales value to both outputs of the joint production process, a procedure defined as *joint product allocation* permits on a volume basis the apportionment of just the same specific joint costs or joint costs per unit volume (€/m^3 loose) to both joint products – namely forest residues and timber. In this regard, the specific joint costs (€/m^3) that are to be apportioned to the different joint products end up showing the same value for all jointly manufactured outputs. This is so provided that the joint products exhibit identical or similar sales values when put on the market. Under these conditions, the respective specific joint costs also adopt the same or even a similar value when calculating the quotient between the portion of joint costs and the corresponding volume of each output.

The resulting joint costs originate from the harvesting activities involved in the felling, extraction and debranching of trees just until the split-off point at the delimbing stage. Thereby, the general formula for the unit costs of both joint products at the forest roadside turns out to be, as follows, the sum of the joint costs (*jc*) of timber and wood chips plus the corresponding specific separable costs of each output. Both quantities are referred to the respective loose volume in $m^3\ l$ (cubic meter loose volume):

$$\textit{Unit costs of timber } (€/m^3\ l) = (\textit{Felling} + \textit{Extraction} + \textit{Debranching})_{jc} + \textit{Moving}$$

Unit costs of chips (€/m^3 l) = (Felling + Extraction + Debranching)$_{jc}$ + Moving + Chipping

where the *Extraction* and *Moving* tasks come to relate to the labours of carrying the produce to the rack and to the roadside, respectively.

In like manner, an additional costs apportionment to the main and the by-product would respectively result in the unit costs of timber and wood chips when assessed at the roadside by means of a *by-product allocation* technique. This procedure aims at considering forest residues as a by-product, thus assigning to them no harvesting costs *(hc*) from felling, extraction and debranching – which are exclusively referred to the loose volume of timber – but indeed the corresponding moving and chipping-related costs originated after the split-off point. The unit costs of both outputs are calculated and expressed below:

Unit costs of timber (€/m^3 l) = (Felling' + Extraction' + Debranching')$_{hc}$ + Moving

Unit costs chips (€/m^3 l) = Moving + Chipping

with both *Moving* and *Chipping* tasks acting as separable costs.

Based on both explained procedures of *by-product and joint product allocation,* forest residues as such or transformed into wood chips are able to be assigned a unit production cost either as a by-product or as a joint product, in that order. Summarising, this methodology gives the chance to techno-economically assess each forest residues-based utilisation pathway by identifying the respective unit costs on the basis of two scenarios, namely a minimal cost scenario with forest residues acting as a by-product and a maximal cost scenario with forest residues regarded as a joint product.

Finally, mention should also be made of the different terminology employed by the English language sources in contrast to the German ones in relation to the use of the term *joint product*. The former refer to joint products as the main products generated in a joint production process in the sense that these main products jointly share the joint costs, whereas a by-product is uncoupled in terms of costs. The latter, however, consider by-products to be intrinsically coupled to the several generated main products – which are only designated as main products and not as joint products. As a result, the German study [FNR 2014] together with both [Cremer 2008] and [Hepperle 2010] from the University of Freiburg as well as the Austrian [Kühmaier et al. 2007] continuously report forest residues to be treated as a joint product (whereas the term used in the English language would be by-product) or a main product. Nevertheless, both studies from Freiburg conclude stating that costs could be apportioned to the German-termed joint products according to two different approaches introduced in English as a by-product allocation (i.e. as a real by-product) or a joint product allocation (as a jointly generated main product). On the other hand, the research sources [Oenning 1997], [Frank 2003] and [Fandel et al. 2004] claim that the concept of joint product as a German label encompasses not only the by-product but additionally also the main product, fully in contrast to the English use whereby it exclusively refers to a jointly manufactured main product.

3.2.2. Cost allocation to chipped landscape wood raw material at the chipping site

Landscape wood raw material appears in copses and groves growing in succession areas dispersed all over the open country of the region of Baden-Württemberg. This feedstock is largely not a currently exploited wood resource. Actually, it represents a free potential of wood biomass of low quality that could be harvested in order to increase the amount of wood resources for energy purposes [LEADER 2012]. This wood resource, unlike forest residues, is derived from the whole tree, which is harvested and subsequently transformed into wood chips as a unique product [Johst et al. 2014]. For that reason, the raw material may also be considered as a unique output (main product) of the production process without any resulting by-product. As a consequence, no cost allocation based on the sales value or other criteria needs to be accomplished, as the final product, wood chips, is assigned the whole production costs.

Accordingly, the simple sum of the expenditures occurring throughout the entire production chain permits, on a volume basis, the assessment of the specific costs expressed as total costs per unit volume (€/m^3 loose) for the unique product, that is wood chips. The incurred costs result from the harvesting activities that include the felling of the tree, its extraction outside the copse, the moving of the raw material from the copse to the chipper – the chipping machine may be quite far away from the copse – and the comminution of the whole tree. Thus, the general formula of unit costs for the resulting unique product – wood chips derived from landscape wood raw material – at the chipping site will be the following equation.

Unit costs of chips (€/m^3 l) = Felling + Extraction + Moving + Chipping

These unit costs are just the same as those of wood chips produced from forest residues, when they are considered as main products in line with the *joint product allocation* technique, minus the amount of expenses owing to the debranching stage – which is absent for the chipping of landscape wood raw material. In this respect, as happens for forest residues, the whole costs of producing wood chips from landscape wood raw material are divided by the total loose volume of both the trunk (timber in the case of forest residues) and branches (forest residues) thereby yielding the unit costs of wood chips from landscape wood resources.

Unlike the kind of cost allocation method implemented for forest residues, whether they are observed as a by-product or as a main product, wood chips produced from landscape wood raw material will always be contemplated as a sole product with a single cost apportionment. Therefore, the introduction of a minimal cost scenario for forest residues as a by-product as well as a maximal cost scenario for forest residues as a joint product is fully consistent with setting an only unit cost for wood chips from landscape wood raw material in both scenarios. This way, the unit costs of landscape-based wood chips will be the same within both the minimal and maximal cost scenarios, with the unit costs of forest residues varying from one scenario to the other as indicated in the previous subsection.

3.3. Non-consideration of further densification processes after chipping

There exist other possible densification processes after chipping within the supply chain of wood resources. These processes are associated with the further densification of chipped wood resources, i.e. wood chips. The corresponding set of processes currently encompasses certain processing techniques such as pelletising, pyrolysis, hydrothermal upgrading and torrefaction for dissimilar states of technological maturity. Whereas pyrolysis and hydrothermal upgrading are conceived for being implemented in bio-refineries in the production of bio-based fuels and chemicals, the procedure of torrefaction is currently not yet mature enough [IFC 2017]. On the other hand, pelletising represents the most cost-effective option compared to the other identified processes. Therefore, it is more established and mainly employed for subsequent transportation over large intercontinental distances [EUBIA 2009]. In this regard, pelletising constitutes an additional process – performed after the stages of chipping and haulage – that unavoidably increases total expenses and thus reduces the whole profitability of the entire bio-based utilisation pathway. This is particularly evident within a relatively small region like the federal state of Baden-Württemberg. Anyhow, all densification processes entail certain advantages in relation to the feedstock storage and handling by consumers. These advantages are likewise translated to higher production costs than in the case in which wood resources are not further densified after chipping. As a result, all aforementioned pre-treatment procedures are excluded for the present study because they necessarily would introduce additional costs compared to the supply chain in which only chipping is contemplated.

3.4. Basics on the different logistic chains for harvesting wood resources

3.4.1. The logistic chains of forest residues from the stand to the forest road

The identification and in-depth description of a series of significant fundamentals involving the logistic chains of forest residues – and, in turn, each of the corresponding harvesting stages of felling, extraction, debranching, moving and chipping – will take place throughout this subsection. These basics refer to a list of issues that turn out to be of major importance when implementing the appropriate logistic chains for harvesting forest residues. In this sense, aspects such as the different types of forest ownership, the several degrees of mechanisation, the steepness of slope in the forest areas, the diameter at breast height in correlation with the unit-mass law and finally the relevance of chipping within the harvesting system are thoroughly discussed. Indeed, they shed light on the complexity of a number of logistic chains that are to be identified. In line with this, the consideration of forest residues separately as a by-product and as a joint product additionally renders the resulting logistic chains even more complex in terms of costs. This is mainly due to the double cost assessment accomplished on the basis of the by-product and joint product allocation techniques.

The types of forest ownership

The ownership structure of woodlands plays an important role by shaping the logistic chains in which forest residues are transformed into wood chips. The form of ownership particularly conditions forest management and, in turn, the suitable selection of the degree of mechanisation necessary for carrying out the harvesting tasks. Based on the last Federal Forest Inventory, the statistical source [ForstBW 2013] categorises the woodlands of Baden-Württemberg into three different groups according to their ownership type (see Table 2.1), namely depending on who is the owner of the inventoried forest areas: both the federation and the federal state, the communal corporations or the private owners. The first two classes (federation/state and communal corporations) and even a not negligible part of private owners possessing above 50 ha of woodland with roughly 10% of total forest surface are managed by large forest owners that are able to implement sophisticated and expensive harvesting systems. In contrast, small private owners managing up to a maximum of 50 ha stand for approximately 26% of total woodlands and utilise a more limited harvesting technology for exploiting forest resources. In line with these insights, the logistic chains for harvesting forest residues can be determined on the basis of these two specific types of forest ownership: the small private owner and the large (public or private) forest owner.

The degrees of mechanisation

Degree of mechanisation as a concept is directly or indirectly employed in a number of studies dealing with harvesting of forest residues. In this regard, research studies such as [FNR 2014], [Stinshoff 2007], [Suchomel 2011], [Siegl 2010], [Wippel et al. 2015], [Frutig et al. 2011], [Johst et al. 2014], [Sauter et al. 2008], [Wittkopf 2005], [Cremer 2008] and [Hepperle 2010] introduce this terminology in the framework of different techno-economic analysis performed for several logistic chains involving collection of forest residues in German woodlands. Most of these sources address specific degrees of mechanisation, which are mainly based on motor-manual as well as partly or fully mechanised harvesting systems for production of timber and/or wood chips. Yet from all aforementioned studies, only [Wippel et al. 2015], [Frutig et al. 2011] and [Johst et al. 2014] make use of a further degree of mechanisation that is categorised as a highly mechanised option. Within this class, [Frutig et al. 2011] relates to a cable-assisted harvesting technique for the extraction of wood raw material from forest areas showing higher steepness of slope. Thereby, the introduction of this additional degree of mechanisation basically permits separating certain highly mechanised extraction methods such as a cable crane from a medium mechanisation level as it may be a winch [Hall 2005].

The techno-economic structure of the logistic chains for harvesting forest residues and their subsequent conversion into wood chips is to be determined according to the degrees of mechanisation. This way, the resulting logistic chains can be reproduced on the basis of certain degrees of mechanisation. These are categorised below in keeping with the insights previously referenced:

- ***Motor-manual*** Most stages are manual (hand-held and motor-driven), whereas a few exclusively supported by machines
- ***Partly mechanised*** Some stages are manual and most are assisted by machines
- ***Highly mechanised*** A few stages are manual and most are supported by machines with any of them being assisted by aerial carrying cable systems
- ***Fully mechanised*** All stages are carried out by self-propelled machines.

According to this classification, four standardised types of logistic chain are identified for each degree of mechanisation with the aim of shaping and characterising any harvesting system. In this regard, the scheme exhibited in Table 3.1 gives insight into the mechanisation level of all the constituent parts of each of these logistic chains defined for each degree of mechanisation with the aim of generating wood chips from forest residues. The mechanisation gradation ranges from a low via a medium through to a high level so that the combination of all stage-specific mechanisation levels for an entire logistic chain renders its overall degree of mechanisation.

Table 3.1: Mechanisation level for each stage of the logistic chains of chipped forest residues on the basis of the four degrees of mechanisation

DEGREES OF MECHANISATION	***MECHANISATION LEVEL OF STAGES***				
	Felling	**Extraction**	**Debranching**	**Moving**	**Chipping**
Motor-manual	LOW	MEDIUM	LOW	MEDIUM	LOW
Partly mechanised	LOW	MEDIUM	LOW	MEDIUM	MEDIUM
Highly mechanised	LOW	HIGH	LOW	MEDIUM	MEDIUM
Fully mechanised	HIGH	HIGH	HIGH	HIGH	MEDIUM

According to [FNR 2014], the most commonly employed logistic chains are those linked to the motor-manual and the partly mechanised degrees of mechanisation. Supporting this idea, [Cremer 2008] and [Hepperle 2010] refer to the fact that both logistic chains largely present lower hourly rates than the remaining options. By contrast, both logistic chains render in general not so high productivities, especially as compared to fully mechanised techniques. The motor-manual logistic chain is generally implemented by small private owners, whose technical means are quite more limited than those of large (public or private) forest owners. The latter mainly apply the remaining harvesting systems, namely the partly, highly and fully mechanised logistic chains. In this context, a partly mechanised harvesting system is employed where accessibility to the stand is restricted for fully mechanised processes or even where there is no such restriction but the partly mechanised logistic chain is technically or economically preferred. On the other hand, the fully mechanised logistic chain is suitable for large, easily accessible woodlands that are managed by large forest owners. This procedure shows the highest productivities if compared with the rest of the logistic chains. However, it also requires more expensive hourly rates that in turn generate not too different unit costs from those of the remaining harvesting systems. With regard to this, [Kofman et al. 2007] makes reference to the similar ratios obtained between both hourly costs and also between both productivities of a fully mechanised and e.g. a motor-manual method. This finally translates to reasonably comparable unit costs for both logistic chains of chipped forest residues. In contrast to a fully mechanised procedure, a highly mechanised logistic chain exhibits not so high productivities in most of its stages but, conversely, the corresponding hourly rates are significantly high – in particular at the extraction phase. This effect inevitably results in a significant cost increase in case of the highly mechanised logistic chain as compared to the partly or fully mechanised harvesting systems.

The slope of forest areas

Together with the degree of mechanisation, a further essential aspect involved in forest harvesting and thus also characterising the logistic chains of chipped forest residues is the steepness of slope within a plot of woodland. Also, the accessibility of machinery to remote and uneven pieces of forest as well as their exploitability as a result of a more or less rugged relief are major factors that may equally condition the harvesting activities and thus the selection of the suitable mechanisation level. This is the case of the standard logistic chains based on the four degrees of mechanisation, which depend on certain particularities associated with the slopes of the forest areas to be harvested. The motor-manual logistic chain does not introduce any slope restriction in general, although there is obviously a physical limit, beyond which it is not feasible for workers to reach and motor-manually extract the full trees for subsequent debranching. In this regard, [Leible et al. 2003] and [Hepperle 2010] point out that the maximal steepness of slope in case of exploiting the full tree for energy purposes lies around 60%. In contrast, if the harvest aims at the extraction of timber together with the chipped forest residues, then this process can be carried out beyond this limit as far as workers are able to motor-manually cut down the trees– circa 90% for [Kappler 2008]. According to [Cremer 2008], the slope of a forest area together with other factors such as the different typology of undergrowth and the length of the crown may have a significant effect on the productivity of motor-manual harvesting. On the other hand, the partly mechanised logistic chain is assigned a maximum steepness of slope in the order of 50% according to [Hepperle 2010]. [Suchomel 2011] and [Hepperle 2010] report that this logistic chain can go technically a further step beyond this cap, but it proves to be techno-economically more favourable to implement the highly mechanised logistic chain for a steepness of slope above 50% by simply substituting the higher mechanised extraction stage (e.g. cable crane [Hall 2005]) for the lower one (winch). Finally according to [Suchomel 2011], [Frutig et al. 2011] and [Hepperle 2010], the corresponding slope upper limit in the case of applying a fully mechanised logistic chain amounts to a maximum of 30% as a consequence of the movement restrictions registered by the wheeled machinery. In this respect, from a list of around 900 forestry companies in Baden-Württemberg, [Wippel et al. 2015] states that between 300 and 400 firms offer a high level of mechanisation, but only a few of these enterprises utilise fully mechanised harvesting systems. In addition, [Frutig et al. 2011] reports great difficulties for forestry machinery to circulate on terrains more sloped than 30%, up to the point that tracked vehicles are more efficiently implemented on slopes between 30% and 60%. Nevertheless, this kind of machinery strongly damages the soil of forests thereby leading, particularly in thinning activities – dominant in Baden-Württemberg –, to the use of the less effective but more environment-friendly logistic chains based on less aggressive harvesting methods. Generalizing for all degrees of mechanisation, several studies analysed by [Cremer 2008] come to the conclusion that harvesting in sloping areas can be more expensive but does not necessarily bring about extreme decreases of productivity for a given logistic chain. It would rather be the increase in hourly rates of the extraction stage, which generates higher unit costs of wood chips derived from forest residues. In reality, within a certain degree of mechanisation – whatever it might be –, provided that the same harvesting system is applied, the increase in slope has no major effect on the resulting unit costs of chipped forest residues [Kappler 2008].

The diameter at breast height and the unit-mass law

The performance and costs of a chosen harvesting system for a given degree of mechanisation – as a whole but also individually for each of its various stages – can widely vary depending on the size of the diameter at breast height (DBH). This property is introduced and referred to as *unit-mass law* by several of the studies consulted for this research work, namely [Stinshoff 2007], [FNR 2014], [Sauter et al. 2008], [Johst et al. 2014], [Wippel et al. 2015], [Cremer 2008] and [Wittkopf 2005]. In this respect, [Stinshoff 2007] states that, in accordance with the law of unit-mass, the performance of an individual harvesting system rises significantly with increasing DBH – while unit costs of wood chips lessen considerably according to the indications of [Wippel et al. 2015]. Alternatively, [Sauter et al. 2008] and [Johst et al. 2014] point out that there are two important factors influencing the unit costs of wood chips at roadside with one being the forest density of the targeted area and the other the unit-mass of trees to be harvested. As a result, some studies such as [Wittkopf 2005] acceptably represent the *unit-mass law* by means of a linear function aiming at describing the dependence of the productivity on DBH. The same is accomplished by [Wippel et al. 2015], who also depicts the productivity versus the growing unit-mass as an increasing linear relation. Consistent with both preceding studies, [Hepperle 2010] likewise constructs a graph shedding light on the development of the productivity for the single stage involving the motor-manual felling (see Figure 3.1). For this labour, the performance linearly increases as DBH and hence the unit-mass grow in size. Appropriately dividing the corresponding hourly rates of this task by its productivity, the unit costs incurred by the motor-manual felling as a function of DBH are also plotted in Figure 3.1 as a good illustration of the significance of the *unit-mass law* – namely that unit costs diminish as both DBH and productivity increase. The magnitude of DBH on the abscissa axis of this chart covers a domain varying from 10 cm to 20 cm i.e. within the range of the most frequent values measured for harvested trees. This is mostly the case of the region of Baden-Württemberg, where forest residues derive to a great extent from small and weak trees harvested in thinning tasks. In line with this, [Kaltschmitt et al. 2001] similarly report that forest residues typically originate from low-quality trees with a DBH ranging from 7 to 20 cm, although [Wittkopf 2005] in general just as [Hepperle 2010] likewise refer to a range between 10 and 20 cm. By contrast, other studies such as [Stinshoff 2007], [Kühmaier et al. 2007] and [Suchomel 2011] directly opted for an average value of DBH at around 15 cm in order to carry out their analyses. Accordingly, [FNR 2014] points out that if production costs of wood chips from trees with an average DBH of 15 cm (i.e. thinning) were considerably lower for a partly mechanised logistic chain when compared to a fully mechanised one (due to the higher hourly rates and the accidentally lower productivity of the latter), then the situation would surprisingly reverse for a 20 cm DBH as a consequence of the increased throughput of the fully mechanised harvesting system. To this effect, these costs might even further decrease as a result of harvesting trees with a DBH higher than 20 cm. Moreover, other studies such as [Cremer 2008] refer to a larger DBH range, specifically between 10 and 40 cm, which gives better insight into the effect of the size of trees on the resulting unit costs of the different logistic chains for harvesting forest resources. As a particular case, [Sündermann et al. 2013] exclusively indicates results in relation to logging activities (clearing tasks without thinning) to a great extent carried out by fully mechanised harvesting systems for a fixed DBH of 30 cm.

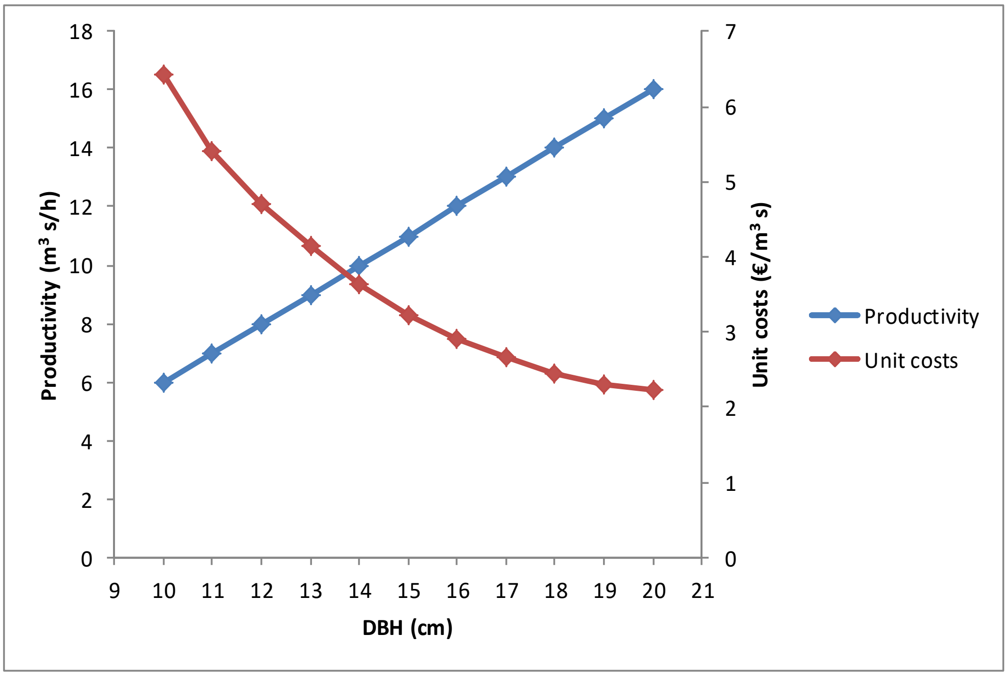


Figure 3.1: Correlation between productivity and unit costs for the motor-manual felling of trees versus their increasing diameter at breast height (based on [Hepperle 2010]) (m^3 s ~ cubic meter solid volume)

The chipping process as a crucial factor

With respect to chipping forest residues, the motor-manual logistic chain exhibits a low mechanisation level for this single stage, which involves a manual or, more infrequently, a crane-assisted feeding of wood material into a small tractor-mounted chipper – though the implementation of a chipper on a small trailer towed by a tractor is also possible [FNR 2014]. In contrast, the rest of the mechanised logistic chains assign a medium mechanisation level to the chipping process by means of the application of a self-propelled chipper either as a lorry or as an all-wheel drive vehicle equipped (in both cases) with loading crane. Both chipping variants require in general an important accumulation of forest residues in order to minimise chipping costs by reducing the waiting times and movements of the chipper. Furthermore, the produce of chipping (wood chips) is subsequently blown – in just one combined operation – into the trailer or container that is ready to be transported when it is full. In this regard, [Wittkopf 2005] and [Kühmaier et al. 2007] recommend harmonising both chipping and transport stages in the sense that the transport capacity may be adapted to the chipper's performance, and not the opposite. The reasoning behind this requirement is the optimisation of the unit costs incurred by the comminution stage. This occurs through the utilisation of the most expensive machine (the chipper) as much as possible to its full capacity, while the transport vehicle remains subordinated due to its lower costs. An unavoidable consequence of this constraint is that both chipping and transport costs are closely linked to each other to such an extent that this conditions the economics of the entire logistic chain.

3.4.2. The logistic chains of landscape wood raw material from the copse to the chipping site

Another wood resource growing all over the open country of Baden-Württemberg is the landscape wood raw material, which is harvested from copses and groves growing in succession areas. The corresponding logistic chains show certain particularities that allow them to be distinguished from the harvesting systems of forest residues. Some important aspects concerning the logistic chains of landscape wood raw material are described here below in relation to the harvesting labours involved. A list of relevant fundamentals on the subject of the logistic chains of landscape-based wood resources are tackled throughout this subsection by analysing different issues such as the multiplicity of owners, the preselected degrees of mechanisation, the effect of a lower diameter at breast height and the location of the chipping site. The aim of this analysis is to lay the foundations for defining a set of logistic chains for harvesting landscape-based wood resources with the purpose of chipping them for conversion into bioenergy. As a reminder, the costs allocation to wood resources derived from copses and groves is simply performed by assigning to them the sum of all costs declared for each stage of the corresponding logistic chain. In line with this, the resulting unit costs present a structure as well as a magnitude similar to those of the expenses of forest residues acting as joint products. This similarity emerges in the sense that both felling and extraction costs are likewise comprised in the total final costs of the harvesting system in contrast to the alternative option of forest residues as a by-product.

The multiplicity of owners

If the ownership structure of forest areas adopts an important role in the configuration of the logistic chains of chipped forest residues, the opposite seems to be the case in relation to the terrains holding both copses and groves. These wooded formations mostly grow on succession areas that are predominantly established in abandoned or underused grasslands and pasturelands – or even occasionally also at the forest edges between farming areas and the woodland itself [LEADER 2012]. In line with this reality, these zones, overgrown and covered with several scattered copses, usually present a complex ownership structure that consists of numerous landlords, on the one hand, and, on the other, shows a high diversity of land tenure systems such as public/private ownership, renting or leasing. According to [LEADER 2012], this high heterogeneity inevitably leads to a situation characterised by the reduced utilisation or even the non-use of these fields. In this regard, owners are usually not able to come to an agreement on the joint execution of certain tasks required either for maintenance or for energy purposes. In such a context, only a higher-level entity belonging either to the public or private sector (a forestry corporation) could implement the necessary measures so as to efficiently and cost-effectively collect the currently underused landscape wood raw material from groves and copses. By means of a staff comprised of a qualified team of workers, the valorisation of landscape-based wood resources could be performed in the succession areas of the region. In this manner, the effectiveness of the harvesting processes would increase because more advanced and sophisticated harvesting machinery could be applied than in the case of management carried out by separate landlords.

The selected degrees of mechanisation

The logistic chains of chipped landscape wood raw material and the corresponding degrees of mechanisation are essentially the same as those identified for producing wood chips from forest residues. In principle, the motor-manual together with the partly, highly and fully mechanised logistic chains – the degrees of mechanisation for harvesting forest residues – are all perfectly applicable to the collection of landscape wood resources.

However, both the motor-manual and the fully mechanised harvesting systems can be omitted as they are not usually implemented on account of certain peculiarities exhibited by the harvesting of wood resources from copses and groves. These particularities are in relation to the dimension and distribution of these wood structures but also associated with the introduction of forestry corporations as the suitable actor for harvesting this raw material. As explained in the previous subsection concerning forest residues, the former harvesting system is normally carried out by small forest owners. In the case of landscape wood raw material, they would correspond to small land owners equally possessing less mechanised harvesting machinery due to their smaller size. The utilisation of the services of a public or private forestry corporation – with a higher level of capacity for implementing collection measures – automatically excludes the motor-manual option. This is because the harvesting tasks must under these circumstances be necessarily carried out by means of a higher mechanisation level – any of the three remaining degrees of mechanisation. In fact, harvesting might be performed by partially mechanised logistic chains or even highly mechanised ones in the event of sloped terrains. Thereby, the fully mechanised procedure should not be applied as the size and dispersion of copses impede an efficient and cost-effective enough collection of landscape wood raw material owing to the frequent waiting times and movements of fully mechanised harvest machinery.

Accordingly, two logistic chains for conversion of landscape wood raw material into wood chips can be appropriately implemented on the basis of both previously identified degrees of mechanisation. Both were already introduced for forest residues, but they are equally valid for harvesting landscape-based resources:

- ***Partly mechanised*** Some stages are manual and most are assisted by machines
- ***Highly mechanised*** A few stages are manual and most are supported by machines with any of them being assisted by aerial carrying cable systems

The effect of a smaller diameter at breast height

As reported for the harvesting of forest residues, productivity and hence also unit costs of the identified logistic chains of landscape wood raw material for both degrees of mechanisation vary to a great extent as a function of the size of the diameter at breast height (DBH). According to the *unit-mass law* previously introduced in the subsection 3.4.1 in relation to the basics of forest residues, unit costs incurred by the harvesting of landscape wood resources decrease as the DBH and therefore the productivity increase. This law applies to each kind or species of tree, irrespective of whether specimens grow in a forest or within a confined area constituted of copses or groves in the middle of the open country. With the aim of highlighting the dependence of both the profitability and unit costs on the parameter DBH, a graph was illustrated in Figure 3.1, where the size of this diameter on the abscissa axis covers a domain ranging from 10 cm to 20 cm. In line with several studies cited in the subdivision dealing with forest residues, the prior domain proved to be the usual dimension of DBH for trees harvested through thinning tasks. However, [Johst et al. 2014] – in an interesting study on the harvesting of landscape wood raw material for energy purposes – refers to five different classes of mixtures that are made up of trees and bushes in different proportions. From them, only three different DBH stretches, which are comprised between 7 cm and 15 cm, are considered as representative for landscape-based wood resources. The smallest and the longest DBH categories respectively including bushes and large trees are correspondingly left out because the former seems to be too small and the latter not so common in landscape zones. Thereby, the preselected range unequivocally represents the most realistic size at breast height for trees exclusively growing in copses and groves. As a result, an intermediate value of 10 cm for the DBH of such trees is taken as an assumption with the aim of determining the unit costs of the two logistic chains involved. Besides the analysis of [Johst et al. 2014], some other studies such as [Wittkopf 2005] and [Hepperle 2010] also provide significant insights in relation to wood chips production costs for a number of logistic chains with different degrees of mechanisation. They place emphasis on the 10 cm DBH along with both sizes of 15 cm and 20 cm – although the latter two are not allowed for as appropriate average values for landscape-based wood resources because of their large magnitude. Anyhow, the ultimate effect of the selection of a DBH of 10 cm is an inevitable cost increase in each stage of the logistic chains of chipped landscape wood raw material with respect to those costs taken into account for forest residues for an averaged DBH of 15cm.

The location of the chipping site

Both partly and highly mechanised logistic chains of chipped wood resources from copses and groves assign a medium mechanisation level to the chipping process. This stage is in both cases implemented with the assistance of a self-propelled chipping machine either as a lorry-mounted chipper or as an all-wheel drive vehicle, in both cases fitted with a loading crane as described for forest residues.

A different issue is where, or in which location, the process of chipping landscape wood raw material should be carried out. In the case of forest residues, chipping is implemented at the forest roadside, at a site close to large extensions of forest areas where the resource is present in a continuous manner. However, landscape-based resources are collected within copses and groves of relatively small dimension, dispersedly located on succession areas as well as on the edges of forests within the open country. As a consequence, the chipping process must be centralised on an intermediate spot by covering a large surface with a few small wooded formations (copses or groves) widely separated from one another. On this issue, [LEADER 2012] suggests at least harvesting a minimum area of around 1 ha[13] – understood as the sum of copses' areas and not as the entire acreage involving the corresponding open country – in order to ensure maximal efficiency during the working day, at full capacity and without any movements of the chipper that could generate a major waste of time.

[13] The dimension of this minimum area is closely linked to the productivity of the chipping machine, which is in turn dependent on the mechanisation level of the process involved. The minimum area of 1 ha responds to the need to implement certain particular conditions, which are present in the tests developed by [LEADER 2012]. In any case, the size of this portion of land might vary if, for example, a lower mechanisation level (i.e. the chipping stage of the motor-manual logistic chain) is implemented with a resulting reduction of the area harvested during a day.

3.5. Techno-economic characterisation of the logistic chains

3.5.1. The logistic chains of chipped forest residues

The basics introduced in the last section in relation to the harvest of forest residues revolve around a series of issues relating to the types of forest ownership, the degrees of mechanisation, the slope of forest areas, the diameter at breast height as well as the actual importance of the chipping process itself. All these aspects show the real system's complexity that has to be coped with, especially when it comes to modelling the value chain of forest residues for bioenergy generation. This subject must then be addressed by means of an appropriate methodology that is explained hereunder. Given the difficulty of analysing the broad spectrum of possible harvesting techniques for thinning and clearing tasks, a set of four standard logistic chains for production of wood chips from forest residues is identified as an adequate approximation. This is constructed on the basis of a methodological approach that is built upon the combination of the four preselected degrees of mechanisation – which show two types of forest ownership and a range of different stretchs of steepness of slope for harvest machinery's access to woodlands – with the two presented cost allocation procedures for wood resources regarded as a by-product or a joint product.

The unit costs of wood chips produced at the forest roadside are strongly linked to each of the four selected degrees of mechanisation. In this sense, the mechanisation levels of each harvesting stage have assigned a specific magnitude for both hourly rates and productivity that fix the overall costs of each logistic chain. Moreover, both proprietorship categories, namely the small private forest owner and the large (public or private) forest owner, are designated as the only standard types of ownership shaping all four basic logistic chains and thus also conditioning their cost structure. Concretely, the motor-manual logistic chain is principally employed by small private owners. Therefore, its harvesting machinery is tendentially less productive than that of logistic chains being managed by large forest owners – with the exception of highly mechanised harvesting systems –, thus slightly increasing the corresponding unit costs of chipped wood resources. In general, each degree of mechanisation together with a specific type of ownership is linked to a specific range for the steepness of slope, which configures the unit costs of each resulting logistic chain.

The selected degrees of mechanisation are then matched with both cost allocations methods in order to techno-economically model the harvesting system of forest residues. For this purpose, chipped wood resources are equally considered either as a by-product or as a joint product according to both procedures of *by-product* and *joint product allocation.* The former technique exclusively allocates the separable costs (incurred by moving and later chipping) to the forest residues-derived chips; whereas the latter approach apportions the sum of joint costs – those jointly generated together with the other joint product, timber – plus the separable costs (moving and chipping) to all produced wood chips at the roadside. Accordingly, each cost allocation procedure generates a different cost scenario for analysis of the wood resources-based bioenergy system, namely a minimal cost scenario with forest residues regarded as a by-product and a maximal cost scenario with forest resources as a joint product.

As a result, the motor-manual as well as the partly, highly and fully mechanised logistic chains are examined in the next sections by breaking them down into their individual stages. These stages are economically described in terms of costs specifically for usual thinning activities carried out in forest areas with an average DBH of 15 cm. Incurred expenditures in each stage are estimated as an average value calculated from a series of cost-related data collected from relevant research studies specialised on harvesting of forest resources for the mentioned DBH. For this final purpose, the volume of loose wood chips as well as solid timber, or even of forest residues, is converted[14] into tonnes FW with 35% moisture content. As already indicated, this moisture level is reached after a seasonal drying process, whereby water content diminishes and thereby both leaves and needles can naturally drop off before chipping.

Consequently, the following subsections comprehensively feature the technical characteristics of each constituent stage as well as their corresponding unit costs in both possible cost allocation variants for each of the four identified logistic chains.

3.5.1.1. Motor-manual harvesting by small private forest owners

The motor-manual logistic chain is made up of a series of five harvesting components (see Figure 3.2), namely a chainsaw for felling, a tractor-mounted winch (also called winch skidder [Hall 2005] or skidding winch)[15] for extraction, a chainsaw for debranching, a tractor trailer for carrying forest residues from the rack to the roadside and finally a tractor chipper. The chipping machine is implemented after a natural drying process of forest residues in a sunny area of the forest roadside.

Both stages of felling and extraction are usually described as a compound phase in most research literature dealing with this logistic chain. Therefore, an average unit cost obtained from values ranging from 3.19 to 3.55 €/m^3 l – and consequently subject to a low uncertainty – is associated with this double stage according to studies such as [Wittkopf 2005] and [Wippel et al. 2015]. On the other hand, due to the fact that debranching costs are not well documented and sometimes not considered or even involved in other tasks of higher rank (such as felling or extraction), an assumption is taken into account on the basis of considering

[14] Bulk density of wood chips is valued at 0.323 t/m3 l FW (35% MC) as a weighted average of the amounts of softwood (coniferous) and hardwood (deciduous) growing in the forests of the districts of Baden-Württemberg according to [ForstBW 2013].

[15] According to [Hall 2005], the extraction of trees may also be carried out by means of a portable winch, which is less mechanised than a tractor-mounted winch but, however, suitable enough for harvesting forest residues at any steepness of slope. The hourly rate and productivity of a portable winch prove to be balanced enough in the sense of yielding similar unit costs to that of a tractor-mounted winch or winch skidder. In contrast to the manoeuvrability of a portable winch for accessing any remote area, wheeled vehicles can exclusively access sloping areas up to a maximum of 30%, albeit they can use a winch for reaching trees growing in more sloped terrains beyond their accessible area.

those felling costs estimated for an average DBH of 10 cm as the actual debranching costs. As a result, debranching becomes a rather expensive task nearly at the same level as felling, as [Wittkopf 2005] and [Hepperle 2010] reported, with values between 2.53 and 3.93 €/m^3 l and hence a moderate uncertainty. The unit costs concerning felling, extraction and debranching are joint costs that arise only when wood chips are considered as a joint product. As of the split-off point occurring during debranching, the incurred costs of labours involving moving and chipping are assignable to the generated wood chips either as a by-product or as a joint product. Moving forest residues with a tractor trailer equipped with loading crane yields separable costs per unit volume between 4.63 and 7.15 €/m^3 l as stated by [Kühmaier et al. 2007], [Wittkopf 2005], [Forstbericht 2008] and [Johst et al. 2014]. The first study represents relatively low costs as a result of moving not only forest residues but also some low-quality timber with small diameter. In relation to the last one, this study mostly contemplates not only forest residues but also landscape-based wood resources that usually offer a lower DBH, thereby elevating the unit costs of moving and hence generating a higher uncertainty. The last stage corresponds to chipping with a tractor chipper, whose corresponding separable costs are reported to vary from 4.24 to 5.26 €/m^3 l according to research studies such as [Schulmeyer et al. 2014], [Wittkopf 2005] and [Cremer 2008]. The statistical dispersion of this array of values is estimated as moderate and therefore as a quite good outcome for the unit costs of the chipping stage.

The cost balance obtained throughout the five harvesting stages from the stand via the rack through to the forest roadside results in two different total unit costs for wood chips regarded as a by-product or as a joint product. The corresponding amounts are finally expressed in euro per unit volume of loose material (m^3 l) as well as per unit mass (tonnes). Consequently, the total unit cost of chipped wood resources as a joint product accounts for a cost level that is roughly 59% higher than that calculated according to the by-product allocation procedure.

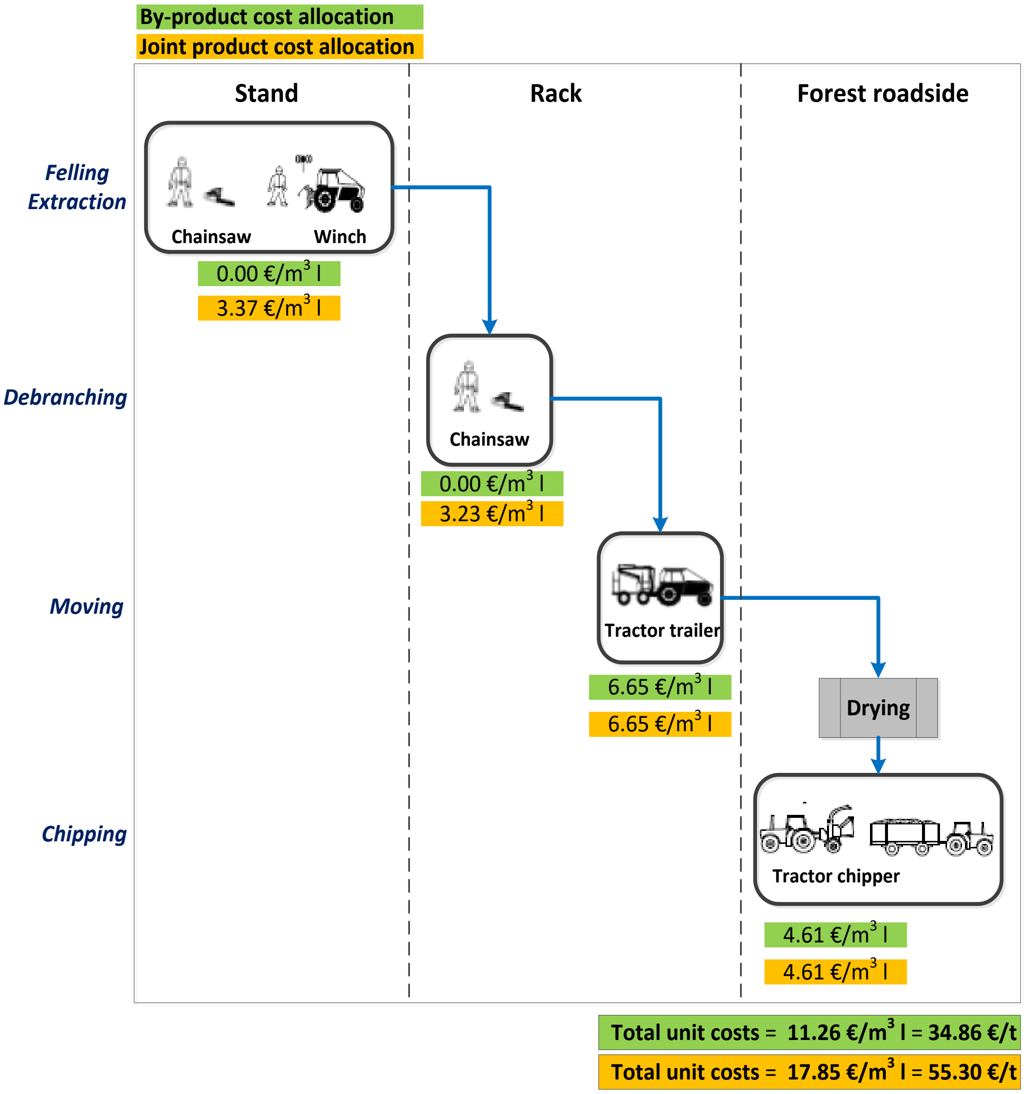


Figure 3.2: Techno-economic breakdown of the motor-manual logistic chain of chipped forest residues for an average DBH of 15 cm and 35% MC on the basis of both cost allocation procedures either as a by-product or as a joint product[16]

3.5.1.2. Partly mechanised harvesting by large forest owners (slope < 50%)

The partly mechanised logistic chain, similarly to the motor-manual one, comprises a succession of nearly the same five elements presented in Figure 3.2, though including a modification based on a more effective chipping process. Accordingly, Figure 3.3 illustrates in detail each stage making up the entire harvesting system from the stand to the roadside: a chainsaw for felling, a tractor-mounted winch or winch skidder for the extraction, a chainsaw for debranching, a tractor trailer for moving forest residues to the roadside and lastly – and this is the change – a more mechanised truck chipper as compared with the tractor-powered

[16] The unit m^3 *l* stands for cubic meter loose volume.

one. As in the motor-manual harvesting system, a natural drying process of forest residues takes place in a sunny area close to the forest roadside and prior to chipping. After the whole chain is completed the produce is ready for haulage.

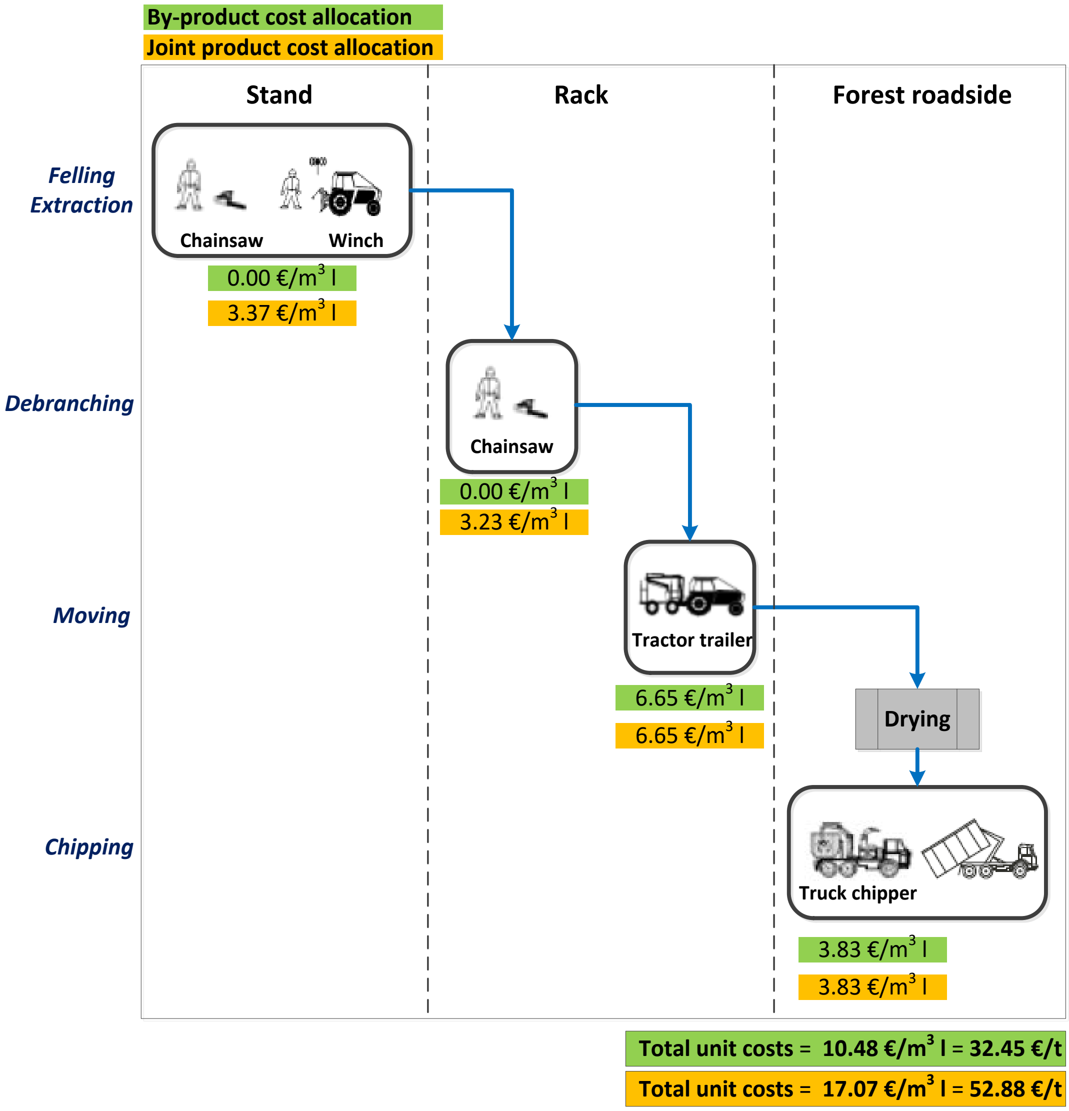


Figure 3.3: Techno-economic breakdown of the partly mechanised logistic chain of chipped forest residues for an average DBH of 15 cm and 35% MC according to both cost allocation procedures either as a by-product or as a joint product

The first four stages of the partly mechanised logistic chain – namely felling, extraction, debranching and moving – exhibit the same techno-economic characteristics as the motor-manual system. In line with this premise, the corresponding unit costs – and therefore their uncertainties – are identical in each of the four stages to the respective ones in the motor-manual logistic chain. As expected, the assumption adopted for the calculation of the debranching unit costs on the basis of an average DBH of 10 cm is equally considered for this harvesting system. The last stage of chipping is however carried out by a truck chipper, which develops a higher productivity at quite similar hourly rates in comparison to the tractor chipper. The outcome is that the incurred unit costs of a truck chipper amount to an order of magnitude ranging from 3.51 to 4.19 €/m^3 l, which is somewhat lower than that of a chipper mounted on a tractor. The incurred unit costs by the truck chipper, including both lower and upper limits respectively published by [Johst et al. 2014] and [Wittkopf 2005], are not too statistically dispersed owing to a resultant low variance, which is why, in this respect, a reduced uncertainty is registered.

Figure 3.3 similarly shows the sum of unit costs originated in the whole logistic chain from the stand via the rack through to the roadside according to both criteria based on the by-product and the joint product allocation methods. The total unit costs are likewise presented in euro per unit loose volume as well as per unit mass (tonnes). They appear to be around 63% higher, when wood chips are considered as a joint product, than in the case of the corresponding assessment as a by-product. The increase of this percentage with respect to that of the motor-manual system is due to the decrease of chipping costs caused by the implementation of a more productive chipper.

3.5.1.3. Highly mechanised harvesting by large forest owners (slope > 50%)

As illustrated in Figure 3.4, the highly mechanised logistic chain is comprised of five constituents, namely a chainsaw for felling, a cable crane for the extraction stage, a chainsaw for debranching, a tractor trailer for carrying forest residues from the rack to the roadside and a truck chipper. Likewise, a natural drying process of those forest residues piled up on a sunny surface at the forest roadside occurs before starting the chipping task. In contrast to the previous logistic chains, the stage of felling is an independent process here, while the extraction of trees is performed by means of suitable aerial cableway systems such as a cable crane. From this point on, the remaining three phases of debranching, moving and chipping are completely the same as those showed by the partly mechanised logistic chain.

Both stages of felling and extraction, in contrast to the compound phase described in both previous logistic chains, are independently analysed for this harvesting system due to the greater documentation from research literature found on this topic. Since the extraction stage is supported by cable crane, this step exhibits a much higher techno-economic complexity than felling. This fact necessarily leads to the dissociation of both stages from each other. In line with the above, [Hall 2005] indicates that the installation of a cable crane may be difficult and therefore rather expensive. In such a context, an average unit cost with a high statistical variance, calculated on the basis of a series of values ranging from 1.29 to 5.19 €/m^3 l, is apportioned to the chainsaw-assisted process of felling according to the following sources [Hepperle 2010], [Cremer 2008], [Wittkopf 2005], [Sündermann et al. 2013] and [Johst et al. 2014]. The extremely high level of unit costs provided by [Johst et al. 2014], 5.19 €/m^3 l, can be accounted for by the use of certain portions of landscape-based wood resources with lower DBH. This results in increased unit costs that elevate the corresponding uncertainty in an exceptional manner. Similarly, the extraction stage carried out by the cable crane is assigned a relatively high unit cost as an average of the values 11.71 and 13.73 €/m^3 l – respectively stated by [Suchomel 2011] and [Sündermann et al. 2013]. On the other hand, the last three stages of the highly mechanised logistic chain – namely debranching, moving and chipping – reproduce the same techno-economic characteristics as the partly mechanised harvesting system. As a result, the respective unit costs – and their associated uncertainties – show identical values in each of the three stages to those of the respective steps in the partly mechanised logistic chain. Besides, as assumed in previous harvesting systems, the calculation of debranching unit costs is likewise based on a smaller DBH of around 10 cm.

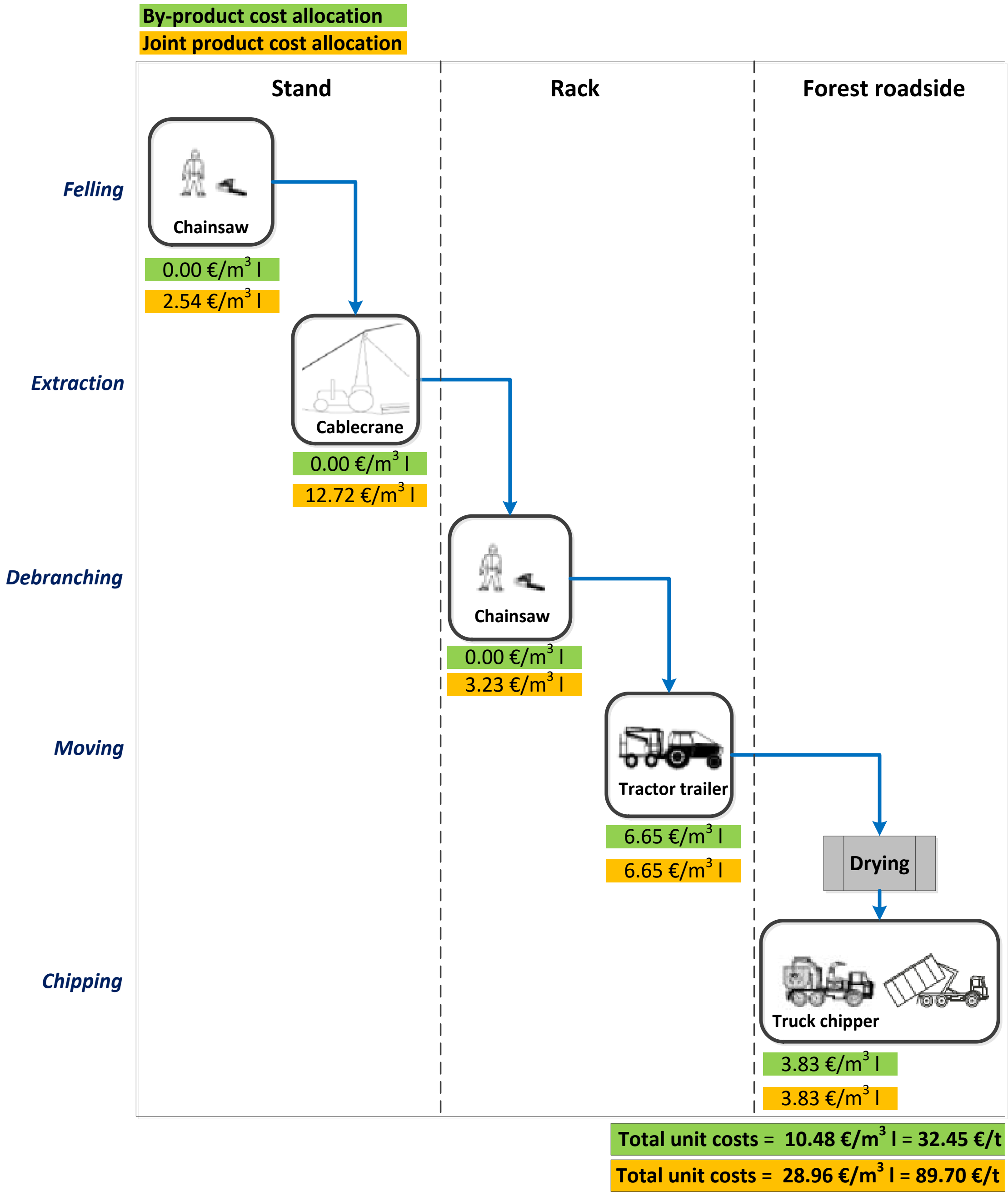


Figure 3.4: Techno-economic breakdown of the highly mechanised logistic chain of chipped forest residues for an average DBH of 15 cm and 35% MC on the basis of both cost allocation procedures either as a by-product or as a joint product

Finally, the respective unit costs of each stage within the whole logistic chain from the stand to the roadside are totalled by appropriately considering wood chips either as a by-product or as a joint product in keeping with both corresponding cost allocation procedures. The total unit costs of wood chips regarded as joint products, correspondingly converted into euro per unit volume of loose material or euro per unit mass (tonnes), represent an amount nearly three times (circa 276%) as much as the resulting total costs of chipped forest residues contemplated as a by-product (see Figure 3.4). The reason behind this enormously increased percentage lies in the high cost contribution of the extraction stage, which is caused by the costly installation and operation of cable cranes.

3.5.1.4. Fully mechanised harvesting by large forest owners (slope < 30%)

The fully mechanised logistic chain of Figure 3.5 exclusively encompasses three harvesting stages, although each equipped with wheeled machinery – i.e. provided with the highest mechanisation level – in contrast to the rest of the harvesting systems. In the first place, a harvester, which is a heavy forestry vehicle that involves the tasks of felling, extraction and debranching (including crosscutting) of trees just in a unique machine and in a combined process. It operates on the boundary among the stand and the rack with the capacity of reaching trees as far as its articulated arm is able to. Occasionally, it has to be assisted by a worker with chainsaw for those trees out of scope; otherwise the enlargement of the rack becomes the last option. Afterwards, a forwarder comes into action for moving – or forwarding – the forest residues that have been previously loaded onto the carrying flatbed of this machine with the assistance of a crane. As both vehicles are fitted with wheels, they usually cause soil damage on the ground of forests, which subsequently gives rise to erosion and environmental deterioration of woodlands. Aiming to prevent this situation, [Kofman et al. 2007] reported the use of a brash mat on the racks in addition to employing wider tyres or even band tracks to reduce the impact of vehicle weight on soil. The last component of the fully mechanised harvesting system, after the indispensable natural drying process of forest residues, is a crane-equipped truck chipper as in the two previous logistic chains.

Thereby, the stages of felling, extraction and debranching are successively carried out by the harvester at a unit cost varying from an exceptionally low 3.82 €/m^3 l to an upper limit of 9.92 €/m^3 l on the basis of the contributions respectively reported by [Cremer 2008] and [Wippel et al. 2015]. Together with both prior research sources, a series of studies including [Kühmaier et al. 2007], [Suchomel 2011], [Sündermann et al. 2013] and [Wittkopf 2005] permits an average unit cost of about 7.19 €/m^3 l to be determined for this combined stage. The high statistical dispersion of this set of expenses is equally associated with a significantly elevated uncertainty. On this issue, a rationale is found in relation to the low unit costs incurred by harvesters according to the study of [Cremer 2008]. This is based on the fact that not only trees with a smaller DBH than 7 cm were harvested but also some with a DBH over 7 cm without being delimbed and crosscut, thus obviously reducing the resulting unit costs. Secondly, the moving stage performed by the forwarder is assigned a level of unit costs at around 6.11 €/m^3 l as an average quantity derived from an array of values between 5.20 and

8.73 €/m³ l originating from [Wittkopf 2005], [Forstbericht 2008], [Kühmaier et al. 2007], [Cremer 2008] and [Hepperle 2010]. The unit costs of the forwarder are slightly lower than those apportioned to the tractor trailer in the remaining harvesting systems mainly as a result of the increased productivity of the former. In such a context, the variance of the different unit costs found for the stage of moving seems to be quite acceptable, which is why their uncertainty is not so relevant. Finally, the last stage of the fully mechanised logistic chain, the chipping process with truck chipper, displays the same techno-economic parameters as the two preceding harvesting systems as far as unit costs and uncertainty are concerned.

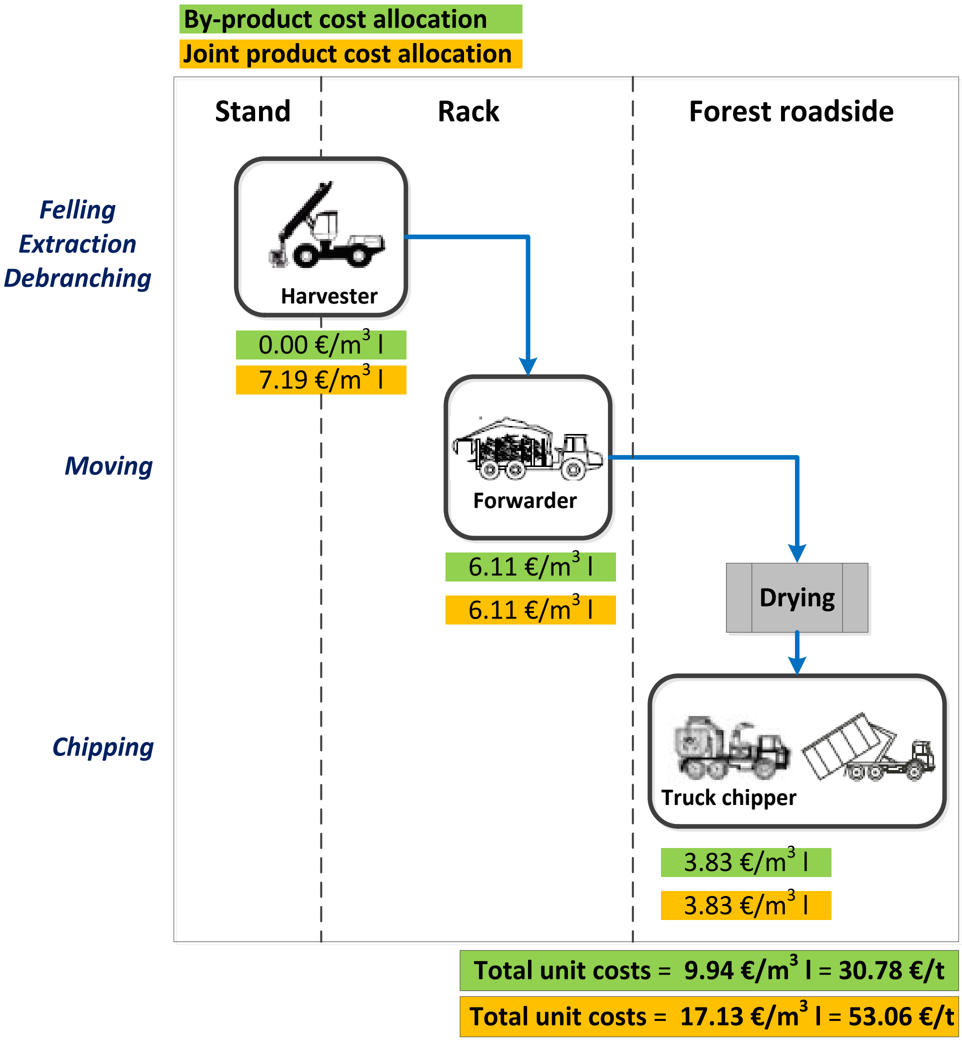


Figure 3.5: Techno-economic breakdown of the fully mechanised logistic chain of chipped forest residues for an average DBH of 15 cm and 35% MC according to both cost allocation procedures either as a by-product or as a joint product

Figure 3.5 also gives insight into the consequences caused by the use of both cost allocation procedures, when they are applied to the complete logistic chain, from the stand to the roadside, for calculating the total unit costs of wood chips either as a by-product or as a joint product. The total costs of chipped forest residues regarded as a joint product – expressed in euro per loose cubic meter as well as in euro per tonnes – prove to be roughly 72% higher than those appraised for the by-product approach. The rise of this percentage in relation to that of the partly mechanised harvesting system (63%) can be accounted for by the diminution of the moving costs induced by the forwarder with respect to those incurred by the tractor trailer – on account of the higher productivity of the former – and also by the increase in costs incurred by the harvester as compared to those allocated to the compound stage involving both chainsaw and winch. Just as a reminder, the referenced percentage of the partly mechanised system had already risen from a lower limit of 59% for the motor-manual logistic chain to that of 63% due to the decrease of unit costs caused by the more productive truck chipper when compared to the tractor chipper. In general – and purposely excluding the highly mechanised harvesting system out of the next reflection due to its disproportionately greater expenses under the joint product cost allocation technique –, the more highly mechanised a logistic chain of chipped forest residues is, the higher the ratio between the total unit costs of wood chips as a joint product and those as a by-product. This behaviour, which occurs with increasing mechanisation, is a noteworthy consequence of the reduction of total unit costs for chipped forest residues regarded as a by-product – because of the diminution of costs involving moving and chipping – and/or the increase in costs of wood chips as a joint product – due to the rise in costs of felling, extraction and debranching. As mentioned above, this rule cannot be extrapolated to the highly mechanised logistic chain – owing to the extremely high costs of the extraction stage – that yields much higher ratios between both joint product and by-product related total unit costs than in the rest of the harvesting techniques.

3.5.2. The logistic chains of chipped landscape wood raw material

According to the analysed basics on the harvesting systems of landscape wood raw material, major aspects such as the multiplicity of owners, the selected degrees of mechanisation, the effect of a lower diameter at breast height as well as the location of the chipping site permit shedding light on the techno-economic description of the exploitation of this wood resource. The objective of this subsection is to characterise the logistic chains of chipped landscape wood resources originating in copses and groves, namely wooded formations of relatively small size and spatially dispersed over forest boundaries and succession areas – mostly grasslands and pasturelands. On account of the particular nature of this resource, two standard logistic chains are selected on the basis of two degrees of mechanisation: partly and highly mechanised harvesting. These harvesting systems are regularly to be implemented by forestry corporations in succession areas with steepness of slope respectively below and above 50%, while considering wood chips as a unique product.

Consequently, both the partly and highly mechanised logistic chains are broken down into their individual stages in order to explain both procedures in detail. The objective is then the techno-economic characterisation of both logistic chains by identifying their respective total unit costs. These are generally achieved as an average amount calculated from costings sourced from studies dealing exclusively with harvesting of landscape wood raw material. As performed for the forest residues-based logistic chains, cost data relating to either the loose volume of wood chips or the solid volume of harvested timber are transformed[17] into euro per tonnes FW with 35% moisture content (natural drying at the chipping site).

Unlike the four logistic chains of forest residues, those of landscape wood raw material only produce a unique output, namely chipped wood resources, without generating any further by-product. This fact results in a direct apportionment of whole production costs to the unique kind of yield according to a sort of unique product cost allocation method. In such a context, the total unit costs of chipped landscape wood raw material will remain unchanged for both intended minimal and the maximal cost scenarios to be created by respectively considering forest residues as by-products or joint products.

On the other hand, the resource harvested from copses and groves is principally constituted of trees and bushes, which are assumed to have an average DBH of 10 cm. This reduced diameter gives rise to the exploitation of entire trees as a whole and exclusively for energy purposes after their complete comminution into wood chips. In comparison to forest trees, such a restriction on the dimension of landscape-derived trees entails a significant constraint on the number of available studies – addressing wood resources with a mean DBH of 10 cm – that can be found and consulted. This is why the corresponding unit costs for both logistic chains show a quite limited quality relating to this scarcity of data.

Finally, the next two subdivisions describe in depth the technical aspects of the machinery employed in each single stage together with their corresponding unit costs for each one of the two identified logistic chains.

3.5.2.1. Partly mechanised harvesting by a forestry corporation (slope < 50%)

The partly mechanised logistic chain of chipped landscape wood raw material presents, as Figure 3.6 shows, a series of four tools in the same order and configuration as the partly mechanised harvesting system of chipped forest residues (see Figure 3.3). The main distinction between the former and the latter refers to the elimination of the chainsaw-assisted debranching process. This is as a result of harvesting and subsequently chipping the entire tree without producing a further more valued product such as timber. The complete list of equipment implemented in this logistic chain is formed of a chainsaw for felling, a winch-based system consisting of a tractor-mounted winch or winch skidder for extraction activities, an adapted tractor trailer for carrying full trees and bushes from the copses to the chipping site and lastly a truck chipper. The natural drying process of landscape wood raw material

[17] The bulk density of chipped landscape wood raw material is equally assessed at 0.323 t/m3 l FW (35% MC) like that of forest residues. Both copses and groves usually present a heterogeneous mixture of tree varieties with a different proportion of coniferous and deciduous species in each district. This is due to the fact that the corresponding areas are not pure woodlands but succession areas or forest boundaries with a prior agricultural or livestock use. As a result, this quantity, which is taken as a weighted average of the amounts of softwood (coniferous) and hardwood (deciduous) registered by [ForstBW 2013] in the forests of Baden-Württemberg, is assumed as a basis for the required unit conversion.

happens as usual in a sunny area but, in this case, located around copses and groves prior to both stages of moving and chipping. By means of chipping, the resulting wood chips are finally blown into the trailer or container of the carrier vehicle for finally being transported.

Due to limitations related to data availability on the basis of performed literature searches, both felling and extraction stages are considered as a compound phase in the same manner that happened for the partly mechanised harvesting system of forest residues. Accordingly, [Wittkopf 2005] estimates the unit costs of this double stage, when carried out for wood resources with an average DBH of 10 cm, at around 7.99 €/m^3 l. On the other hand, [Johst et al. 2014] publishes for landscape wood raw material extremely high unit costs on the order of 17.4 €/m^3 l, which are definitely reduced by about 40% when employed in the framework of the present research study. As a result, an average unit cost of 9.22 €/m^3 l is assigned to this double stage according to both mentioned studies. In this regard, a remarkably high numerical dispersion is observed for the unit costs of felling and extraction, especially owing to the high expenses presented by [Johst et al. 2014]. The task consisting in moving landscape wood resources as a whole tree (or bush) with a tractor trailer fitted with crane generates costs per unit volume of loose material between 5.78 and 6.98 €/m^3 l according to the tests accomplished by [Johst et al. 2014] for a DBH of 7 cm and [Wittkopf 2005], respectively. The resulting low statistical dispersion showed by these values is associated with a moderate uncertainty for the corresponding unit costs. Moreover, the respective average unit costs of around 6.38 €/m^3 l are in effect slightly lower than those calculated for carrying forest residues. This is because of the somewhat higher DBH of full trees from landscape (in the order of 10 cm) with respect to the reduced diameter size of forest residues being basically made up of crowns and branches. Finally, the last stage corresponds to chipping with a truck chipper, whose unit costs for an average DBH of 10 cm are reported to vary from 4 to 6.47 €/m^3 l according to [Johst et al. 2014], [Cremer 2008] and [Wittkopf 2005]. The corresponding average unit costs of 5.31 €/m^3 l are higher than those obtained for the chipping of forest residues (3.83 €/m^3 l) despite the smaller size of forest-derived branches and crowns. These unexpectedly increased unit costs for chipping landscape wood raw material might be accounted for by the more frequent movements of the truck chipper among different succession areas than in the case of woodlands, where the chipping device remains on the same site for longer periods. To conclude, the set of referenced values also exhibits a high statistical dispersion, which is in this case basically attributable to the low contributions of [Johst et al. 2014].

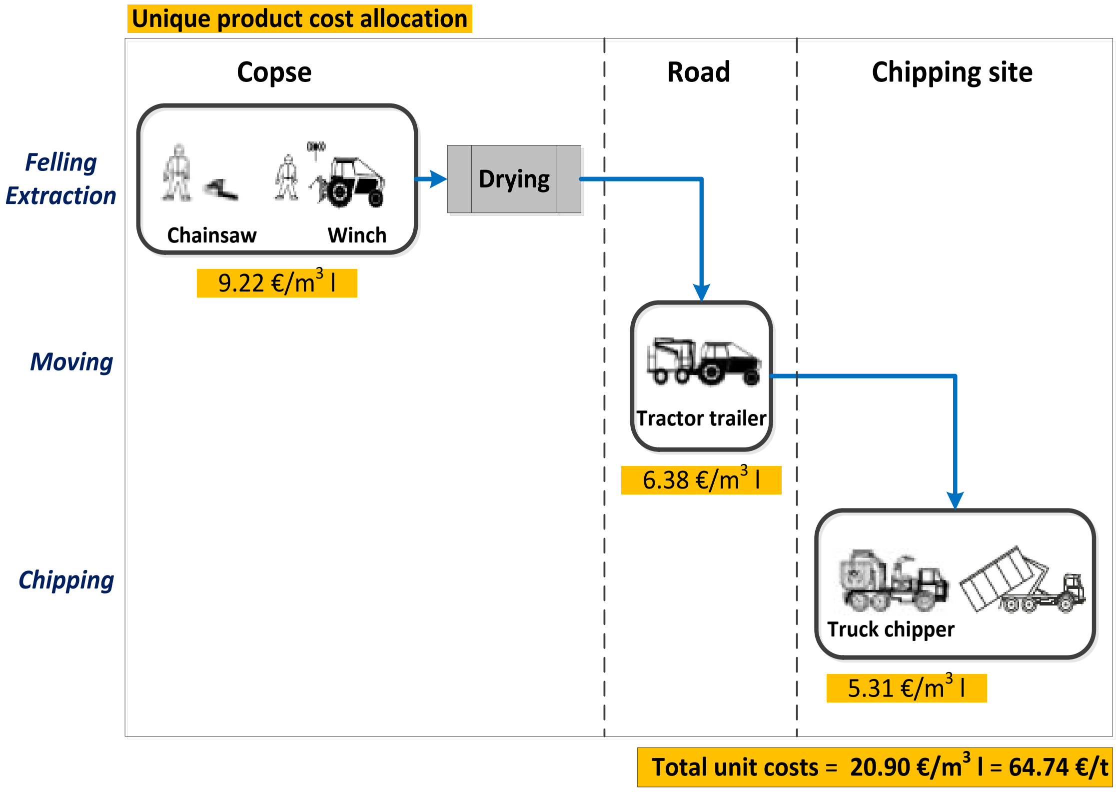


Figure 3.6: Techno-economic breakdown of the partly mechanised logistic chain of chipped landscape wood raw material as a unique product for an average DBH of 10 cm and 35% MC

The cost analysis of the entire logistic chain, which is implemented throughout all four harvesting stages from the copses to the chipping site at an intermediate spot within the open country, yields as illustrated by Figure 3.6 the total unit costs of wood chips as a unique product by expressing these expenses in euro per unit volume of loose material as well as per unit mass (tonnes).

3.5.2.2. Highly mechanised harvesting by a forestry corporation (slope > 50%)

The highly mechanised logistic chain of chipped landscape wood raw material in Figure 3.7 shows a similar structure to that of the also highly mechanised harvesting system of wood chips gained from forest residues (see Figure 3.4). On the one hand, a difference lies basically in the elimination of the debranching labour from the former logistic chain. This is owing to the fact that delimbing is no longer required as trees and bushes are systematically harvested as a whole and subsequently chipped for energy purposes. On the other, the natural drying process of landscape-based wood resources does not take place anymore before chipping – as happens for forest residues in order to take full advantage of sunny areas out of the forest – but before the process of moving on a quite sunny spot close to the copses.

According to Figure 3.7, the highly mechanised harvesting system of chipped landscape wood raw material encompasses a set of four components, specifically a chainsaw for felling, a cable crane for extraction, a tractor trailer for carrying the raw material to the chipping site and a truck chipper. Contrary to the preceding harvesting procedure, the process of felling is an independent stage here, while the task of trees' extraction is implemented by a suitable aerial carrying system consisting in a cableway. From this stage onwards, the remaining two phases of moving and chipping are identical to those exhibited by the previous method concerning the partly mechanised logistic chain.

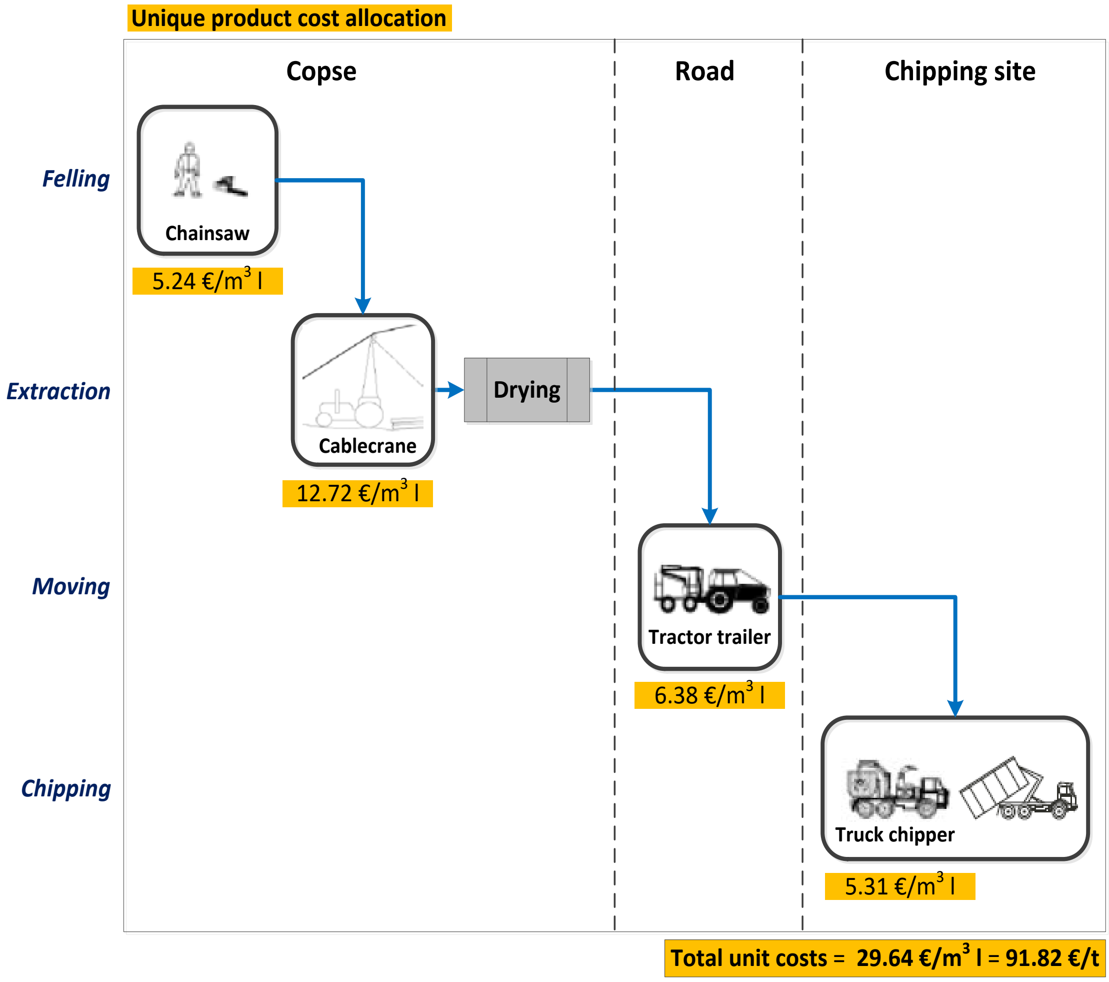


Figure 3.7: Techno-economic breakdown of the highly mechanised logistic chain of chipped landscape wood raw material as a unique product for an average DBH of 10 cm and 35% MC

The cost structure of each stage within this logistic chain is in general expected to become more expensive than in the case of the highly mechanised harvesting system of forest residues (joint product) on account of dealing with an average DBH of 10 cm. Therefore, the chainsaw-assisted process of felling is assigned an average unit cost of around 5.24 €/m^3 l, which is associated with an extremely high statistical variance for a sample of values ranging from 2.57 to 9.21 €/m^3 l according to [Hepperle 2010], [Wittkopf 2005] and [Johst et al. 2014]. In this connection, it is worth noting the particularly high level of the costs provided by [Johst et al. 2014], which gave rise to an important increase of the respective uncertainty. On the other hand, the stage of extraction, which is performed by cable crane, is assumed to be the same as that of the highly mechanised harvesting system of forest residues. The rationale for this rests on the fact that the removal of landscape and forest-derived trees out of the sloped areas implies a similar effort in terms of expenses regardless of their specific size of DBH. In such a context, the unit costs incurred by a cable crane remain identical as for forest residues and average 12.72 €/m^3 l with a relatively low statistical dispersion. Finally, the last two stages of this highly mechanised harvesting system – moving and chipping – exhibit the same techno-economic features as those of the partly mechanised logistic chain for harvesting landscape wood raw material. In consequence, the respective costs along with their corresponding uncertainties are for both stages equal to those of the previously introduced harvesting technique.

The highly mechanised logistic chain is conducted in copses and groves growing in sloped areas with the consequence of inevitably generating relatively high harvesting costs. The labours are performed throughout the four indicated harvesting stages from the slopes of the copses to an intermediate chipping site situated within the open country. Figure 3.7 illustrates the specific costs for each stage as well as the total unit costs of wood chips as a unique product – expressed in either euro per unit volume of loose material (m^3 l) or euro per unit mass (tonnes).

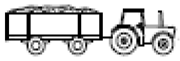
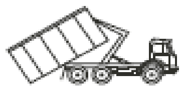
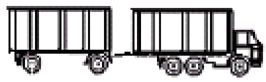
3.6. Transport of wood chips to conversion plant

Based on the spatial dimension of the federal state of Baden-Württemberg along with the specificities of its road network, the longer distances between any two geographic points within this region are those connecting the borders either from northwest to southeast or from northeast to southwest. In both extreme cases, and therefore in general for every route within the boundaries of the federal state, a maximum distance of 300 km is to be taken into consideration.

Under these particular conditions, the transport of wood chips from the forest roadside or the chipping site (landscape) to the different conversion plants for distances up to 300 km can be accomplished by means of the following three different methods of transport (see Table 3.2): namely a *tractor with a trailer*, a *truck with a container* and a *truck with two containers*. These three techniques for the transportation of chipped wood resources are commonly employed in the German forestry sector according to certain studies such as [Dobers et al. 2007], [Kaltschmitt et al. 2009] and [Kappler 2008].

[Dobers et al. 2007] analyses the economics of different modes of transport such as tractor with one or two trailers for short distances as well as the option of truck with a container for a maximum length of 200 km. In keeping with this approach, the implementation of railway transportation is completely dismissed for wood chips. On the other hand, [Kappler 2008] gives insight into the high costs of hauling chipped wood resources by truck in comparison to train transport, while considering the expenses of a prior truck from the forest to the railway loading station in addition to the corresponding transhipment costs. [Kaltschmitt et al. 2009] goes a step further and includes a requirement for transportation of wood chips by train. This suggests the eventual construction of storage facilities close to the conversion plants, provided that they are connected to the railway network, so as to minimise total unit costs of chipped wood resources before transformation into bioenergy. According to this study, if longer distances than 300 km are allowed for, then the transport of wood chips by train could be carried out in direct competition with ship transportation through the federal states' waterways. In this regard, some international studies such as the Canadian [Hoque et al. 2006] and the Dutch [Suurs et al. 2002] reinforce the idea of hauling chipped wood resources by train exclusively for distances over 500 km, while leaving road transport for somewhat shorter distances in the order of 200 km. As the above spatial constraints for both railway and waterway transportation are far from the physical reality of Baden-Württemberg, then the corresponding means of transport are not taken into account within the framework of this dissertation.

Table 3.2: Different transport modes of wood chips for distances between the source and the conversion plant within 300 km (based on [LB 2005])

			
	Tractor with trailer	**Truck 1 container**	**Truck 2 containers**
Maximum volume (m^3)	16	40	80
Maximum permitted load (t)	14	13	23
Transported load of wood chips (t)	5.8	12.9	23

Based on the aforementioned rationale for the identification of the three transport modes of Table 3.2, a suitable methodological approach is developed in the following three subsections respectively for the selection of the most cost-efficient means of transport, the determination of its distance-specific transport costs as well as the estimation of the corresponding loading and unloading costs.

3.6.1. Selection of the most cost-efficient mode of transport

A methodology for choosing an appropriate transport mode of chipped wood resources is introduced below on the basis of the identified transportation techniques of Table 3.2. From the three above mentioned means of transport, which are considered as adequate for wood chips haulage, the option of *tractor with trailer* is mostly – although not always – reported to be more suitable than that of a *truck* for distances[18] ranging approximately up to 15 km. In

[18] Throughout this study, the covered distances are systematically conceived as a two-way journey. However, they are numerically identified by means of the outward journey that is expressed in km. For instance, a route

relation to this issue, [Wittkopf 2005] refers to a maximum covered distance of 15 km with a tractor being more cost-efficient than a truck. Similarly, according to the studies [Leible et al. 2003], [Leible et al. 2007] and [LB 2005], a distance of 10 km is found to be the turning point, over which the transport costs incurred by a tractor become higher than those generated by a truck as far as transportation of wood chips is concerned. Others such as [LBD 2005] and [FNR 2014] determine a maximum travelled distance of 5 km in regard to this aspect and even [Dobers et al. 2007] and [Leible et al. 2011] suggest that the transport costs of a tractor are systematically higher than those of a truck when dealing with chips haulage.

Against this background, it is not a simple task to determine whether one means of transport is more appropriate than another for the haulage of wood chips over a distance between the source and the conversion point. On the one hand, transport costs for short routes are extremely variable and, on the other, the option of a tractor with trailer is indeed limited to distances not longer than 15 km. In consequence, the remaining transport methods of a truck with one or two containers turn out to be the best options for any distance to be covered. This gives rise to the non-consideration of the transport mode based on a tractor with trailer, which was included in Table 3.2. Therefore, it is also not taken into account in the optimisation analysis involving the cost-effectiveness of the transport sector of any wood resources-based bioenergy system.

Likewise, the two remaining transportation methods based on a truck with either one or two containers can be reduced to a unique means of transport in agreement with [LBD 2005], [LB 2005] and [FNR 2014]. All these studies confirm that which seems to be evident in relation to the level of transport costs if both transportation options are compared. As might be expected, they all point at a lower amount of transport costs for the option of a *truck with two containers* with respect to that of a *truck with one container*. This fact can be easily accounted for by the higher transported load of wood chips in the case of the former (see Table 3.2), which finally results in cheaper haulage costs despite a somewhat higher investment and operating expenses for the former versus the latter.

As a consequence of the previous comparative analysis, the means of transport based on a *truck with two containers* is selected as the only and most cost-efficient transportation option for wood chips from the forest and landscape areas to the conversion plant.

of 15 km is travelled by a truck from the forest (source) to the conversion plant (sink) and afterwards it returns from the sink to the source thus doubling this figure to 30 km. In this manner, the distance is according to this methodology registered at the half-way point of the complete journey as a 15 km long stretch measured between source and sink. Needless to say, the incurred transport costs for chips haulage do consist of the full round trip costs including both the outward and the return transport costs.

3.6.2. Determination of the distance-specific transport costs for a truck with two containers

The costs incurred by a means of transport for carrying wood chips over a certain distance can be deduced by means of a linear function that introduces the transport costs *TC* (€/t) on the basis of the following mathematical formula: $TC = a+b \cdot x$. This linear function consists of two terms, namely an independent term a involving the fixed costs in euro per tonne (e.g. wages, leasing) and a further term that includes a coefficient b referring to the distance-specific variable costs in euro per tonne-kilometre (e.g. diesel), which multiplies the covered distance x (km).

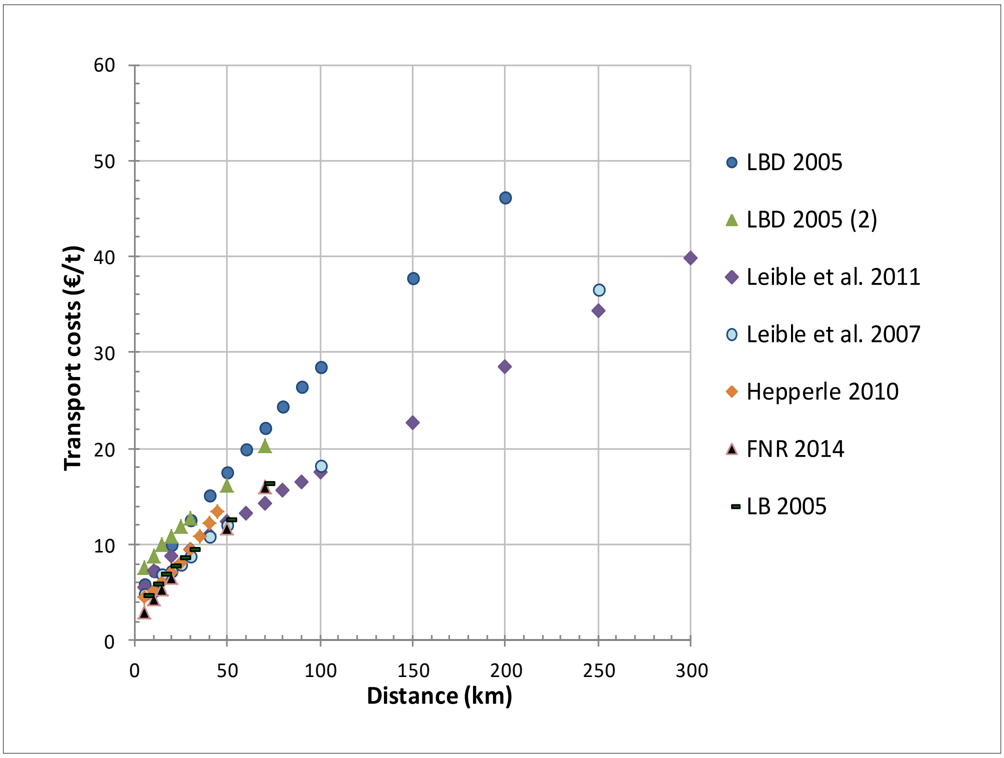


Figure 3.8: Linear dependence of transport costs on the covered distance for different research studies dealing with the socio-economic context of Germany

In this sense, especially the Spanish study [Gómez et al. 2010] but also other research sources such as the Canadian [Kumar et al. 2003] and the Swedish [Uddin 2004] implement – in greater or lesser detail – the prior mathematical expression for describing the transport costs of forest residues or even their resultant wood chips when being carried by different load vehicles such as a train or a truck. As this dissertation aims at modelling the wood resources-based bioenergy system of the federal state of Baden-Württemberg, exclusively German literature on wood chips transportation are consulted for obtaining the dependence of transport costs on the covered distance between the forest roadside and the conversion plant. Through a comprehensive literature search, different databases on transport costs of wood chips as a function of diverse distances are found. Particularly, two different case studies published in [LBD 2005] besides other specialised sources such as [Leible et al. 2007], [Leible et al. 2011], [Hepperle et al. 2010], [FNR 2014] and [LB 2005] contribute to the construction of the plot showed in Figure 3.8. The graph illustrates the linear dependence of transport costs on the distance for carrying wood chips with a *truck with two containers* up to a maximum of 300 km. As a result, several series of transport costs from the aforementioned studies are averaged for each specific distance with the aim of performing a regression adjustment for best fitting the data sample. Thus, a linear function relating to the dependency between transport costs and each distance is derived in Figure 3.9.

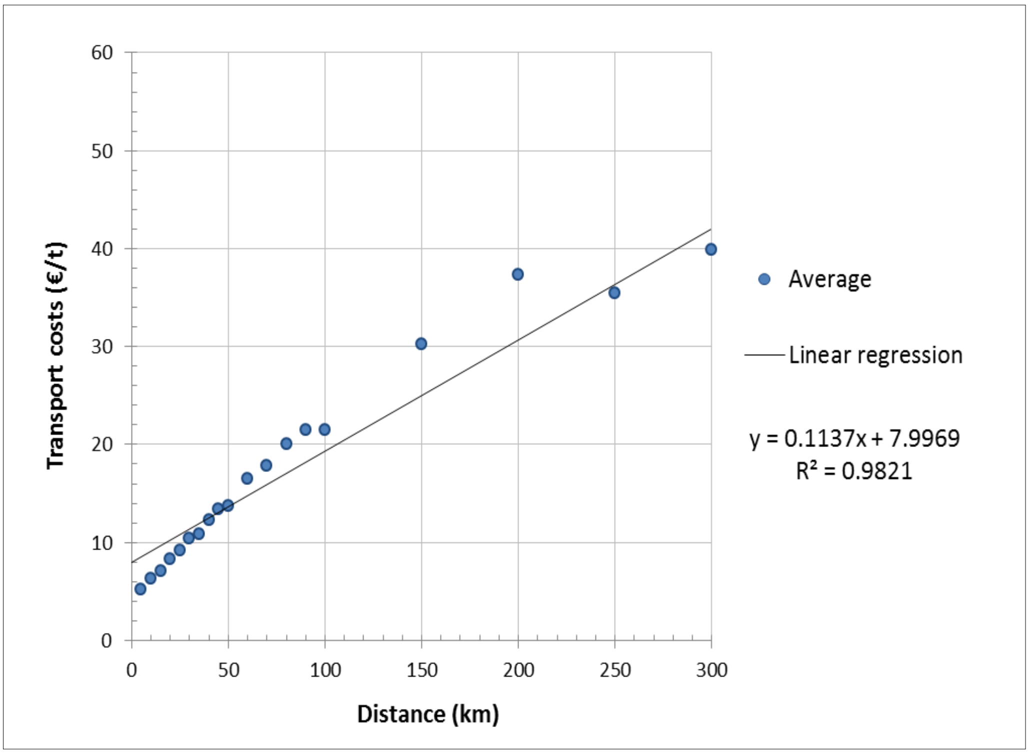


Figure 3.9: Linear regression of averaged transport costs versus the covered distance

Based on the equation of the trend line obtained from the previous linear regression, the coefficients a and b of the linear function $TC = a+b\cdot x$ – describing the transport costs TC as a function of distance – can be calculated. According to this formula, the distance-specific transport costs $DSTC$ of carrying wood chips with a truck with two containers can be derived by simply dividing the transport costs TC by the variable x – the travelled distance of the journey. The resulting outcome finally describes a curve showing the dependence of distance-specific transport costs ($€\cdot t^{-1}\cdot km^{-1}$) on the distance. The plot can be contemplated in Figure 3.10 besides the data series obtained from the different consulted studies. In the same vein, these data are appropriately converted from transport costs into distance-specific transport costs by merely dividing them by the specific distance as reported by the corresponding research studies.

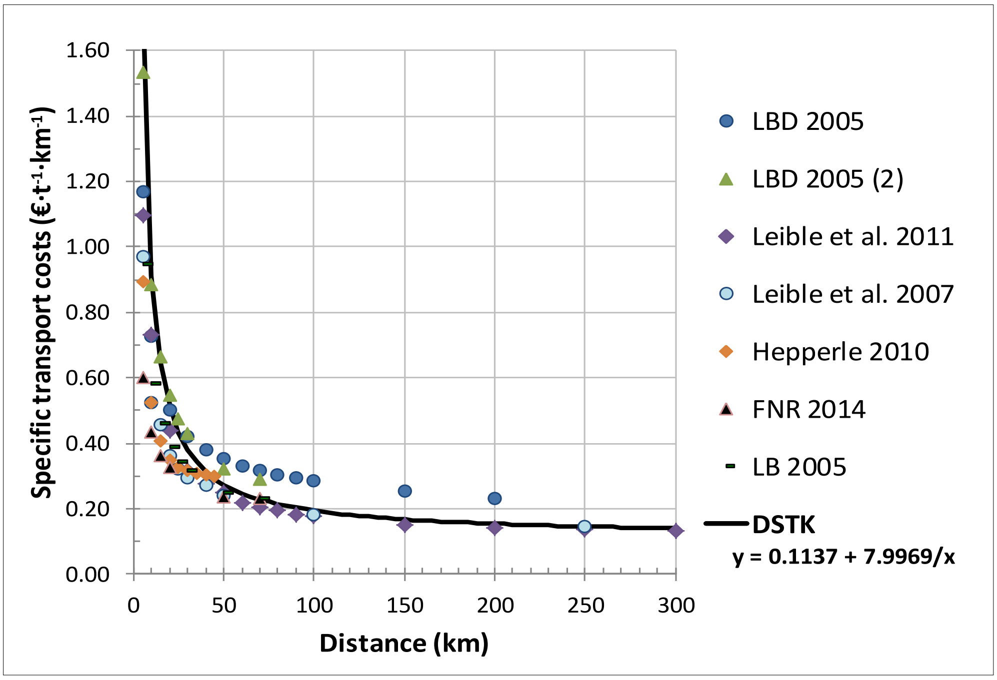


Figure 3.10: Distance-specific transport costs of carrying wood chips by a truck with two containers up to a maximum distance of 300 km

3.6.3. Loading and unloading costs

Wood resources are collected by means of any of the six previously presented logistic chains, specifically four techniques for harvesting forest residues and two for landscape wood raw material. Through the last stage of chipping – carried out by either a tractor or truck chipper – these wood resources are transformed into wood chips, while directly blowing them into the containers left at the roadside in the forest and landscape areas. This mechanised transfer of wood chips to each of the two containers – which are finally towed by the same truck – is accomplished without any further effort, thus incurring no additional costs derived from loading this material into both containers [FNR 2014]. Nevertheless, the two full containers placed at the roadside must be attached to the truck somehow or other. To this respect, the preselected means of transport consisting of a truck with two containers is technically limited to loading a single container onto the rear flatbed of the truck. This is carried out with the assistance of a mounted crane by lifting the container clear of the ground; whereas a second container lying on a truck trailer is placed by the side of the wooded formations that are to be harvested.

When the truck with both containers full of chipped wood resources arrives to the conversion plant, wood chips from both containers have to be unloaded by tipping them. Thereby, chips unloading operations have to be performed for both containers with the subsequent generation of a certain level of unloading expenditures. In contrast, no actual loading of wood chips takes place at the roadside in the forest and landscape areas – as previously declared. Instead, truck manoeuvring tasks for loading the first container onto the truck's flatbed as well as coupling the trailer with the second container to the truck are certainly accomplished.

All in all, manoeuvring/attaching and unloading-related costs are roughly assessed at 2.28 €/t as an average of both loading and unloading costs reported by [Frick et al. 2005], [EUBIA 2009], [Wiik et al. 2009] and [Hamelinck et al. 2005] for solid biomass energy carriers. This estimation is taken as an assumption of the more complex real costs of those tasks involving the manoeuvre and subsequent loading of a container on the truck's flatbed as well as the coupling of the trailer to the truck. Regrettably, these expenditures cannot be easily reproduced on account of a lack of suitable data for these stages of the supply chain to the conversion plant. In the same vein as for the costs incurred throughout the entire logistic chains of chipped wood resources, the averaged costs for transhipment of wood chips can be accordingly used as input data for the optimisation of a wood resources-based bioenergy system.

3.7. Tabulation of unit costs incurred by the harvesting systems of wood resources

The total unit costs of the four degrees of mechanisation for the corresponding logistic chains of chipped forest residues are broken down into the unit costs of each harvesting stage on the basis of both by-product and joint product allocation techniques (see Table 3.3).

Table 3.3: Cost breakdown and total unit costs of the four logistic chains of chipped forest residues regarded either as a by-product (BP) or as a joint product (JP) for an average DBH of 15 cm and 35% MC

<table>
<tr><th colspan="2" rowspan="2">LOGISTIC CHAINS</th><th colspan="5">UNIT COSTS OF STAGES (€/m³ l)</th><th rowspan="2">TOTAL
(€/m³ l)</th></tr>
<tr><th>Felling</th><th>Extraction</th><th>Debranching</th><th>Moving</th><th>Chipping</th></tr>
<tr><td rowspan="2">Motor-manual</td><td>BP</td><td colspan="2">0.00</td><td>0.00</td><td rowspan="2">6.65</td><td rowspan="2">4.61</td><td>11.26</td></tr>
<tr><td>JP</td><td colspan="2">3.37</td><td>3.23</td><td>17.85</td></tr>
<tr><td rowspan="2">Partly mechanised</td><td>BP</td><td colspan="2">0.00</td><td>0.00</td><td rowspan="2">6.65</td><td rowspan="2">3.83</td><td>10.48</td></tr>
<tr><td>JP</td><td colspan="2">3.37</td><td>3.23</td><td>17.07</td></tr>
<tr><td rowspan="2">Highly mechanised</td><td>BP</td><td colspan="2">0.00</td><td>0.00</td><td rowspan="2">6.65</td><td rowspan="2">3.83</td><td>10.48</td></tr>
<tr><td>JP</td><td>2.54</td><td>12.72</td><td>3.23</td><td>28.96</td></tr>
<tr><td rowspan="2">Fully mechanised</td><td>BP</td><td colspan="3">0.00</td><td rowspan="2">6.11</td><td rowspan="2">3.83</td><td>9.94</td></tr>
<tr><td>JP</td><td colspan="3">7.19</td><td>17.13</td></tr>
</table>

Likewise, the total unit costs of the two degrees of mechanisation for the corresponding logistic chains of chipped landscape wood raw material as a unique product are split into the unit costs of each harvesting stage (see Table 3.4).

Table 3.4: Cost breakdown and total unit costs of the two logistic chains of wood chips as a unique product for landscape wood raw material with an average DBH of 10 cm and 35% MC

LOGISTIC CHAINS	***UNIT COSTS OF STAGES** (€/m³ l)*				**TOTAL** *(€/m³ l)*
	Felling	**Extraction**	**Moving**	**Chipping**	
Partly mechanised	9.22		6.38	5.31	20.90
Highly mechanised	5.24	12.72	6.38	5.31	29.64

4. The bio-based technologies for conversion of wood resources into power

The last stage of the utilisation pathway of wood resources for power generation, namely that including the conversion technologies, has to be determined so as to model the corresponding bioenergy system of Baden-Württemberg. To this end, different technologies based on combustion and gasification of wood resources for power production purposes are identified and described. Subsequently, the most appropriate processes are preselected from this array of feasible techniques on the basis of cost-effectiveness criteria. The combustion technologies under consideration consist of a converter system and a prime mover in the form of a boiler coupled to a Stirling engine, a stoker boiler attached to a steam turbine, a fluidised bed boiler coupled to a steam turbine or a co-firing based steam cycle. Regarding gasification, the technical options based on fixed bed gasification plus a gas engine, a fluidised bed gasifier coupled to a gas engine or equally to a combined cycle rank among the most feasible technologies made up of a gasifier and a further prime mover.

For this broad spectrum of bio-based technology options, a preselection procedure is carried out on the basis of a well-founded rationale for integrating into the model the most cost-effective conversion processes for all capacity ranges varying from small via medium through to large scales. To this effect, a simple methodological approach consisting in a comparative analysis of the specific electricity production costs of all referenced technologies is applied to both ranges of small and medium scales, on the one hand, and large scales, on the other. This preselection of technologies is put forward with the aim of excluding the less cost-effective conversion processes from being integrated in the intended modelling of the bioenergy system. As an interim conclusion, direct co-firing as well as a fluidised bed gasifier coupled to a gas engine or alternatively a combined cycle are identified for the first time as the most cost-efficient bioenergy conversion pathways within the value chain of wood resources.

Finally, the previously preselected bio-based processes are techno-economically characterised on the basis of a comprehensive literature search that provides the fundamentals of both combustion and gasification technologies. A series of the most decisive techno-economic parameters including capital costs, the fixed and variable share of operation and maintenance costs as well as the electric and total efficiencies are calculated for the three preselected technologies by means of a specific methodology based on the use of appropriate (power or logarithmic) regression techniques. This approach represents a substantial step towards assigning a reliable dimension to the specific parameters of such cost-efficient technologies for their respective electric capacity ranges. In addition, this section also refers to the problem of data uncertainty that is measured by estimating the coefficient of determination within the framework of each regression adjustment. In essence, the resulting graphs constitute an interesting research outcome, which was never published by the same author in the domain of bioenergy technologies for conversion of solid biomass resources into power. In this sense, this permits offering a consistent data base on the most cost-efficient techniques for the whole range of electric scales so that it may be subsequently implemented in a wood resources-based bioenergy system analysis for Baden-Württemberg or any other particular region.

4.1. Combustion technologies

According to [EPA 2007], the most common utilization of solid biomass is direct combustion with the resulting hot flue gases producing steam in a boiler – a technology that goes back to the 19th century. Boilers burn a variety of fuels and continue to play a major role in heating and electricity generation. The bio-based fuel is burned in a boiler to produce high-pressure steam that is used to power a condensing turbine-driven power generator. In many applications, steam is taken from extraction and back-pressure turbines at medium pressures and temperatures and is used for process heat, space heating or space cooling. Besides steam turbines, steam engines and Stirling engines are also based on direct combustion.

[EPA 2007] reports that the two most commonly used types of combustion systems for biomass firing are stoker boilers and fluidized bed boilers. Either of these can be fuelled entirely by biomass fuel or co-combusted as a combination of biomass and coal (co-firing). With respect to the technical configuration, stoker boilers are categorised into three different types: underfeed, overfeed and spreader stokers. In line with [IRENA 2012], underfeed boilers supply both fuel and air from under the grate, whereas overfeed boilers feed fuel from above the grate and air from below. Based on [EPA 2007], spreader stokers propel the fuel particles into the air above the grate.

[Zhang et al. 2010] also introduces a further combustion system based on an entrained flow reactor. This type of reactor together with the fluidised bed design and the stoker boiler exhibit a different array of gas velocities within their respective combustion chambers. In this regard, stoker and fluidised bed boilers along with entrained flow reactors are characterised by a markedly increasing rate of gas velocity, which increases according to the former enumeration order. A higher gas velocity translates to a more intensive mixing of feedstock, which enhances its combustion efficiency together with the heat exchange rate. Although the entrained flow systems are expected to exhibit a better performance than the other two, it proves to be very expensive and is therefore not included within the analysis of this dissertation.

As stated by [Zhang et al. 2010], there are three main stages occurring during biomass firing, namely drying, a combination of pyrolysis and reduction and thirdly combustion of both volatile gases and solid char. The combustion of volatiles gases contributes to more than 70% of the overall heat generation. It takes place above the fuel bed and is generally evident by the presence of yellow flames. Char is combusted in the fuel bed and is noted by the presence of small blue flames. This thermochemical process consists in the complete oxidation of biomass in the presence of abundant oxygen.

Hereafter, four different combinations of combustion system and prime mover for power generation are introduced.

4.1.1. Boiler coupled to Stirling engine

Based on [EPA 2007], the Stirling engine is a reciprocating engine that is externally powered by means of feeding to it heat from an external combustion process carried out in a boiler.

Heat is transferred to the working gas (e.g. air, helium, hydrogen, nitrogen) via a heat exchanger and subsequently converted into mechanical work via the Stirling thermodynamic cycle. For this purpose, this cycle must be completed by being externally cooled through the implementation of forced or free convection cooling as well as by using a suitable coolant circulating through a jacket surrounding the engine. Since heat is supplied externally, a wide variety of heat sources at any temperature level can be used beyond biomass (e.g. fossil fuels, solar, nuclear and waste heat). As an external combustion engine, fuel is burned in a continuous manner outside of the Stirling engine's cylinders. This is unlike in an internal combustion engine, where fuel is injected into the cylinders intermittently and then exploded. Thereby, external combustion results in a better and more complete burning of fuel while generating lower emissions. The external combustion also provides the extra benefit of reduced noise and vibration compared to internal combustion engines. This is attributable to the lack of valves and the absence of periodic explosions [Wang et al. 2016].

[Obernberger et al. 2008a] declares that Stirling engines are based on a closed cycle, where the working gas is alternately compressed in a cold cylinder and then expanded in a hot cylinder. Certain aspects concerning the use of biomass fuel are to be reported especially with regard to the heat transfer from the flue gas to the working gas. On the one hand, the temperature of the heat source must be high enough to reach an acceptable power output and efficiency and, on the other hand, the heat exchanger must be designed so as to minimise deposit formation. Stirling engines show in any case low maintenance requirements mainly due to their simplicity.

Besides, the usual scale of Stirling engines is limited to low power capacities of not more than a maximum of 300 kW_e on the basis of projections that include the upcoming years [Oros et al. 2014]. This scale limitation is based on the efficiency reduction that Stirling engines experience while scale increases [Kim et al. 2008].

4.1.2. Stoker boiler coupled to steam turbine

As stated by [IRENA 2012], a Rankine cycle is implemented in a stoker boiler conceived as a fixed bed system that is coupled to a steam turbine. A high pressure stoker boiler burns biomass on a stationary or moving grate while producing hot flue gases that are then used to produce steam for feeding the following steam turbine. Ashes from the combusted biomass fuel are removed continuously by the grate.

Based on [Zhang et al. 2010], fixed bed systems have been widely used for biomass combustion for a number of years. The simplest fixed-bed system is composed of one combustion room with a grate. As biomass is fed to the furnace, it is pyrolysed into volatile gases and chars. Primary and secondary air supplies are provided under and above the grate for the combustion of chars and volatile gases, respectively. The heat generated through the combustion of chars is responsible for providing enough heat for the pyrolysis of newly added biomass. Because of the high content of volatile matter in biomass fuels, a greater secondary air supply is required beyond the primary air supply – in contrast to the process of coal combustion. A fixed bed biomass combustion system is typically operated at around 850-1400°C. Certain developments have been made to enhance the fixed combustion efficiency. An example is the cyclonic combustion system, which may be viewed as a modified fixed bed system, suitable for the combustion of agricultural residues and wood wastes at a high efficiency.

According to [Bridgwater et al. 2002], the basic steam turbine Rankine cycle is bound by thermodynamic and materials limitations to modest efficiencies of around 35%. Such cycles are optimised through the use of high pressure, highly superheated steam, reheat or regeneration options. This extra complexity increases capital costs dramatically at small scale, with only minor increases in system efficiency. As a result, most steam cycles at the small scale are relatively simple and consequently inefficient as cycle enhancements are not cost-effective under these conditions.

As far as steam turbines are concerned, [EPA 2007] reports that this thermodynamic device converts the energy of steam into shaft power or mechanical work. The steam causes the turbine blades to rotate, creating power that is turned into electricity with a generator. A condenser and pump are used to collect the steam exiting the turbine, feeding it into the boiler and completing the cycle. There are several different types of steam turbines:

- A condensing steam turbine is for power-only applications and expands the pressurised steam to low pressure at which point a steam/liquid water mixture is exhausted to a condenser
- Extraction turbines have openings in their casings for extraction of a portion of the steam at some intermediate pressure
- Back-pressure turbines exhaust the entire flow of steam at the required pressure

When it comes to electricity production, systems that are made up of a stoker boiler coupled with a steam turbine are perfectly suited to the entire array of scales ranging from small via medium through to large dimensions.

4.1.3. Fluidised bed boiler coupled to steam turbine

According to [EPA 2007], fluidised bed boilers are developed specifically for solid fuel combustion. The primary driving force for development of fluidised bed combustion was the reduction of SO_2 and NO_x emissions from coal combustion. As the technology developed, it became apparent that the process could efficiently burn biomass and other low-grade fuels that are difficult or impractical to burn with conventional techniques. [Zhang et al. 2010] further reports that fluidised systems have higher combustion efficiency and they are more suitable for large scale operations than fixed bed systems.

On the basis of [EPA 2007], biomass is burned in a bed of hot inert, or incombustible, particles suspended on upward blowing jets of air that are injected from the bottom of the reactor to keep the bed in a fluidised state. Fluidised bed systems employ silica sand, limestone, dolomite or other non-combustible element for the bed material [Zhang et al. 2010]. The bed materials act as the heat transfer media, which are fluidised by the air flow coming from the bottom [Zhang et al. 2010]. The scrubbing action of the bed material on the fuel enhances the combustion process by stripping away the CO_2 and the solid residue (char) that normally forms around the fuel particles. This process allows oxygen to reach the combustible material more readily and increases the efficiency of the combustion process. Natural gas or fuel oil can also be used as a start-up fuel to preheat the fluidised bed or as an auxiliary fuel when additional heat is required. The effective mixing of the bed makes fluidised bed combustion well-suited to burn solid refuse, wood waste, waste coals and other non-standard fuels. Typically, biomass is burned with 20% or higher excess air. Only a small fraction of the bed is combustible material; the remainder is comprised of inert material, such as sand. This inert material provides a large inventory of heat in the furnace section with the effect of dampening the brief fluctuations in fuel supply or heating value. Due to long residence time and high intensity of mass transfer, fuel can be efficiently burned in a fluidised bed combustor at temperatures considerably lower than in conventional combustion processes (760-870° C compared to 1,200°C of a stoker boiler). For [Zhang et al. 2010], the typical operating temperature in a fluidised bed system is 700-1000°C, which is lower than that of fixed bed systems, thus lengthening the lives of the gasification system [Roos 2010]. Furthermore, the lower temperatures produce less NO_x, a significant benefit when burning high nitrogen-content wood and biomass fuels. SO_2 emissions from wood waste and biomass are generally insignificant, but anyway limestone can be added to the fluid bed to achieve a high degree of sulphur capture – e.g. construction debris or paper mill sludge are fuels typically contaminated with sulphur.

As stated by [EPA 2007], fluidised bed boilers are categorised as either atmospheric or pressurised units. However, combustion processes are mainly developed under atmospheric conditions because a pressurised combustion would generate a sort of gaseous product as in the case of gasification. Furthermore, although a pressurised fluidised bed boiler is more efficient than the atmospheric option, it also proves to be more complicated and expensive. At any rate, both atmospheric and pressurised fluidised bed boilers are further divided into bubbling-bed and circulating-bed units. The fundamental difference between bubbling-bed and circulating-bed boilers is the fluidisation velocity (higher for circulating). Circulating fluidised bed boilers separate (in a cyclone) and capture fuel solids entrained in the high-velocity exhaust gas and return them to the bed for complete combustion. Atmospheric-pressure bubbling fluidized bed boilers are most commonly used with biomass fuels. Furthermore, the bubbling bed technology is generally selected for fuels with lower heating values, whereas the circulating bed is most suitable for fuels of higher heating values. Due to the high mixing rate at high velocity, circulating fluidised bed systems behave more efficiently than those based on the bubbling technique [Zhang et al. 2010]. They also exhibit several advantages, such as the adaptation to various fuels with different properties, sizes, shapes and moisture (up to 60%) as well as ash contents (up to 50%) [Zhang et al. 2010].

Similarly to the prior case of the stoker boiler coupled to a steam turbine, the converter system based on a fluidised bed boiler can also be connected to a steam turbine for electricity production. Regarding its scale, this combination of converter system and prime mover is especially appropriate for medium and large scales on account of the higher investments required.

4.1.4. Co-firing

According to [IRENA 2012], co-firing is the process of adding a percentage of biomass to the fuel mix in a coal-fired power plant. Based on this definition, there are three possible technology setups for co-firing in dust firing-based combustion systems:

- *Direct co-firin*g: biomass and coal are fed into a boiler with shared or separate burners
- *Indirect co-firin*g: solid biomass is converted into a fuel gas that is burned together with the coal
- *Parallel co-fi*ring: biomass is burned in a separate boiler and steam is supplied to the coal-fired power plant.

In line with [IRENA 2012], direct co-firing can be carried out up to a co-fire rate of 5-10% of biomass (in energy terms) and 50-80% with extensive pre-treatment of the feedstock in case of indirect co-firing with certain changes in the handling equipment. Technically it is possible to co-fire up to high levels of capacity; however, most existing co-firing plants use only up to about 10% biomass. For co-fire rates above 10%, changes in dryers, mills and burners are required to be carried out. With respect to the type of combustion technology, the implementation of fluidised bed boilers can substitute higher levels of biomass than pulverised coal-fired or grate-fired (stoker) boilers. At any rate, co-firing higher portions of biomass will usually require more sophisticated boiler process control and boiler design, as well as different combustion considerations related to fuel blend and fuel handling systems. Biomass is also co-fired with natural gas, but in this case the natural gas is often used to stabilise combustion when biomass with high moisture content is burned.

A major advantage of biomass co-firing is that, on average, electric efficiency in co-firing plants is higher than in dedicated biomass combustion plants with the same bio-based capacity [IRENA 2012]. Consistent with this argument, [IEA 2007] also declares that combustion efficiency of biomass can be, in general, 10 percentage points lower than for coal at the same installation. In this regard, co-firing efficiency in large-scale coal-fired plants is in the order of 35-45% and therefore higher than that of biomass-dedicated plants ranging between 22 and 34%. On the other hand, co-firing presents the most stringent requirements for moisture content and feedstock size if efficiency is not to be degraded [IRENA 2012].

As stated by [IEA-IRENA 2013], co-firing can play an important role in increasing the use of biomass in power generation and reducing greenhouse gas (GHG) emissions because only a relatively modest incremental investment is needed to retrofit existing coal-fired plants or build new co-fired units. Compared to dedicated power plants burning 100% biomass, co-firing offers several advantages – beyond that of a higher efficiency – including lower capital costs with improved economies of scale and therefore lower electricity costs due to the larger size and the superior performance of modern coal-fired power plants. According to [USDOE 2006], as much of the existing power plant equipment can be used without major modifications, co-firing is far less expensive than building a new bio-power plant.

[Korshidi et al. 2014] reports that co-firing biomass might increase slagging and fouling on the walls of the combustion chamber and boiler tubes and that the severity depends on many factors such as fuel composition, among others. For example, co-firing herbaceous biomass at high levels would lead to a higher degree of slagging and fouling in comparison with woody biomass. In contrast, co-fired biomass reduces sulphur dioxide (SO_2), nitrogen oxides (NOx) as well as other air emissions [USDOE 2006].

4.2. Gasification technologies

Based on [EPA 2007], gasification technologies using biomass by-products are popular in the pulp and paper industry where process steam and electricity are generated at higher efficiencies and with lower capital costs than conventional technologies. Nevertheless, the process of gasification was first employed at the start of the industrial revolution for conversion of both coke and coal into a low calorific gaseous fuel for lighting and heating purposes.

According to [IRENA 2012], gasification consists in the partial combustion of biomass in a low oxygen environment leading to the release of a non-condensable gaseous product called producer gas or syngas. The gasification process is a predominantly endothermic process that requires significant amounts of heat. Anyhow, gasification reactions take place at lower temperatures than in combustion, thus increasing the technical life of the conversion system [Roos 2010].

For [EPA 2007], the process of biomass gasification involves heating solid biomass in an oxygen-starved environment to produce a low or medium calorific gas referred to as syngas. This gas can also be produced through direct heating under the conditions of partial oxidation or via indirect heating with steam in the absence of oxygen. For partial oxidation, a typical share of around 35% of the O_2 demand for complete combustion is required according to [Zhang et al. 2010]. In coal gasification, pure oxygen or oxygen-enriched air is preferred as an oxidant – due to the lack of oxygen in coal – because the resulting syngas has a higher heating value, and the process becomes more efficient. In biomass gasification, pure oxygen is generally not used because biomass ash has a lower melting point than coal ash, and because the scale of the plants is generally smaller.

In line with [IRENA 2012], biomass gasification comprises a two-step process that leads to the final gaseous product. The first step, pyrolysis, includes the decomposition of the biomass feedstock by heat. This yields 75 to 90% volatile materials in the form of liquids and gases, with char as the remaining non-volatile products. These volatile components are released during the step of pyrolysis at a temperature of around 600°C through a series of complex reactions [EPA 2007]. The second step is made up of a gasification process, where the volatile hydrocarbons and the char are gasified (reduced) at higher temperatures in the presence of a suitable reactive agent to produce CO and H_2 with some CO_2, H_2O, methane, other higher hydrocarbons and compounds including tar and ash. These two steps are typically achieved in different zones of the reactor vessel but do not require separate equipment. A third step is sometimes added by introducing a gas clean-up to remove those contaminants such as tars or particulates.

Consistent with [IRENA 2012], gasifiers can be classified according to four specific features:

- *Oxidation agent*: air, oxygen, steam or a mixture of these gases
- *Heat input*: direct/autothermal (caused by the exothermal reaction of the combustion process within the reactor vessel) or indirect/allothermal (provided from an external source to the reactor)
- *Operating pressure*: atmospheric or pressurised
- *Reactor type*: fixed bed, fluidised bed or entrained flow gasification (similar to combustion processes)

This research study also reports that air-based gasifiers are relatively cheap and typically generate a producer gas with high nitrogen content (derived from air) and low energy content (5-6 MJ/m^3 on a dry-basis). Gasifiers using oxygen or steam as the reactive agent tend to produce a syngas with relatively high concentrations of CO and H_2 with a much higher energy content (9-19 MJ/m^3), albeit at a greater cost than an air-blown gasifier. Based on [EPA 2007], the heating value of the syngas can range from 10 to 50% of that showed by natural gas depending on the carbon and hydrogen content of biomass as well as the gasifier's properties.

As stated by [IRENA 2012], the resulting gas can be used in reciprocating engines, gas turbines or fuel cells after clean-up and conditioning of syngas. When syngas is used in (simple or combined-cycle) turbines and fuel cells, higher electrical efficiencies can be achieved than those obtained in a steam turbine. However, when gasification is not fully completed a syngas composed of significant amounts of alkali metals, nitrogen compounds, particulate, char and tars is produced. The producer gas composition as well as its level of contaminants depends on the kind of biomass, the type of gasifier and the selected operating parameters. In such a context, tars can clog engine valves and accumulate on turbine blades, leading to increased maintenance costs and decreased performance. These contaminants do not prevent combusting the syngas in a boiler or an internal combustion engine. Nevertheless, when used in turbines to achieve higher electric efficiencies, some form of gas clean-up is strictly required to ensure the gas reduces contaminant concentrations to harmless levels. Tars are a major problem, as they can build up on turbine blades and foul turbine systems. Against this background, gasification clearly offers a major advantage over direct combustion since the gas can be cleaned and filtered to remove problematic chemical compounds before it is burned [EPA 2007].

Three different combinations of gasification system and prime mover for power generation are presented in the following subsections.

4.2.1. Fixed bed gasifier coupled to gas engine

On the basis of [IRENA 2012], fixed bed gasifiers have a fixed grate at the bottom of a refractory shaft. This grate permits supporting the biomass and maintaining a stationary reaction bed, where the fuel presents a long residence time in the reactor due to a low gas velocity. These gasifiers are suitable for feedstocks with high enough bulk densities in order to guarantee stable fuel flow [Obernberger et al. 2008a].

In keeping with [Zhang et al. 2010], an air-blown fixed bed gasifier can be divided into four different zones, which are laid down throughout the whole reactor from top to bottom:

- *Drying zone*: Water resulting from moisture content of biomass is evaporated
- *Pyrolysis zone*: Biomass is pyrolysed into medium-energy calorific volatile gases, liquid and char
- *Combustion zone*: Oxidation reactions take place with limited amounts of reactive agent
- *Reduction zone*: Chemical substances CO and H_2 together with CO_2 and CH_4, are produced.

[EPA 2007] reports that the fresh biomass in the reactor of fixed bed gasifiers remains on top of the pile of fuel, where the drying process begins just before the step of pyrolysis. The reactive agent, however, enters the combustion zone and passes through the entire reactor up to the outlet of syngas.

There are three types of basic design for fixed bed gasifiers according to [IRENA 2012]:

- *Updraft fixed bed gasifier*: Biomass enters at the top of the reactor and the reactive agent (air, steam and/or oxygen) below the grate in counter-current direction. The latter flows up through the grate and leaves as a syngas at the top where it is collected. The products originating from the drying and pyrolysis zones are occasionally entrained by the resulting syngas without further decomposition reactions thus causing high tar contents in the producer gas [Obernberger et al. 2008a]. The syngas including tars and volatiles exits from the top while chars and ashes fall through the grate to the bottom. Ash is completely oxidised and ends up without any significant amount of unburned carbon, while the dust content of syngas is comparatively low due to the reduced gas velocities and the filtering effects of the fuel bed in both drying and pyrolysis zones [Obernberger et al. 2008a]. Slagging problems can also arise if high-ash biomass is used. As a result of all this, updraft fixed bed gasifiers are often used exclusively for heating. They are relatively insensitive towards varying particle size [Obernberger et al. 2008a], and can accept biomass with relatively high moisture content (up to 60%) [Zhang et al. 2010]. Stable operating conditions can usually be reached because the partial load behaviour is good [Obernberger et al. 2008a].

- *Downdraft fixed bed gasifier*: Biomass and the reactive agent are introduced at the top of the reactor and move co-currently. The latter flows down through the bed and leaves as a syngas under the grate. The tars pass through the oxidation and reduction zones, which brings about much lower levels of tar in the syngas produced by downdraft fixed bed gasifiers than in the updraft design. This makes possible the combustion of syngas in engines without clean-up despite a minor level of fouling. Downdraft gasifiers tend to require a homogenous feedstock to achieve the best results. They are sensitive towards increasing the particle size of fuel, which may lead to the presence of unconverted carbon in the ash [Obernberger et al. 2008a]. They require quite dry fuels (less than 20% MC), while their partial load behaviour is rather poor [Obernberger et al. 2008a].

- *Cross-draft fixed bed gasifier*: Similar to downdraft gasifiers, the reactive agent enters at the side and moves down through the reactor vessel parallel to biomass. The syngas is collected at the other side of the reactor under the grate. These gasifiers respond rapidly to load changes. However, they are more complicated to operate. If a fuel high in volatiles is used, high amounts of tars and hydrocarbons will be present in the producer gas. Significant levels of unconverted carbon (up to 33%) appear in the ash as a result of incomplete gasification [EPA 2007].

Based on [Obernberger et al. 2008a], several other concepts of fixed bed gasifiers exist, specially double fired gasifiers, which try to combine the advantages of updraft and downdraft technologies, or even multi-stage gasifiers, where drying and pyrolysis as well as reduction and combustion are performed in separate reactors.

[IRENA 2012] also informs that fixed bed gasifiers are the preferred solution for small to medium scale applications. Updraft gasifiers can scale up to as much as 40 MW_{th}. However, down-draft gasifiers do not scale well beyond 1 MW_{th} in size due to the difficulty in maintaining uniform reaction conditions. Updraft fixed bed gasifiers have fewer restrictions on their scale, although they show certain difficulties in relation to the syngas quality due to tar formation. [EPA 2007] asserts that the physics of the refractory shaft reactor vessel of both updraft and downdraft fixed bed gasifiers limits the diameter and thus the throughput of the reactors.

The use of a gas engine with capacities in the order of small and medium scales permits the generation of electricity with efficiencies up to 25-30% [IEA 2007], which are higher than those of a steam turbine [EPA 2007]. Both diesel and spark ignition engines are suited for operation with low calorific gases and are also a well-known technology. They both require a prior treatment of syngas, which consists in cooling and cleaning the producer gas to achieve the desired performance specifications.

4.2.2. Fluidised bed gasifier coupled to gas engine

As stated by [EPA 2007], gasification takes place in a bed of hot inert materials suspended by an upward motion of a reactive agent in a similar manner to fluidised bed boilers. Nevertheless, the gasification process presents the particularity that this gasifying agent is either deprived of oxygen or contains small amounts of it for fostering sub-processes of partial oxidation. By exclusively reducing the quantity of air and the process temperature, it is possible to operate fluidised bed boilers as gasifiers. In direct combustion, 10 to 14 times the weight of the fuel is introduced as air. In gasification, the air entering the reactor, if any, is only one to two times. Furthermore, fluidised bed gasifiers can be designed to use a portion of the pyrolysis gases to generate the heat to drive the process (autothermal), or they can be externally fired (allothermal). While air is usually used as gasification medium in autothermal gasification, steam is employed in allothermal processes as an oxidation agent provided from outside the reactor [Obernberger et al. 2008a]. As the amount of oxidation agent is progressively augmented to achieve greater throughput, the bed begins to expand and levitate and become fluidised. Sand or alumina is often used to further improve the heat transfer. The use of inert materials in the fluidised bed increases the rate of reaction of both the biomass and oxidant in comparison to fixed bed reactors [IRENA 2012]. Thereby, biomass is pyrolysed and cracked through contact with the hot bed material [Zhang et al. 2010].

[Obernberger et al. 2008a] indicates that the different zones drying, pyrolysis, combustion and reduction cannot be clearly distinguished due to the intense mixing. Hence, the temperature is relatively uniform throughout the bed and therefore easy to control. The resulting gaseous product exhibits a high energy content but contains certain amounts of tars – although less than updraft fixed bed gasifiers – as well as high concentrations of dust that need to be removed. Notable benefits of fluidised bed devices are their high productivity and flexibility [EPA 2007]. Moreover, they offer higher performance than fixed bed systems, though with greater complexity and investments [EPA 2007]. On the contrary, fluidised bed gasifiers must be operated at full load in order to maintain the entire bed material circulation. Partial load operation is in this regard limited to about 70% on account of its slow response to load changes. As a consequence, a fully automatic process control is required due to the complexity of the whole process. In relation to the feedstock, a clearly defined fuel particle size is required, which unavoidably relates to a smaller magnitude of biomass particles with a corresponding higher gas velocity. Additionally, fluidised bed gasifiers can also handle a wider range of biomass feedstocks with moisture contents up to 30 percent on average [EPA 2007].

According to [IRENA 2012], fluidised bed gasifiers are categorised into bubbling and circulating fluidised bed systems, which can be either atmospheric or pressurised. In this sense, operating the gasifier at higher pressures inevitably increases the throughput but also the gasifier's complexity and the expenses [EPA 2007]. As the gas velocity is increased, the bed begins to bubble at a temperature of 700-900°C [Zhang et al. 2010]. With a further increase in airflow, the bed material lifts off the bed. In a circulating fluidised bed gasifier, the hot bed material is circulated between the reactor and a cyclone separator [Zhang et al. 2010]. During this circulation, bed materials and char go back to the reactor, while the ash is separated in the cyclone and finally removed from the system [Zhang et al. 2010]. With still higher velocities, the bed material would be entrained, i.e. picked up and carried off in the airflow thus giving rise to the entrained flow gasification concept [EPA 2007].

Fluidised-bed gasifiers can be sized effectively for middle or large scale facilities [Zhang et al. 2010]. As gas engines are only appropriate for small and medium applications, the matching of a fluidised bed gasifier and a gas engine (FBG+E) will exclusively allow power generation with medium scales of up to 15-20 MW_e [Wideskog 2011]. Regardless of the type of fluidised bed gasification (FBG) applied, the gasifier is in any case connected to a gas cleaning system followed by a suitable prime mover in the form of a medium-sized gas engine [Obernberger et al. 2008a].

4.2.3. Fluidised bed gasifier coupled to combined cycle

Fluidised bed gasifiers can be coupled to a further type of prime mover that is more suitable for larger scales than the gas engine itself. This is the case of the gas turbine, which produces a shaft work that can in turn be transformed into power by means of an electric generator. As certain requirements regarding the quality of the syngas have to be fulfilled prior to burning the syngas in a gas turbine, the gaseous fuel must be cleaned up to eliminate contaminants like tars and dust. After cleaning, the syngas produced in the fluidised bed gasifier is compressed and delivered to the gas turbine system at temperatures – quite higher than in the case of a gas engine – in the order of 500°C [Bridgwater et al. 2002]. Thereafter, the producer gas is burnt in the internal combustion chamber (combustor) before the flue gases expand down through the gas turbine.

If the aforementioned system is equipped with a heat recovery steam generator (HRSG), the waste heat resulting from the recovered exhaust of the gas turbine can be converted into high-pressure steam for production of additional power via a conventional steam turbine. The final outcome is a combined cycle: a well-known technology usually applied in natural gas fired power plants. This prime mover may also be coupled to a fluidised bed gasifier in the form of a so-called biomass integrated gasification combined cycle (BIGCC) for exclusive power production. Moreover, this bio-based power plant has the potential to achieve much higher efficiencies than conventional biomass combustion-based power generation [IRENA 2012]. As gas and steam turbines scale up without problems up to large power outputs, the highly efficient BIGCC power plant turns out to be an appropriate conversion system for medium and large scale applications in strong consistence with the middle and large size of fluidised bed gasifiers.

On the other hand, the prime mover of a BIGCC system might also be fitted with a gas engine as a simple cycle instead of a gas turbine, while the steam turbine could be substituted by an organic Rankine cycle (ORC). Nevertheless, the reduced exhaust temperature of the gas internal combustion engine as well as the low throughput of the ORC would translate to a combined cycle with less performance and lower efficiency than the targeted gas/steam turbine combine cycle. This approach, however, could be a good solution for small-sized BIGCC-based facilities with a capacity in the order of a few electric MW.

4.3. Rationale for the selection of technologies

The objective of this study is the optimisation-based analysis of the wood resources-based bioenergy system of Baden-Württemberg when it comes to the exclusive generation of power. Therefore, only the existing combustion and gasification technologies comprised of a converter system and a coupled prime mover aiming at power production have been presented and explained in the previous sections 4.1 and 4.2, respectively. Nevertheless, questions arise regarding which of these thermochemical conversion processes are the most cost-efficient so as to prevail in this federal state within the liberalised energy market of Germany. In order to shed light on this issue, a methodology based on a comprehensive comparative assessment of all previously introduced technologies is applied to all capacity ranges varying from small via medium through to large scales. This analysis gives rise to the preselection of an array of combustion and gasification-based conversion techniques for power purposes under the condition that any other disregarded technology should exhibit noticeably higher costs per unit of power output when measured for the same electric capacity and number of full load hours. This analysis should be a task to be accomplished by means of a computational process by contemplating all options together within a model describing the entire targeted bioenergy subsystem. However, the proposed methodology is considered more appropriate because it prevents creating an extremely large database with a clearly identified fraction of more expensive technology options. Furthermore, this oversized databank might also include the techno-economic parameters of highly costly novel technologies that are in general difficult to be found because they are simply immature or early commercial techniques. In this way, a model encompassing all possible conversion paths would be incredibly huge and therefore highly laborious to be constructed and solved. This would be the case of such an analysis that might result in being unnecessary to be done as most expensive conversion technologies could already be excluded in advance without the assistance of any computing resources.

Actually, the aforementioned strategy was somehow already employed for establishing the aim of the bioenergy system in the framework of this dissertation, namely the production of power – and not heat, biofuels or wood-derived chemicals. In this sense, the omitted energy carriers are either cheaper (heat) or more expensive (biofuels and bio-based chemicals) than power and also show a different nature that leads to preferably carrying out a separate analysis for each of them. By applying this methodology to power generating conversion processes in order to predetermine the most cost-efficient ones, excluding certain technologies due to their relatively higher production costs is perfectly feasible and does not incur any inaccuracy or error. As a result, some power generating technologies such as ORC as well as steam engines are automatically ruled out from being considered in this study because either they necessarily use waste heat – and not the whole thermal energy from biomass combustion – for producing power as a bottoming cycle as in the case of the former or their efficiency and hence their performance are rather poor as stated by [Evald et al. 2010] and [Salomón et al. 2011] for the latter. A similar situation arises when coupling a boiler and a Stirling engine as a solution for power generation in the terms previously described in subsection 4.1.1. The capacity of a Stirling engine does not go beyond 300 kW_e [Oros et al. 2014] as its maximum output power is limited by the fact that the efficiency extraordinarily decreases with increasing size [Kim et al. 2008]. For this range of small scales, Stirling engines are linked to quite high investments and also present long start-up times as well as a limited adaptability to partial load [Jradi et al. 2014]. This, together with a relatively low level of electric efficiencies in the order of 17-22% [Evald et al. 2010], results in extremely high specific electricity production costs with a magnitude over 20 $cent/$kWh_e$ [Pawananont et al. 2017], which definitely accounts for the exclusion of this technology option from the intended analysis. In the same vein, other non-power generating upstream processes within the supply chain such as the pre-treatment of raw biomass including pyrolysis, hydrothermal upgrading, torrefaction or even pelletising are equally discarded for this study as they necessarily involve additional costs for the mere production of power as compared to the supply chain in which only chipping is contemplated (see section 3.3).

Accordingly, a comparative analysis between combustion and gasification technologies for different scale ranges is conducted throughout this section and both following subsections by comparing the specific electricity production costs (EPC) of each pair of representative technologies for the same electric capacity and number of full load hours. This assessment can be accomplished exclusively via consulting research studies in which the corresponding author includes the specific EPC of all relevant bio-based technologies under identical or similar values of both aforementioned parameters.

In view of the low incremental investments incurred by the installation of co-firing (see subsection 4.1.4), there is clear evidence that such a technology must be included in the suggested optimisation-based analysis. The utilisation of already existing coal-fired power plants for implementing this technology will render the investment more economical than the remaining combustion and gasification techniques thus ensuring a higher level of cost-effectiveness. Reduced electricity production costs will mainly result from the incremental nature of co-firing capital costs, which only account for a portion of the investment costs of a new coal-fired power plant or even of a dedicated bio-based facility with the same size. This cost reduction effect is confirmed by several studies that publish the specific electricity production costs (EPC) registered in certain co-firing projects in comparison with those of other combustion or even gasification technologies. This is the case of [UNIDO 2014], which publishes a range of specific EPC between 2.9 and 5.3 $cent/$kWh_e$ for power outputs of respectively 100 and 5 MW_e for an undefined but anyhow equivalent number of full load hours. This spectrum of production costs for the respective capacities of biomass co-firing lies clearly under the levelised cost of electricity published for direct combustion as well as any other type of gasification technologies coupled to a power generating prime mover. On the other hand, both [IPCC 2012] and [Chum et al. 2011] as publications carried out in the framework of the Intergovernmental Panel on Climate Change (IPCC) point out that biomass co-firing in already existing coal-fired power plants for a range of electric capacities comprised between 25 and 100 MW_e renders a specific EPC varying from 2.5 to 6.5 \$cent/kWh_e. This interval of power production costs remains well below that of combustion-based power generating technologies such as stokers or fluidised bed boilers connected to a condensing steam turbine when operating during an unknown but similar number of full load hours per year. But it turns out to be quite similar or even higher than the production costs of gasification if both plants' sizes are equated to 25 MW_e by means of a suitable scale correction. This last possibility does not diminish the relevance of co-firing as one of the cheapest biomass conversion technologies, although certain gasification schemes might reach equal or even higher levels of cost-efficiency. In coherence with these publications, [Bauen et al. 2009] also reflects a high cost-efficiency for co-firing plants with a power output of 5-100 MW_e and EPC in the order of 3 to 5.2 \$cent/kWh_e that prove to be lower than the levelised cost of electricity from combustion and gasification for comparable capacities and yearly operating hours. Likewise, [IRENA 2012] reports a feasible range of specific EPC between 3.44 and a maximum of 9.54 €cent/kWh_e when producing power from biomass co-firing. The aforementioned study also refers to the comparison of co-firing with other conversion technologies including combustion and gasification-based power plants of equivalent size but without any indication of the number of full load hours. In spite of this omission, it can be hold that all compared conversion technologies were operated for the same yearly amount of full load hours. Under these conditions, the specific EPC involving co-firing of wood chips reaches a value of approximately 5.50 €cent/kWh_e that turns out to be undoubtedly cheaper than the rest of the shown technologies. In line with this trend, [Ehrig et al. 2013] makes reference to the EPC of co-firing in large coal-fired power plants in Belgium and United Kingdom. Both production costs are in the order of 6 €cent/kWh_e for a 10% share of pellets in an 800 MW_e coal power plant yearly operating for 5,000 hours in the framework of the respective national policies. Similarly, [DENA 2011] analyses the necessity of promoting power generation from co-firing investments for different price scenarios and concludes for Germany that the required funding – which is indicative of the level of production costs – should be not more than 4.5 €cent/kWh_e for a number of full load hours between 4,500 and 6,800. Regrettably, no mention is made, in both last studies, concerning an eventual comparison between the levelised costs of electricity generated by co-firing and those resulting from equally sized power plants based on direct combustion and gasification technologies. Anyhow, the relatively low values published for the specific EPC of co-firing suggest that the electricity gained from combustion or gasification should definitely be more expensive for any equivalent power capacity and similar operating conditions.

The fact remains that all prior consulted studies involving the comparison between co-firing and the remaining combustion and gasification technologies exclusively address the first conversion method as a general process regardless of which technology setup is considered – whether direct, indirect or parallel co-firing (see subsection 4.1.4). In addition, the co-fire rate of both indirect and parallel arrangements can be raised as much as desired in contrast to the limitation of the direct technique (around 10%). This is because solid biomass is neither mixed with coal in the pre-treatment stage prior to shared burners nor combusted in the coal boiler after having been injected through shared or separate burners, thus preventing most significant constraints involved by direct co-combustion of coal and biomass. In this sense, the respective substituting bioenergy inputs of indirect and parallel co-firing, syngas and steam, exhibit no restriction for an unproblematic conversion into power; albeit the corresponding processes (adjacent gasifier or separate boiler) require more expensive investments than in the case of direct co-firing (mill/grinder). As both indirect and parallel options would equate to the installation of more expensive conversion structures respectively based on gasification and combustion, the most cost-efficient co-combustion scheme consisting in direct co-firing is preselected over the remaining two methods for its subsequent techno-economic modelling. This assertion represents per se a conclusion that must be taken into account in future investments in the wood resources-based bioenergy sector.

Beyond direct co-firing, it is not easy to foresee the relative economic behaviour of the remaining analysed technologies, particularly if the specified combustion-based matchings of converter system and prime mover such as a boiler coupled to a Stirling engine or a stoker boiler and a fluidised bed boiler connected to steam turbine are faced to the other group of processes in which a fixed or fluidised bed gasifier is attached to a gas engine or a combined cycle. As formerly explained, although all technology solutions could be integrated in the intended model for assessing their corresponding production costs, the preselection of the more cost-efficient conversion techniques – if possible – will permit the comprehensive data search and their subsequent harmonisation as well as the corresponding computing effort to be appropriately reduced. For this reason, the specific electricity production costs concerning the previously introduced combustion-based power technologies – except for co-firing – in section 4.1 are to be compared with those resulting from the gasification technologies from section 4.2 for each pertinent scale range (small, medium and large) and equivalent full load hours so that the most cost-efficient processes can be identified. With this purpose, comparable data on specific electricity production costs incurred by direct combustion and gasification techniques have been collected from research studies conducted principally – in the same vein as the prior cost comparison involving co-firing – in OECD[19] countries so as to employ them as a tool to clarify this topic.

4.3.1. Range of small and medium scales

For small and medium applications, the value of the specific electricity production costs resulting from the operation of combustion and gasification technologies seems to show a trend, according to which gasification appears to be cheaper than – or at least it shows similar production costs to – combustion for this scale domain. In order to confirm this tendency, several real cases including both types of feasible combustion and gasification technologies in

[19] Organisation for Economic Co-operation and Development.

the form of stoker boiler or fluidised bed boiler coupled to steam turbine, on the one hand, but also fixed or fluidised bed gasifier plus gas engine – or even combined cycle –, on the other, are accordingly compared under equal or similar operating conditions so that the most cost-efficient options can be identified. In keeping with this premise, both research sources [IPCC 2012] and [Chum et al. 2011] publish a range of specific electricity production costs that amounts to roughly 7-14 \$cent/kWh$_e$ for a stoker or fluidised bed boiler coupled to steam turbine with power output between 25 and 100 MW$_e$, while a gasification system equipped with an internal combustion engine of 2.2-13 MW$_e$ yields EPC ranging from 4 to 13 \$cent/kWh$_e$ under an identical number of yearly operating full load hours. After an adequate scale correction aiming at rendering both technological options equally sized, the gasification ensemble stands out as a more economical solution as compared to the combustion-based power unit. In terms of costs, both small and medium scale ranges can be completely determined by appropriately projecting each domain into the other so that missing costs can be gained. A further contribution comes from the study conducted by [Frederiks et al. 2017] for small-scaled combustion and gasification projects between 20 and 200 kW$_e$ when operated for 3,000 full load hours per year. This economic analysis reproduces higher specific EPC for wood chip combustion (39-62 €cent/kWh$_e$) as against those registered by gasification, which amount to 21-35 €cent/kWh$_e$. Similarly, [Bauen et al. 2009] also confirms the aforementioned trend on the basis that a Rankine cycle with a power capacity of 10-100 MW$_e$ provides specific EPC of 7.5-9 \$cent/kWh$_e$ that renders the process less cost-efficient than a small-scaled gasifier connected to a 0.1-1 MW$_e$ gas engine with EPC around 7-8 \$cent/kWh$_e$ –likewise calculated for equivalent operation conditions. In this sense, both processes can be assigned a numerically equivalent output capacity by scaling them up or down as necessary without losing the indicated hierarchy between both referenced levelised costs of electricity – i.e. that gasification should remain in any case cheaper and therefore more interesting for investors than combustion. This study also makes reference to another gasification-based power generating unit consisting of a fluidised bed gasifier attached to a combined cycle (BIGCC) with a capacity of 5-10 MW$_e$. The resultant EPC (10.5-13 €cent/kWh$_e$) are higher than those production costs derived from the earlier combustion case, because this gasification concept definitely involves a more suitable conversion technology for large scales (see next subsection 4.3.2). On another front, the research work [Brown et al. 2006] presents a prognosis for the production costs of electricity in the year 2020 for both possible combustion and gasification-based power generating processes in the domain of small and medium scales. With respect to this time period, the study reports a more economic range of specific EPC as for a gasifier coupled to either diesel engine or gas turbine within a scale between 50 kW$_e$ and 30 MW$_e$ (5-12 €cent/kWh$_e$) than in case of a grate or fluidised bed boiler with steam turbine (5.7-14 €cent/kWh$_e$) when operation is carried out for identical power output and number of full load hours. Similarly, the specific production costs of a gasifier with a coupled gas engine of 2.5 MW$_e$ are around 14.77 €cent/kWh$_e$, whereas those of a 2.9 MW$_e$ Rankine cycle amounts to about 19.87 €cent/kWh$_e$ if costs are estimated under the framework of the German energy system as stated by a relatively old but still applicable study conducted by [Hiller 2004]. In addition, [Gard 2008] refers to the power plants of 2 MW$_e$ in Güssing (Austria) and 5.9 MW$_e$ in Ciudad Real (Spain), which are based on a fluidised bed gasifier coupled to gas engine. Their specific EPC for small scales are unequivocally lower – 9.3 and approximately 5.6 €cent/kWh$_e$ for 7,000 full load hours per year respectively – than those obtained for an equivalently sized steam cycle when biomass is burned. A dedicated steam cycle showing a size of 5-25 MW$_e$ gives specific EPC of roughly 11 €cent/kWh$_e$ according to the Turkish study [Balat et al. 2009], just the same amount as a gasifier coupled with a gas engine in a lower scale range of 0.2-1 MW$_e$ but for the same full load hours. As an effect of economies of scale, this gasification-based power generation unit could anyway decrease its production costs for a scale of around 20 MW$_e$ thereby proving more cost-efficient than the corresponding combustion ensemble. In line with the aforementioned case studies, [Kalt et al. 2011] also highlights the higher EPC of a steam cycle of 1-5 MW$_e$ (21-33 €cent/kWh$_e$) as compared to those of an integrated gasification system plus prime mover with a power output of 0.6-5 MW$_e$ (15-22 €cent/kWh$_e$) when assessed under similar operation conditions. Likewise, it is expected that the cost behaviour exhibited by small scales should also continue to display the same trend of the range of medium sizes if these specific EPC are appropriately scaled down. Lastly, the research study [Bridgwater et al. 2002] – albeit extremely old and belonging to a period in which bioenergy was an incipient concern – manage to largely forecast the potential electricity production costs for future energy system conditions. For the prospect of small and medium scales between 1 and 20 MW$_e$, this reference gives slightly more economical EPC (6.4-17 €cent/kWh$_e$) for medium-scaled BIGCC power plants as well as largely less expensive production costs in a range between 7.4 and 15.1 €cent/kWh$_e$ for at least small-scaled gasifiers coupled to gas engine than those costs incurred by a Rankine cycle (6.5-17.4 €cent/kWh$_e$) when equivalent capacities and yearly operating full load hours are considered.

Meanwhile, other studies such as [UNIDO 2014], [Yassin et al. 2009], [RENET 2007] or even the interesting research work conducted in the beginning of the last decade by [Rabou et al. 2001][20] reproduce equivalent electricity production costs for both gasification and combustion technologies under similar power output capacities as well as identical amount of full load hours for both low and medium-scaled applications. At the other end of the spectrum, the study [TBG 2011] makes reference to more expensive costs for a 1 MW$_e$ power plant based on gasification than in the case of combustion (1.2 MW$_e$). This becomes clear if both capacities are made equal by means of an approximate scale correction and the resulting costs calculated under identical operation conditions for 8,000 full load hours per year. Likewise, the research work conducted by [Obernberger et al. 2008a] illustrates under Austrian framework conditions the more costly behaviour of fixed and fluidised bed gasifiers with an array of power capacities up to 6 MW$_e$ if compared to the EPC of steam cycles showing the same scale range for operating full load hours varying from 2,000 to 8,000 hours per year [Obernberger et al. 2008]. The former technological options involving gasification refer to power production expenses averaging 17-26 €cent/kWh$_e$, while the latter exhibits lower generation costs in the order of 12-18 €cent/kWh$_e$. Furthermore, it should be expected

[20] Even though the consulted source is completely outdated, it yields a surprisingly good cost projection into the present for both combustion and gasification-based conversion processes when they are respectively fitted with steam turbines or gas engines.

that projecting the scale into the medium size would also reproduce an identical trend to th at displayed by the small capacity domain with combustion being cheaper than gasification in terms of specific electricity production costs. By the same token, [EPA 2007] reports on the specific EPC of two different combustion-based power generation units, namely a 15.5 MW_e stoker boiler-based steam cycle (7.6 \$cent/kWh_e) and a 16.2 MW_e circulating fluidised bed combustor coupled to steam turbine (7.2 \$cent/kWh_e), and three further technological ensembles producing electricity through gasification, i.e. a 4 MW_e atmospheric fixed bed gasifier connected to a gas engine (9.6 \$cent/kWh_e) as well as two atmospheric fluidised bed gasification processes feeding syngas into a coupled combined cycle (BIGCC) of 6.6 and 11.6 MW_e (13.5 and 11.6 \$cent/kWh_e, respectively) for nearly 7,900 yearly operating full load hours. Albeit the small-sized fixed bed gasifier plus engine proves to be the most economic option when the process dimension is roughly increased up to the level of medium scales, power from small and medium BIGCC units ends up clearly or even slightly more expensive than that of both Rankine cycles. This would confirm the higher cost-efficiency of combustion techniques versus gasification – though the BIGCC technology usually proves more costly than other gasification-based setups fitted with e.g. a gas engine.

Although all formerly introduced references are categorised into three different trends by performing a direct comparison of the specific EPC incurred by gasification and combustion techniques, most of the consulted studies point to gasification-based power being cheaper than – or equivalent to – that produced through combustion when the compared processes at small or medium scales are run under the same operation conditions. Furthermore, albeit not always unmistakably declared, some studies also analyse combined heat and power (CHP) combustion systems that – via extraction or back pressure steam turbines – forcedly lessen the corresponding EPC by subtracting the revenues obtained through the sale of heat. This is the case of certain research studies such as [Obernberger et al. 2008a] and [Bolhàrd-Nordenkampf et al. 2003], whose results are correct but do not properly describe the real specific EPC of a net power generating combustion-based unit as initially planned in the framework of this dissertation.

Besides, the prior analysis concludes that the most convenient prime mover for generating power at small and medium scales from harvested wood resources is the gas-fuelled internal combustion engines. In this connection, research works such as [UNIDO 2014] or [Bauen et al. 2009] as well as [Balat et al. 2009] or several older studies such as [Brown et al. 2006] corroborate the technical suitability of gas engines over that of gas turbine combined cycles. This is principally on account of the lower specific EPC showed by the former technique as opposed to the latter when run under strictly equivalent operation conditions. As a result, most of the presented references allocate the combined cycle as a prime mover and, in consequence, also the entire ensemble formed by a biomass integrated gasification combined cycle (BIGCC) to the exclusive use in larger scale ranges (see next subsection 4.3.2). Regarding the sort of gasifier to be implemented, four different types were identified as suitable for an efficient gasification of wood resources according to [IRENA 2012]: the downdraft, updraft and cross-draft fixed bed gasifier as well as a fourth kind named (bubbling or circulating) fluidised bed gasifier. Based on their respective techno-economic characteristics, all fixed bed gasification techniques including the downdraft, updraft and cross-draft options are excluded from the intended optimisation-based analysis owing to a series of issues. These basically encompass the production of high tar content in the resulting producer gas, the size limitation forcing the use of more expensive small scales as well as the highly complicated operation of certain gasification-based converter systems (see 4.2.1). Accordingly, a bubbling or circulating fluidised bed gasifier coupled to a gas-fuelled internal combustion engine is then preselected as the more appropriate gasification technology for the range of small and medium scales.

Turning again to the comparative analysis between gasification and combustion, mention should be made of a couple of factors that determine the higher cost-efficiency and appropriateness of the former conversion technology as against the latter. A fluidised bed gasifier coupled to a gas engine, unlike a stoker boiler connected to a condensing steam turbine, additionally produces waste heat while maximising power generation for small and medium scales as a result of its higher efficiency – 25-30% for this scale range according to [IEA 2007] versus a typical value of around 18-20% [EPA 2007] in the case of medium-scaled Rankine cycles. In this vein, a more recent study such as [Evald et al. 2010] also points out similar electric efficiencies in the order of 23-28% for gasification-based power production and 17-22% for steam cycles in both cases exclusively for small scales. In the worst case scenario, though electricity originating from a fluidised bed gasifier attached to a gas engine might be more expensive than that derived from a steam cycle, power production costs of such a gasification setup could be covered by the sum of power and heat revenues in contrast to the only power generating case of stoker or fluidised bed boilers coupled to a condensing steam turbine. In addition, both emissions and social aspects involving gasification-based power plants for small and medium scales are in general better valued than those concerning combustion, as published in a number of research studies such as the qualitative analysis conducted by [Cramer et al. 2016]. As a sample of that trend, this study reports lower air pollution and greenhouse gas emissions for gasification-based power generation units (with capacities ranging from 2.5 to 12.5 MW_e) than in the case of combustion under the same operating conditions. Likewise, the same positive performance in relation to gasification is displayed for health and safety considerations based on a combination of impacts associated with pollution (air and noise), traffic hazards due to biomass transport and also security aspects concerning power plant operation.

All formerly mentioned reasons lead to considering the fluidised bed gasifier connected to a gas-fired internal combustion engine as a more cost-efficient solution than other equivalent combustion and gasification-based technologies mainly for the range of small and medium scale applications. In this sense, this claim emerges as an important conclusion that enables taking further steps into the intended optimisation-based analysis. Therefore, the combination of a converter system and a prime mover in the form of a fluidised bed gasifier and a gas engine for the referenced scale range is accordingly preselected for being implemented in the cost minimisation model of the wood resources-based bioenergy system of Baden-Württemberg.

4.3.2. Range of large scales

With respect to the domain of large scales, cost comparison between gasification and combustion seems to give a similar economic pattern to that of small and medium scales. In this sense, the specific electricity production costs incurred by gasification-based power generation units tend to be cheaper than – or at worst equal to – those of combustion technologies when run under the same operation conditions for the range of large scales. Several research studies are scrutinised in order to find all possible combustion and gasification technologies, namely the stoker and the fluidised bed boiler plus steam turbine in addition to the fluidised bed gasifier attached to combined cycle (BIGCC). These technical solutions are compared in terms of costs for equivalent scales and full load hours with the aim of preselecting the most cost-efficient option. In accordance with this strategy, a production cost comparison between a biomass integrated gasification combined cycle and a combustion-based power generation unit for the same capacity (112 MW_e) is performed by [Michailos et al. 2017] under the equal amount of full load hours per year. As a conclusion, this report predicts further emission and cost reductions in upcoming generations of the BIGCC technology for the next ten years. This will definitely favours this technique instead of direct combustion. Likewise, [UNIDO 2014] as a source published by United Nations estimates for the decade 2020-2030 the cost projection of direct combustion in the form of a Rankine cycle with the converter system being either a stoker boiler or a fluidised bed combustor in contrast to the corresponding evolution of BIGCC processes. In this context, the operation of two different 100 MW_e combustion-based conversion units, namely a stoker boiler and a fluidised bed boiler likewise coupled to steam turbine, results in specific EPC in the order of 7.5 and 6.3 \$cent/kWh_e, respectively; while the projected costs achieved for the 300 MW_e BIGCC unit account for 4.6 \$cent/kWh_e when calculated for an identical number of yearly operating full load hours. As the cost decreasing effect caused by economies of scale drastically reduces for large gasification-based power generation units above roughly 40 MW_e (see 4.4.3), the specific EPC of a potential 100 MW_e BIGCC facility would end up being slightly higher than – albeit similar to – those costs exhibited by the real 300 MW_e scale (i.e. 4.6 \$cent/kWh_e). Therefore, it can be asserted that BIGCC processes are much more cost-efficient than both suggested combustion-based options when assessed for the same power outputs under equal conditions. Along the same lines and with equivalent techno-economic data, high levels of cost-effectiveness for future concepts of gasification-based power generation, specifically for large-scaled BIGCC systems over 30 MW_e, are claimed by [Bauen et al. 2009] with respect to the outcomes rendered by large bio-based power plants consisting of combustor and steam turbine.

The aforementioned trend is likewise clearly exposed by an array of old but nevertheless not absolutely outdated research studies – at least as far as their estimations for the comparison of gasification versus combustion are concerned – such as [Brown et al. 2006], [Bain 2004], [Obernberger et al. 2003], [Gustavsson et al. 2003] and [Overend 2000]. The first one renders for the year 2020 the specific EPC of a gasifier coupled to a combined cycle (5.3-10 €cent/kWh_e) for a scale range between 30 and 100 MW_e. In contrast, an equivalently sized fluidised bed boiler plus steam cycle yields higher production costs of around 5.7-14

€cent/kWh$_e$ when evaluated for the same amount of yearly operating full load hours. In the same vein, [Bain 2004] illustrates the lower specific EPC (7.4-8.1 $cent/kWh$_e$) of gasification-based power generation for the scale range of 75-150 MW$_e$ as compared with the costs incurred by combustion for a size of 25-100 MW$_e$ if calculated under equal conditions (9.3-11.6 $cent/kWh$_e$), thus highlighting the higher cost-efficiency of gasification over combustion. Similarly, the electricity production costs of two 40 MW$_e$ power generation units, namely a steam cycle and a gasification process, are compared by [Obernberger et al. 2003] by operating them for equivalent techno-economic parameters. For 3,000 full load hours per year, the former technology renders a specific EPC of around 8 €cent/kWh$_e$ while the latter lies in a more cost-efficient domain on the order of 6.4 €cent/kWh$_e$ that renders gasification more interesting for stakeholders. Following the same trend, [Gustavsson et al. 2003] refers to the lower EPC (5.7 $cent/kWh$_e$) of a 100 MW$_e$ BIGCC power plant as against the production costs of 5.9 $cent/kWh$_e$ achieved for a much larger 200 MW$_e$ sized Rankine cycle equipped with condensing turbine when both units are operated for 5,500 annual full load hours. The same study also compares both power plants in the case of combined heat and power cogeneration with the same effect already mentioned in the prior subsection (4.3.1), according to which the resulting EPC of both processes lessen in size when heat revenues are regarded by deducting them from the sum of production costs. In this particular case, the specific electricity production costs of the steam cycle-based CHP unit are – as expected – lower than those incurred by the BIGCC plant when equally being operated in CHP mode on account of the larger thermal efficiency of the former with respect to the latter. Finally, [Overend 2000] determines the costs of electricity (8.3 $cent/kWh$_e$) for a steam cycle being fed with biomass crops as well as the specific EPC of an equally sized BIGCC power plant (5.1-5.6 $cent/kWh$_e$) for a capacity of 50 MW$_e$ under the same annual full load hours. Notwithstanding the fact that this research source is extremely old, it perfectly describes the prospective cost ratio between combustion and gasification at large scales for the forthcoming decades.

On the other hand, some other research studies put the specific production costs of both conversion technologies at a similar level. This is the case of [IRENA 2012], which refers to a steam cycle and a gasification-based power generation unit showing the same capacity (50 MW$_e$) and specific EPC of roughly 15 $cent/kWh$_e$, when they are run under the same framework conditions. But this parity also arises in the case of [Jin et al. 2009], a research source that publishes specific EPC of about 5.2 $cent/kWh$_e$ for two large BIGCC power plants with 431 and 442 MW$_e$, while a somewhat smaller 295 MW$_e$ steam Rankine cycle presents costs in the range of 6 $cent/kWh$_e$ if equivalent full load hours are considered. Unambiguously, the production costs estimated for the steam cycle would result in a similar amount to those incurred by both prior BIGCC plants if its original capacity were scaled up into a higher dimension over 400 MW$_e$. Finally, slightly higher, though in practice similar production costs for gasification are claimed by [Pfeiffer et al. 2009]. They point to EPC between 10 and 13 €cent/kWh$_e$ for fluidised bed gasification in comparison to a cost range of 9-11 €cent/kWh$_e$ in the case of fluidised bed combustion – in both cases without any mention of the scale. Conversely, [EPA 2007] makes reference – as cited for both small and medium scales – to the higher EPC, valued at 7.9 $cent/kWh$_e$, of a pressurised fluidised bed gasifier coupled to a combined cycle with a power output of 39 MW_e if compared with the generation costs (6.6 \$cent/kWh_e) of a fluidised bed combustor plus a condensing steam turbine of 24.3 MW_e if both are calculated under equivalent operation conditions. This outcome derives from the single study that could be encountered through an exhaustive literature search conducted in keeping with the premise that combustion should be more cost-efficient than gasification within the range of large scales. Nevertheless, the importance of this sole publication is not significant enough for corroborating this trend.

As a result of all exposed above, a higher cost-efficiency for gasification over combustion when aiming at power generation at large scales can undoubtedly be substantiated when both processes are operated for equal operation conditions. As an intermediate conclusion, it can be claimed that there is a marked future trend for the next decade on this subject. This entails higher electricity production costs for stoker boiler and fluidised bed combustor-based steam cycles as against those of biomass gasification combined cycles (BIGCC), which eventually prove to be the most cost-efficient power generation method for large scales. This is absolutely in harmony with the higher efficiencies exhibited by large BIGCC power plants compared against those of equally scaled Rankine cycles if that comparison is performed under the same conditions. This assertion is made evident by the modest electric efficiencies showed in general by steam cycles, either as a stoker boiler or as a fluidised bed combustor, which actually rarely go beyond 35% for large scales [Mott MacDonald 2011]. On the contrary, a BIGCC power plant based on the coupling of a fluidised bed gasification system and a combined cycle is in any case associated with rather higher electric efficiencies in the range of roughly 48-50% [Jin et al. 2009] that eventually translate to more economical production costs.

4.4. Techno-economic characterisation of the selected technologies

Direct co-firing as well as fluidised bed gasifier coupled to a gas engine or even a combined cycle are the three preselected bio-based power generation technologies according to the conclusions drawn in section 4.3 above. These processes are to be modelled with the assistance of specific regression techniques by creating trend lines for four of the most significant techno-economic parameters [Dornburg et al. 2001]. The specific amount of capital costs, the fixed and variable portion of operation and maintenance (O&M) costs along with the electric efficiency – and the total efficiency including the thermal share for CHP systems – are the required parameters to be reproduced so as to techno-economically characterise each preselected conversion technology. All the aforementioned parameters exhibit noticeable scale effects with increasing electric capacity. For that reason, their magnitudes must be determined for the whole range of capacities in order to understand the impact of scale economies on the cost-effectiveness of each technology. To this effect, a regression analysis together with the respective statistical variance is presented in the following subsections with the aim of identifying such dependence on scale for each parameter of the three preselected conversion pathways.

An array of research studies[21] (see Tables 4.1-3) dealing with the techno-economic description of the three bio-based technologies is used as a basis for constructing the regression-based trend lines of each parameter. Regarding the employed methodology, a power/logarithmic regression adjustment technique is performed with the aim of creating the best regression fit – also called best fitting curve or regression curve – to the set of collected data on each techno-economic parameter. The power regression enables mathematically representing the most optimal dependence of capital costs or the fixed and variable share of O&M costs on the electric capacity. In this regard, this method proves to be an accurate practice for characterising such techno-economic parameters showing apparent economies of scale. This is mainly due to the fact that the corresponding scale effect equally presents a similar behaviour to that of power functions with negative exponent. On the other hand, the electric efficiency, but also the total efficiency, as a function of the electric capacity significantly approximates the form of the natural logarithm of the power output raised to a positive exponent plus a non-negative constant term. This similarity inevitably results in using the cited logarithmic regression adjustment as a suitable statistical tool for modelling such relationship between efficiency and scale.

As a result of the power and logarithmic regression, the uncertainty of each techno-economic parameter can be addressed as a statistical measure of the corresponding data dispersion with respect to the best fit and thus assessed by means of the coefficient of determination R^2. This figure is a percent and gives insight into the proportion of data points falling within and around the regression curve, thus providing an indication of the quality of the regression adjustment. But the fact remains that the specific amounts of capital costs as well as fixed and variable O&M costs together with both electric and total efficiencies are subject to dissimilar levels of uncertainty that in turn may be linked to diverse causes. An overall examination of all the targeted parameters enables the identification of some common reasons for the resulting statistical variance from the collected data with respect to the estimated fitting curve. The grounds are principally related to the different framework conditions, in which projects are carried out, but also refer to the diverse levels of technical maturity exhibited in each case. As regards the former factor, it is important to emphasise that most analysed studies are carried out in different states of the European Union, while others in several sites of the USA. This unavoidably leads to further difficulties for drawing correct conclusions on account of the high inhomogeneity of the sample. In respect of the latter aspect, it has to be mentioned that the different bio-based power plants are usually built under diverse states of maturity: namely research, development, demonstration or deployment. Conversely, certain assessed power generating units are fitted with mature technologies that constitute technically proven solutions with high levels of performance. This disparity inevitably introduces a significant factor of uncertainty.

[21] As the dates of the consulted studies refer to different years since 2001, original costs from these research works are adjusted according to an annual inflation rate of 2% while additionally considering the effect of learning curves [Fritsche et al. 2004] as well as a cost projection based on [DECC 2011] in order to estimate the resulting costs at the base year 2017.

4.4.1. Direct co-firing

The process of direct co-firing is techno-economically characterised by calculating the trend lines of its most significant parameters, namely the specific capital costs, the specific fixed O&M costs, the specific variable O&M costs as well as the electric efficiency, on the basis of data collected from the studies referred to in Table 4.1. These magnitudes are graphically illustrated in Figures 4.1-4 below as a function of the total output capacity – i.e. that relating to both fossil and biomass inputs. The resulting trend lines permit modelling the bio-based conversion processes of large pulverised coal power stations as well as small and medium coal power plants based on fluidised bed combustion, in both cases for a 10% co-fire rate of wood resources. As expensive technical changes have to be performed especially when it comes to retrofitting pulverised coal power plants for co-fire rates above 10% (see subsection 4.1.4), a modest rate of 10% based on an energy basis is chosen for the calculation of the corresponding trend lines for both feasible pulverisation and fluidised bed-based coal firing systems.

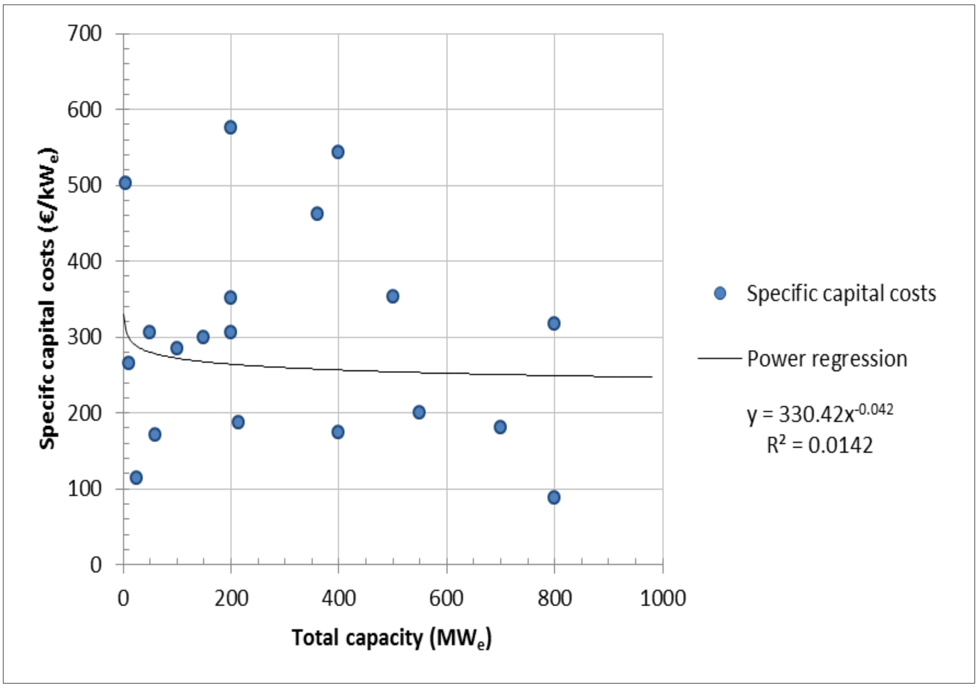


Figure 4.1: Specific incremental capital costs of co-firing for a 10% fraction of wood resources as a function of the total electric capacity

As existing coal power stations have to be upgraded for adapting them to co-firing biomass, only incremental investments are made to this effect in largely depreciated power generation units. Therefore, the specific capital costs of co-firing account for a kind of supplementary expenditures that are wholly differentiated from the original investments performed in the commissioning of new coal-fired power plants. This incremental nature makes capital costs become a relatively small share of the initial capital costs incurred by a new coal power plant for each particular scale. Consequently, a series of case studies dealing with co-firing at different scales ranging up to a total output capacity of 1000 MW_e are properly analysed in order to estimate the specific (incremental) capital costs as a function of the electric scale by using a suitable regression technique. The incremental capital costs published by a number of studies are depicted in Figure 4.1 together with their resulting best fit. This is generated with the assistance of a power regression adjustment method, which enables the dependence between capital costs and the total electric scale to be mathematically reproduced. As displayed by Figure 4.1, the regression adjustment of the specific capital costs for co-firing entails a quite elevated uncertainty that is equally linked to a relatively low coefficient of determination (0.014). The reason for such a high uncertainty can be ascribed to the diverse techno-economic framework conditions employed in each study as well as the different biomass feeding system installed for direct co-firing, namely based either on co-feeding or separate burners ([EPA 2007], [Robinson et al. 2003]).

Most references included in Figure 4.1 report scale-dependent specific capital costs in a range between 100 and 500 €/kW$_e$, whereas a few research sources of relative significance point out costs beyond both bounds. In this connection, [IEA Bioenergy 2007] refers to a specific capital cost of 1000 €/kW$_e$ while [IRENA 2012] provides them in the order of 850 €/kW$_e$. Additionally, a value of around 620 €/kW$_e$ is reported by [DENA 2011] – in all cases for an indeterminate capacity. On the contrary, some energy policy studies such as [USDOE 2004] and [McIlveen-Wright et al. 2011] as well as [Royo et al. 2004] – based on field tests empirically performed on a real coal power plant – show more adjusted results on the order of 250-300 €/kW$_e$ for specific scales in keeping with the course of the derived trend line.

The specific amount of fixed O&M costs for direct co-firing are to a certain extent well documented. However, there is a significant part of authors that do not properly publish this parameter within their research works. In this sense, fixed O&M costs are, in some studies, added up to the variable part of expenditures in form of a sole quantity that acts as overall O&M costs. If such is the case, the deduction of the fixed O&M costs from the entire O&M costs is due and consequently to be performed by apportioning to both a certain percentage of specific capital costs. For this purpose, [IEA-IRENA 2013] estimates O&M costs at approximately 2.5-3.5% of the incremental capital costs for direct co-firing. This study also asserts that O&M costs for co-firing are similar to those incurred in ordinary coal power plants, since increased fuel handling costs are offset through decreased desulphurisation costs. In the same vein, other sources such as [IRENA 2012] – albeit dealing with other bioenergy technologies based on combustion or gasification – also refer to O&M costs as a percent of capital costs. But in general, modelling co-firing necessarily must include the whole bio-based share of the total O&M costs – and not only the incremental portion – by calculating them as a percentage of the total capital costs invested in a completely new co-firing based power station. Thus, the comprehensive process – both handling and processing of wood resources, combustion as well as the power generation itself – can indeed be considered to its full extent. Otherwise, the incremental O&M costs would exclusively have accounted for the retrofitted phases – namely handling, processing and combustion – but not the unmodified stage of electric production that also includes a bio-based share of operation and maintenance costs for both the steam turbine and the electric generator.

For this purpose, the total O&M costs employed in a co-firing based power station are assumed to be those derived from the maximum percentage share reported by [IEA-IRENA 2013], specifically 3.5%. But this percent is applied to the total capital costs originating from the corresponding coal power plant plus the co-firing based retrofit. Besides, fixed O&M costs usually make up 50-70% of total O&M costs according to most of the consulted references, which publish both fixed and variable O&M costs. Among others, [Lüschen et al. 2010], [Zhang 2010], [McIlveen-Wright et al. 2011], [Skone 2012], [IEA-IRENA 2013], [Boardman et al. 2013] and [Nderitu 2014] provide fixed costs accounting for approximately such a percentage with respect to total operation and maintenance costs. As a result, fixed O&M costs for co-firing are assessed at 2.1% – approximately 60% of total O&M costs – of total capital costs; whereas the remaining 1.4% is allocated to variable O&M costs.

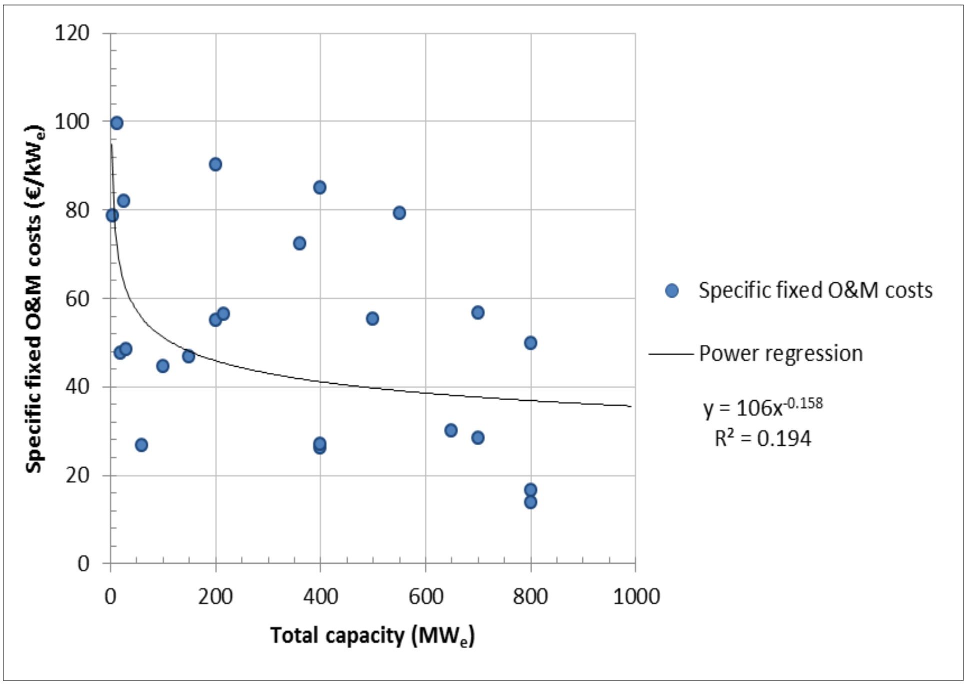


Figure 4.2: Specific fixed O&M costs of co-firing for a 10% fraction of wood resources as a function of the total electric capacity

In accordance with the above discussion, Figure 4.2 highlights the specific fixed O&M costs throughout the entire array of total electric capacities for the co-firing technology. The graph is constructed on the basis of a power regression adjustment technique for data gathered from the same techno-economic literature sources found for assessing the specific capital costs. The regression, which aims at better fitting the specific fixed O&M costs of co-firing, highlights a lower uncertainty – associated with a higher coefficient of determination (0.194) – than that formerly achieved for the incremental capital costs. The causes of such a decreased uncertainty as compared to that of the incremental capital expenses can not be accounted.

A further parameter is required for economically describing a biomass co-fired coal power plant, concretely the specific variable O&M costs. They are normally published by research studies in €cent/kWh$_e$ as costs per energy unit, but sometimes also integrated in combination with the fixed portion of specific O&M costs. The latter case requires subtracting fixed costs from total O&M costs by using the above deduced fraction of fixed costs – 2.1% of total capital costs. A third and final option consists in making use of the complementary share of fixed costs, i.e. a 1.4% portion of total capital costs that yields this share as real variable O&M costs.

Figure 4.3 gives insight into the dependence of the specific variable O&M costs on the total electric scale of a co-firing based power plant. For this purpose, the best fit of all found data sets of variable costs for the entire range of capacities is calculated on the basis of a power regression adjustment technique. The plot displays a rather large uncertainty that is tied in with a quite low coefficient of determination (0.038). The reasons for this high uncertainty might be related to the already mentioned causes encountered throughout the analysis of capital costs, namely the use of diverse techno-economic framework conditions as well as different feeding systems for wood resources.

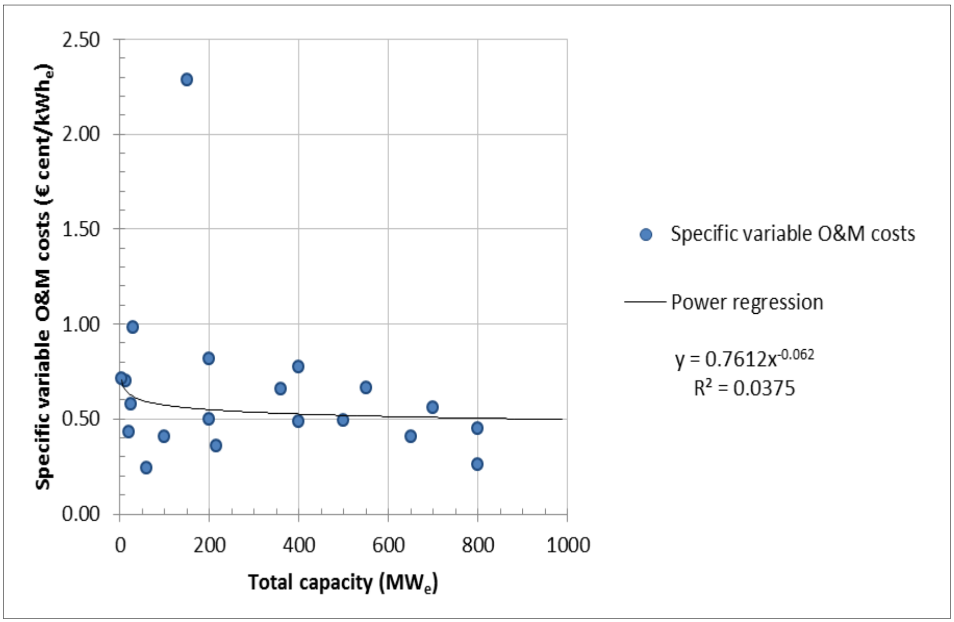


Figure 4.3: Specific variable O&M costs of co-firing for a 10% fraction of wood resources as a function of the total electric capacity

Together with the undesired uncertainty, the resultant best fit is also characterised by a slight scale effect throughout the total electric capacity range. Certain research sources such as [Royo et al. 2004] contribute significantly to the increased data dispersion and thereby to the high uncertainty, which is linked to extremely great specific variable O&M costs on the order of 2.23 €cent/kWh$_e$. The rationale behind the high dimension of these variable costs might lie in the empirical nature of this project, where an actually inexpensive torsional chamber was installed within a coal boiler maybe thus generating rather high variable costs.

A further parameter that is needed to quantitatively model a co-firing based coal power plant is the electric efficiency. For this aim, dependence of electric efficiency on total electric output is to be determined for coal power plants operated with a co-fire rate of 10%. However, certain discrepancies arise in relation to the change in efficiency that occurs after retrofitting an existing coal-fired power generation facility. In this regard, [Nitsch et al. 2004] indicates that electric efficiency in the case of co-firing is greater than that measured in conventional coal power plants under the same operating conditions – although it does not specify the fundamentals for this assertion. On the other hand, [Royo et al. 2004] reports that no efficiency penalty is attributable to biomass feeding into a coal boiler and, consequently, that no changes are reflected for electric efficiency when co-firing modification is accomplished. In contrast, [EPA 2007] informs of boiler efficiency losses of 2% at a 10% biomass co-fire rate. Hence, it recommends implementing adjustments, such as increasing overfire air (i.e. additional oxygen input) or even fuel feeder rates, so as to maintain capacity and operating process at similar levels of former coal power plants. [USDOE 2004] points in the same direction with respect to elevating both the overfire air and the fuel feeder rate. But it also adds that these technical modifications could be ruled out, because boilers typically run below their rated output and if more power is required, they can be operated at a higher performance or even in a coal-only mode so as to avoid derating. Other research sources refer to efficiency reductions derived from the use of biomass as a result of its high moisture content, which significantly affects flame stability [McIlveen-Wright et al. 2011]. Likewise, [Ortiz et al. 2011] points out a decrease in efficiency when co-firing biomass, mainly due to its lower energy density and the additional parasitic load needed to process it for feeding into the boiler. Depending on the efficiency of a coal power plant, which usually lies between 39% and 46%, the corresponding value associated with co-firing use may range from 36% to 44% [Vatopoulos et al. 2012].

The graph of Figure 4.4 illustrates the electric efficiency versus the total capacity on the basis of the best fit, which is calculated through the logarithmic version of the regression adjustment technique. The logarithmic curves describing the electric efficiency are characterised by an asymptotic behaviour that reaches a maximum of 38% at a maximum total electric scale of 1000 MW_e. This parameter is not seriously affected by uncertainty, as its coefficient of determination amounts to a value over 0.60. Especially for scales below 50 MW_e, [McIlveen-Wright et al. 2011], [Ortiz et al. 2011] and [Faaij 2006] presented various case studies for 12 MW_e, 25 MW_e, 30 MW_e and 50 MW_e that perfectly fit the resultant regression curve. Regarding the rest of the analysed sources, they yield higher levels of uncertainty, to a great extent owing to the diverse technical maturity of the co-firing based units as well as to the different feeding systems set up – namely either co-milling [Korshidi et al. 2014] or separate burners ([EPA 2007], [Robinson et al. 2003]).

The consulted references provide electric efficiencies between 27-40% (see Figure 4.4). This outcome corroborates that co-firing biomass in existing coal power plants at a 10% co-fire rate inevitably leads to a loss of efficiency compared with the case of pure coal-based operation. In this respect, [IEA Bioenergy 2007] yields a similar efficiency range of around 30-40% for an array of total electric capacities varying from 5 MW_e to 100 MW_e. Similarly to the previous reference, a somewhat higher efficiency between 35% and 42% is indicated by [IEA-IRENA 2013] for total scales reaching up to 1000 MW_e.

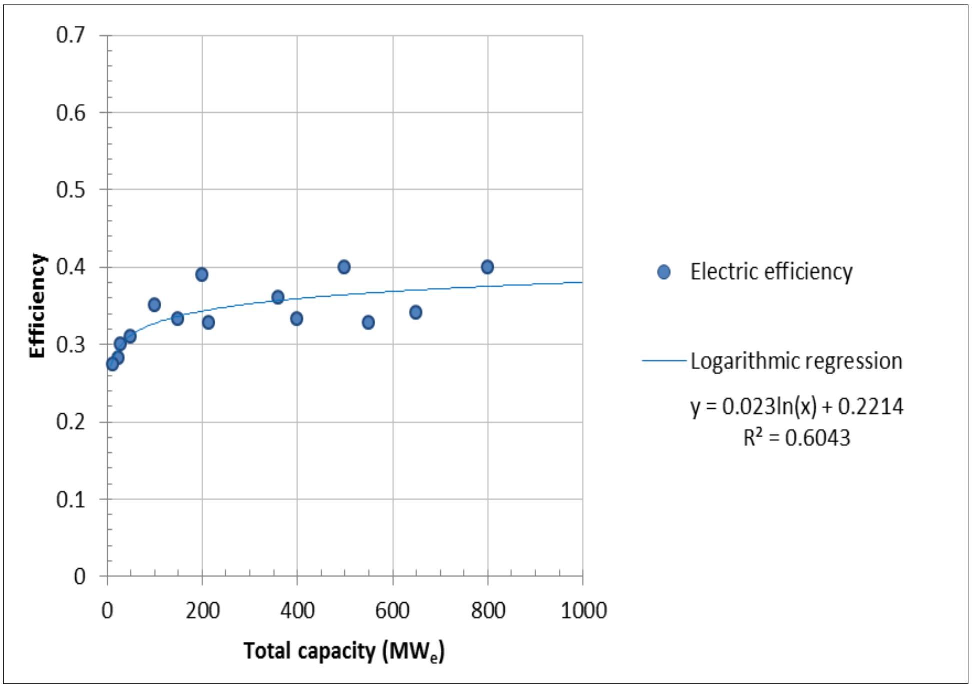


Figure 4.4: Electric efficiency of co-firing for a 10% fraction of wood resources as a function of the total electric capacity

As co-firing based coal power stations are operated with the aim of maximising power production, no heat is generated as a joint product. However, a small source of low grade waste heat acting as a by-product emerges from exhaust gases [Mikielewicz et al. 2016] as well as even from the cooling fluid that circulates through power plants' refrigeration units [Rodríguez et al. 2015]. As a result, the latent heat of gases (around 90°C) but also the sensible heat of cooling water (roughly 20-30°C) can separately be recovered instead of releasing it to the environment, thus resulting in an increased performance and cost-efficiency of the entire conversion system. Anyhow, this bioenergy contribution is not considered for modelling this technology on account of its reduced dimension.

4.4.2. Fluidised bed gasifier coupled to gas engine

Similarly to the last subsection, small and medium-scaled power generation units based on a fluidised bed gasifier connected to a gas engine (FBG+E) are likewise characterised throughout this section. Whilst fluidised-bed gasifiers can be easily scaled up from medium to large sizes, gas engines are only available in the ranges of small and medium scales up to a maximum power output of 20 MW_e (see subsection 4.2.2). The intended characterisation is performed by estimating the trend lines of the most relevant techno-economic parameters for this technology with data originating from a list of research works included in Table 4.2. Besides power, this conversion system also produces a heat yield that allows this technology to be categorised as a combined heat and power (CHP) cogeneration process. In line with these technical particularities, the specific amount of capital costs as well as fixed and variable O&M costs in addition to the electric and total efficiency of this bioenergy conversion pathway are assessed so that significant scale effects with increasing capacity can be identified.

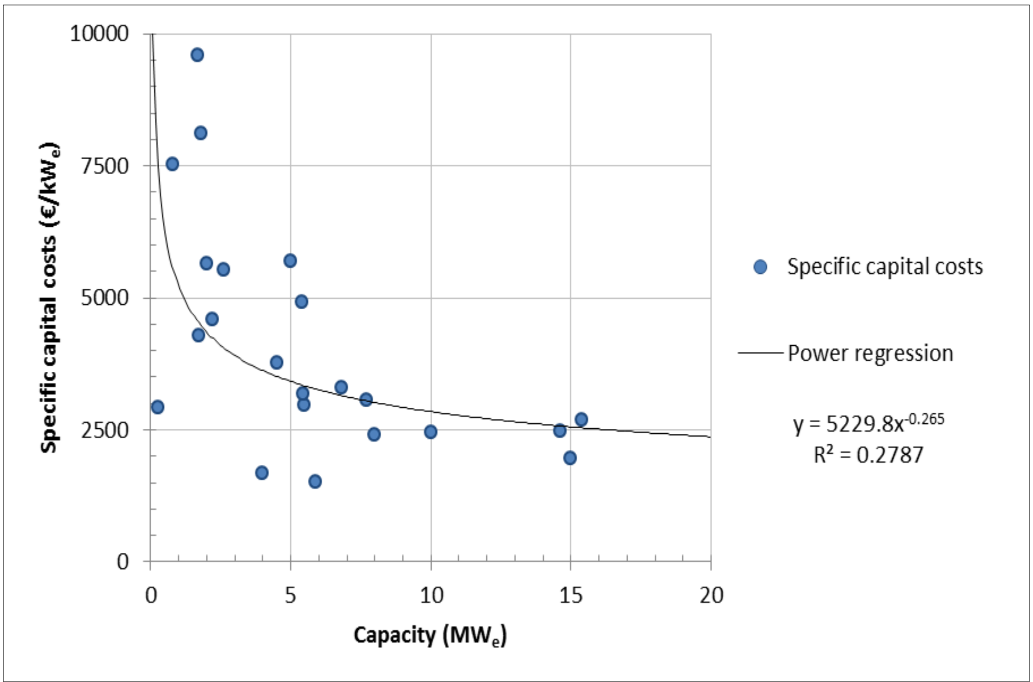


Figure 4.5: Specific capital costs of a fluidised bed gasifier coupled to a gas engine as a function of the electric capacity

The specific capital costs of several power plants fitted with a fluidised bed gasifier coupled to a gas engine for a range of scales up to 20 MW_e are depicted in Figure 4.5 along with their corresponding regression adjustment for best fitting the curve representing the dependence between capital costs and electric scale. The graph shows a high uncertainty as well as a correspondingly low coefficient of determination (0.28) for the whole array of specific capital costs with respect to the calculated best fit. To this extent, the different framework conditions in the countries under consideration as well as the dissimilar maturity level of the implemented technologies might explain the relatively high divergence of the specific capital costs – and indeed of the rest of the analysed techno-economic parameters. Most projects were built in states of the European Union, although some were raised in the USA over the last two decades. A number of these combined heat and power plants were promoted as research, development, demonstration or deployment projects, whereas others served as technically proven solutions equipped with completely mature technologies.

Several CHP plants based on fluidised bed gasification coupled to gas engine actually correspond to significant projects fostered to demonstrate the state of the art of this technology. They are in any case financed by governments, other public institutions or even private ventures for supporting bioenergy obtained from gasification of wood resources. In this sense, the research studies [RENET 2007] and [NNFCC 2009] describe a 1.7 MW_e demonstration plant based on dual fluidised bed gasification, which was built in the Austrian city of Güssing. Another relevant combined heat and power cogeneration plant based on bubbling fluidised bed gasification is the project carried out in Skive (Denmark) for an electric capacity of 5.5 MW_{e}. According to [NNFCC 2009], it was launched as a private initiative and commissioned in the year 2008 [Roos 2010]. Both publications [Sánchez 2006] and [Gard 2008] equally make reference to a project in which a combined heat and power plant based on fluidised bed gasification is attached to three gas engines generating 5.9 MW_e from winery residues in Ciudad Real (Spain). Besides, [Do et al. 2014] reports on several CHP plants based on circulating fluidised bed gasification for diverse scales, namely 800 kW_e, 2.6 MW_e, 7.7 MW_e and 15.4 MW_e. Each of these capacities is modelled with the process simulator Aspen Plus for three different prime movers: a gas engine, a gas turbine and a combined cycle. In the same vein, the performance of two combined heat and power plants conceived as FBG+E with 6.8 MW_e and 14.6 MW_e is simulated in a comprehensive study carried out by [Yassin et al. 2009]. The resulting techno-economic parameters for both simulated plants prove to be more economical than those obtained in real cases such as those of Güssing or Skive, where the analysis was clearly performed under a marked demonstration character.

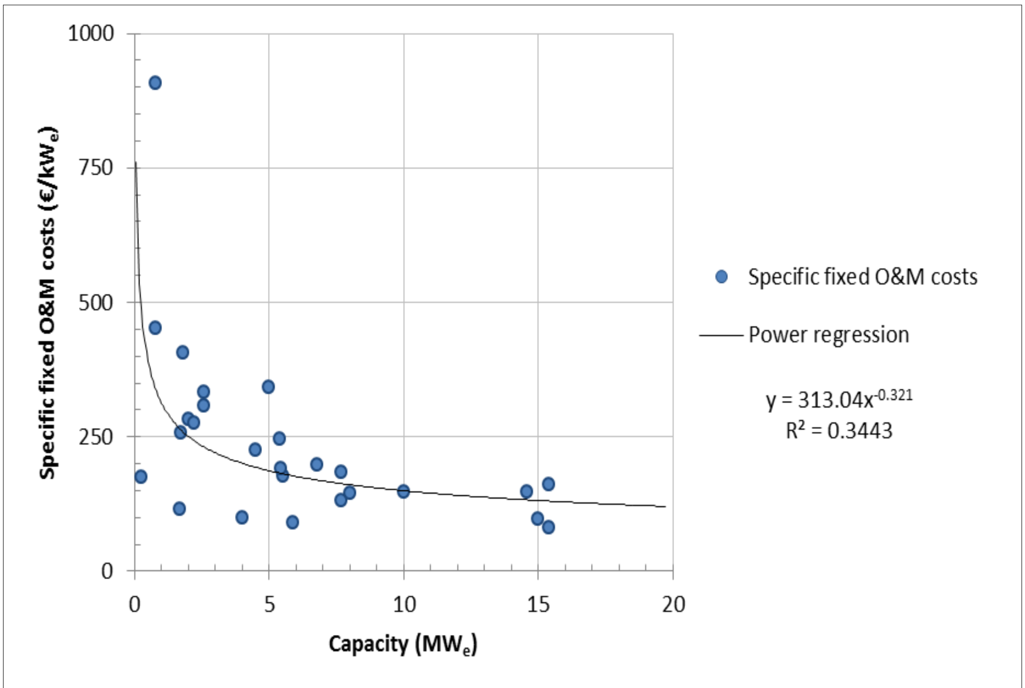


Figure 4.6: Specific fixed O&M costs of a fluidised bed gasifier coupled to a gas engine as a function of the electric capacity

In relation to specific fixed O&M costs, it is a fact that not all consulted references publish this important economic parameter. On certain occasions, fixed O&M costs appear added up to the variable costs expressed as a single quantity, thus complicating the identification of both different types of O&M costs. For these cases, a statement based on [IRENA 2012] can be employed, according to which fixed O&M costs account for 3-6% of capital costs. As an assumption, a percentage of 6% is used for combined heat and power plants with a capacity smaller than 10 MW_e and, in turn, 5% for scales ranging from 10 MW_e to the predefined 20 MW_e. Thus, Figure 4.6 illustrates the data set of fixed O&M costs for the whole range of electric capacities. The graph also shows the best fit, which is achieved by applying a power regression adjustment technique for the whole array of data. The resulting best fit renders a relatively high uncertainty that is associated with a proportionally small coefficient of determination (0.34). As in the case of capital costs, the dimension of these statistical parameters can be accounted for by the dissimilar framework conditions and the different development state of implemented technologies.

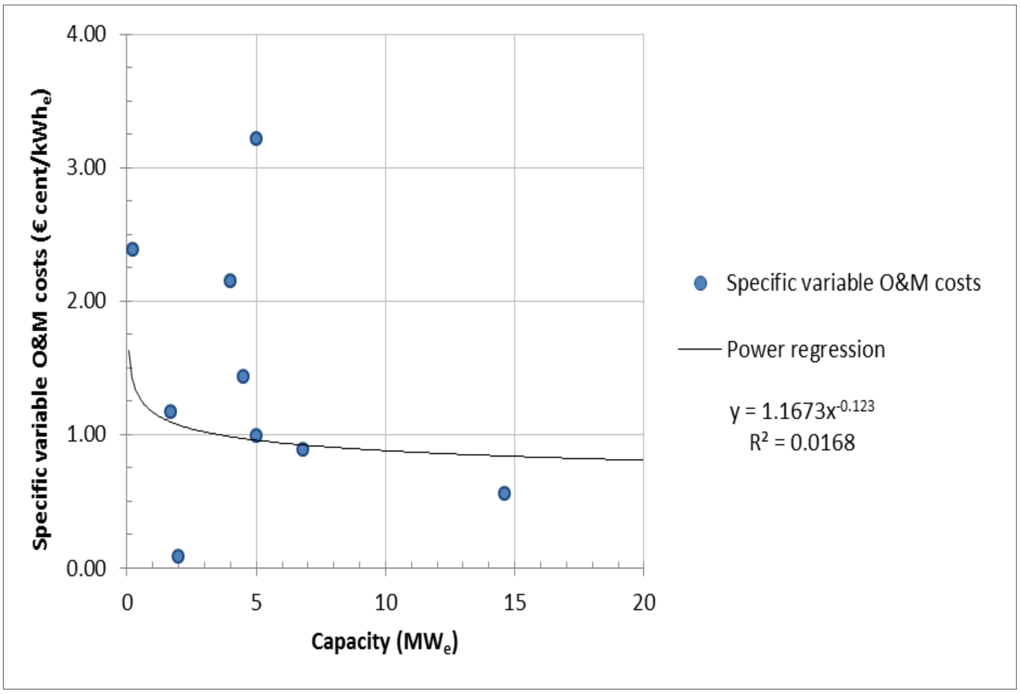


Figure 4.7: Specific variable O&M costs of a fluidised bed gasifier coupled to a gas engine as a function of the electric capacity

On the other hand, the specific variable O&M costs derived from all examined case studies are plotted in Figure 4.7 together with the corresponding best fitting curve. This trend line is calculated by means of a power regression adjustment technique that generates a smooth curve with a moderate scale effect throughout the whole scale range. The aim of this graph is representing variable costs versus the electric scale of the bio-based plant. As a singularity, [NNFCC 2009] reports, however, extremely low specific variable O&M costs for a small-sized CHP plant – concretely below 0.25 €cent/kWh$_e$ – without indicating the reasons for that. Meanwhile, the rest of the publications show quite higher specific variable costs on the order of a few €cents per electric kWh within the same scale range. Nonetheless, the scarce information found on variable operation costs usually leads to significant difficulties for graphically representing this dependence on electric capacity – as it occurred for determining the fixed part of O&M costs. In this regard, variable operation costs are also calculated by subtracting fixed O&M costs from the whole operation and maintenance expenses, which are normally well documented. Furthermore, the resulting regression curve is characterised by an enormously large uncertainty as well as a very low coefficient of determination (around 0,017), largely due to the same causes exposed for fixed operation costs. At any rate, a much better curve representing the specific variable costs could be constructed if more techno-economic studies could be found involving CHP plants based on fluidised bed gasification coupled to gas engine.

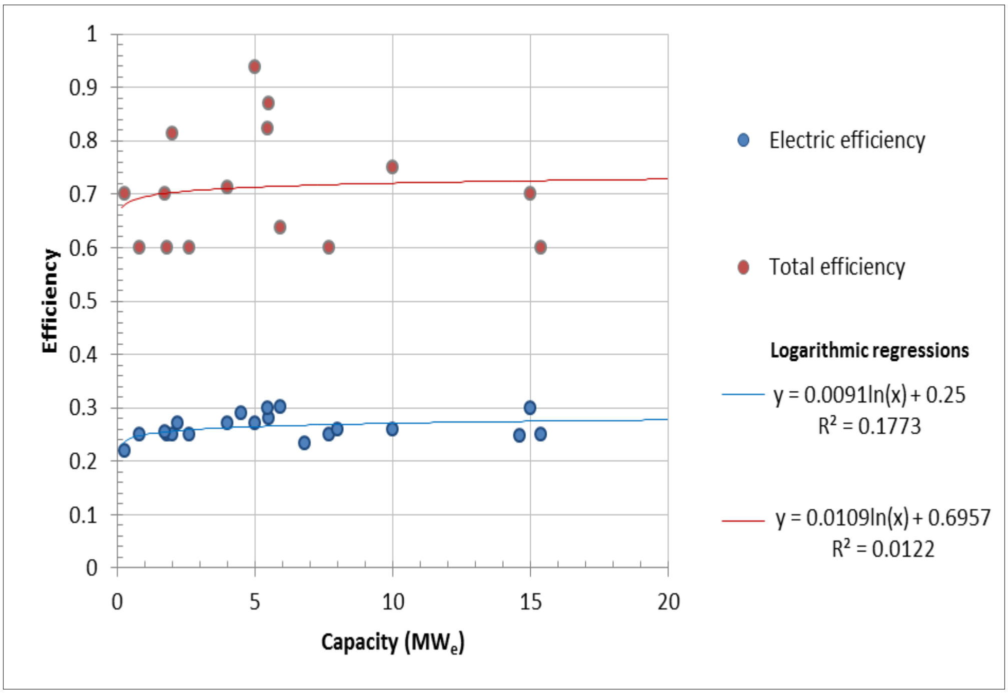


Figure 4.8: Electric and total efficiency of a fluidised bed gasifier coupled to a gas engine as a function of the electric capacity

Finally, the dependence of the electric and total efficiency on scale is analysed for CHP plants based on a fluidised bed gasifier coupled to a gas engine. Both magnitudes strongly determine the performance of the conversion process at the level of power and heat generation. Dependence of both types of efficiency on scale is calculated by constructing the best fitting curve on the basis of a logarithmic regression technique (see Figure 4.8). The logarithmic behaviour of both curves exhibits an asymptotic approximation, where the efficiencies reach a limit value at the maximum power output of 20 MW_e: 28% for the electric efficiency and 73% for the total efficiency. Between both bounds, this technology presents the particularity that both efficiencies show a noticeably mild scale effect. The graph also shows some high uncertainty for both parameters, albeit total efficiency is specially affected with an extremely low coefficient of determination in the order of 0.012. Whereas discrete data referring to electric efficiency are reasonably adjusted, those related to total efficiency appear displaying a much higher dispersion on the plot. This deviation from the best fit might be caused by the different rate of cogeneration (heat recovery) that is carried out for the different analysed CHP plants. In this sense, although a FBG+E-based facility is conceived as a power-operated plant, it also generates heat as a by-product. Concretely, this source of low grade waste heat comes from the latent heat of exhaust gases (90°C) and the sensible heat of the cooling fluid (80-90°C).

4.4.3. Fluidised bed gasifier coupled to combined cycle

As performed in the previous subsection for the analysis of CHP plants based on a fluidised bed gasifier and a gas engine, a further technological ensemble equally composed of a fluidised bed gasifier but now attached to a prime mover in the form of a combined cycle is to be techno-economically characterised. Likewise, the aim of this analysis is to estimate the trend lines of the four most significant techno-economic parameters for describing the biomass integrated combined cycle (BIGCC): capital costs, fixed and variable O&M costs and the electric efficiency. These parameters are derived from a list of publications addressing BIGCC plants for different scales varying from 3 MW_e up to 160 MW_e. Their trend lines are graphically represented in Figures 4.9-12 below as a function of the electric capacity on the basis of the research studies listed in Table 4.3.

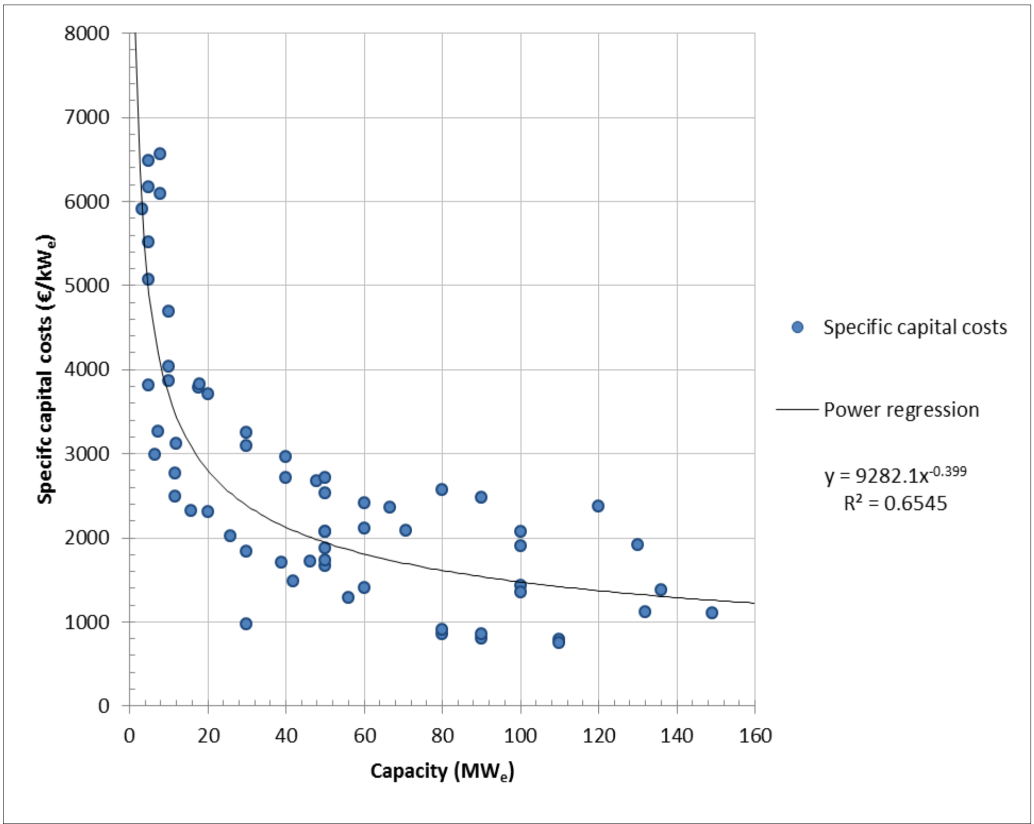


Figure 4.9: Specific capital costs of a fluidised bed gasifier coupled to a combined cycle as a function of the electric capacity

Most of the erected BIGCC plants at small and medium scale were co-financed by public institutions in collaboration with private stakeholders within the framework of demonstration and deployment projects, whereas only a few projects were launched by fully private undertakings. Originally, the BIGCC technology was developed for producing bio-based power from gasification of biomass predominantly at high scales with the aim of decreasing production costs via economies of scale. In spite of this, [Pang et al. 2006] and [Kwant et al. 2004] report on two small-scaled atmospheric BIGCC units of 6 MW_e and 8 MW_e in Värnamo (Sweden) and Yorkshire (UK), respectively – both within the framework of the ARBRE program. But both projects were cancelled after demonstration was accomplished and no public funding was assigned to the projects mainly because the bioenergy produced was less profitable than fossil energy generation. On the other hand, two further atmospheric BIGCC plants with medium capacities (30 MW_e/42 MW_e) are mentioned by [NNFCC 2009] as conventional turnkey projects developed by Silva Gas Corporation (USA). In contrast, other research studies such as [Do et al. 2014], [Yassin et al. 2009], [Klimantos et al. 2009] and [Jin et al. 2009] refer to a number of atmospheric and pressurised BIGCC plants for small to large scales. In these cases, the plants are not real but modelled with different process simulators such as Aspen Plus or Gatecycle.

The specific capital costs of a list of studies reporting on BIGCC power plants are illustrated in Figure 4.9 along with their best fit, which is estimated by making use of a power regression adjustment technique. This regression method is implemented for best fitting all capital costs-related data, thus rendering a curve that represents the dependence between capital costs and electric scale for the BIGCC technology. The graph shows a relatively low uncertainty for this adjustment, albeit deviation of discrete data from the best fit is still significant in some parts of the scale range. The corresponding coefficient of determination amounts to 0.65 as a clear evidence of the comparatively high quality of the performed power regression fit. Nonetheless, a deeper analysis of each case study permits certain possible causes for this uncertainty to be identified. Concretely, fluidised bed gasification reactors are categorised as atmospheric or pressurised depending on what pressure is employed during the gasification process and hence, whether a compressor must be installed or not. Indeed, each technical configuration exhibits different specific capital costs that in turn induce increased uncertainties. But this information is not always present in the referenced studies and sometimes other reasons may arise as the main source of this capital costs' uncertainty in both pressurised and atmospheric gasification power plants. To this extent, a further explanation for such statistical data dispersion seems to be related to the different framework conditions as well as the diverse state of technological maturity among the projects. Likewise, the uncertainty of the remaining techno-economic parameters is also related to the wide variety of economic areas involved as well as the different maturity status of the BIGCC plants under study. In this regard, it should be noted that most projects were built in states of the European Union and a few in the USA, whereas some studies concerning plants set up in third countries are intentionally not included in the present analysis.

As already discussed for direct co-firing and FBG+E, the lack of information regarding fixed O&M costs in BIGCC power plants is equally a constant, because not all consulted studies publish this economic parameter as part of their research activities. In some cases, fixed O&M costs are disclosed together with variable O&M costs combined into a unique figure that equates to total O&M costs. This fact introduces a certain difficulty when it comes to breaking down this total amount into both separate shares. The same methodology based on [IRENA 2012] and applied to the FBG+E technology is also employed for BIGCC plants, according to which fixed O&M costs make up 3-6% of capital costs. As an assumption, a percentage of 6% is used for BIGCC plants with an electric capacity smaller than 10 MW_e, whereas an intermediate rate varying between 5% and 6% is set for scales ranging up to 50 MW_e. From this scale on up to 140 MW_e, a decreasing percent between 5% and 4% is assumed while letting it gradually descend to 3% for larger electric capacities over 150 MW_e. The aforementioned variation of fixed O&M costs as a decreasing percentage of capital costs intends to reproduce the typical cost reduction effect brought about by the economies of scale. In addition, the continuous decrease of this percentage across the whole scale range is numerically harmonised with the supplementary portion describing variable costs so that the sum of both terms yields the usually known value of the entire O&M costs. As a result, Figure 4.10 illustrates for the BIGCC technology the specific fixed O&M costs as a function of the electric capacity as well as their best fitting curve – calculated via a power regression adjustment technique – in the scale range between 3 MW_e and 160 MW_e.

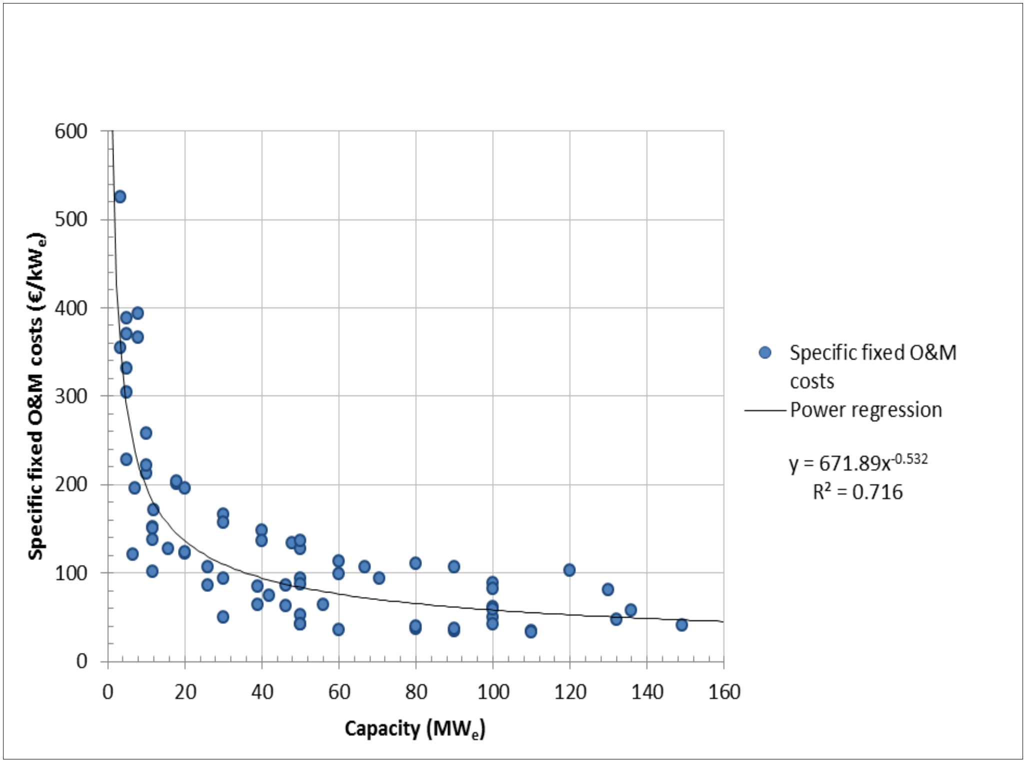


Figure 4.10: Specific fixed O&M costs of a fluidised bed gasifier coupled to a combined cycle as a function of the electric capacity

Another economic parameter that allows techno-economically modelling a BIGCC plant is the specific variable O&M costs. But the scarcity of collected data concerning variable operation costs is even more severe than in the case of fixed operation expenses, thus contributing to serious difficulties for plotting the dependence of this magnitude on electric scale. This scale dependence is illustrated in Figure 4.11 together with the best regression fit to the sample of discrete costs. The best fitting curve – derived from a power regression adjustment – displays a relatively large uncertainty and hence a correspondingly low coefficient of determination (0.276). In this regard, some studies such as [Kalt et al. 2011] contribute greatly to this increased data dispersion with quite low specific variable O&M costs in the order of roughly 0.15 €cent/kWh_e. On the contrary, the opposite case is represented by [Caputo et al. 2005], which reports very high total and, therefore, variable O&M costs, particularly for large electric capacities from 20 MW_e onwards. Anyhow, both statistical parameters behave much better than those achieved for co-firing and FBG+E technologies, which rendered extremely smaller coefficients of determination. In relation to the dimension of variable costs, although a BIGCC plant presents in general higher capital costs than a process based on FBG+E (cf. Figure 4.5 and Figure 4.9), the reverse appears to be for fixed (cf. Figure 4.6 and Figure 4.10) and variable (cf. Figure 4.7 and Figure 4.11) O&M costs when both technologies are compared for the same scale range up to 20 MW_e. In this connection, the higher electricity yield generated by a combined cycle as against that of a gas engine would substantially decrease both fixed and variable[22] O&M costs of the BIGCC over those of the FBG+E to the extent of lowering the corresponding trend line of the former with respect to that of the latter.

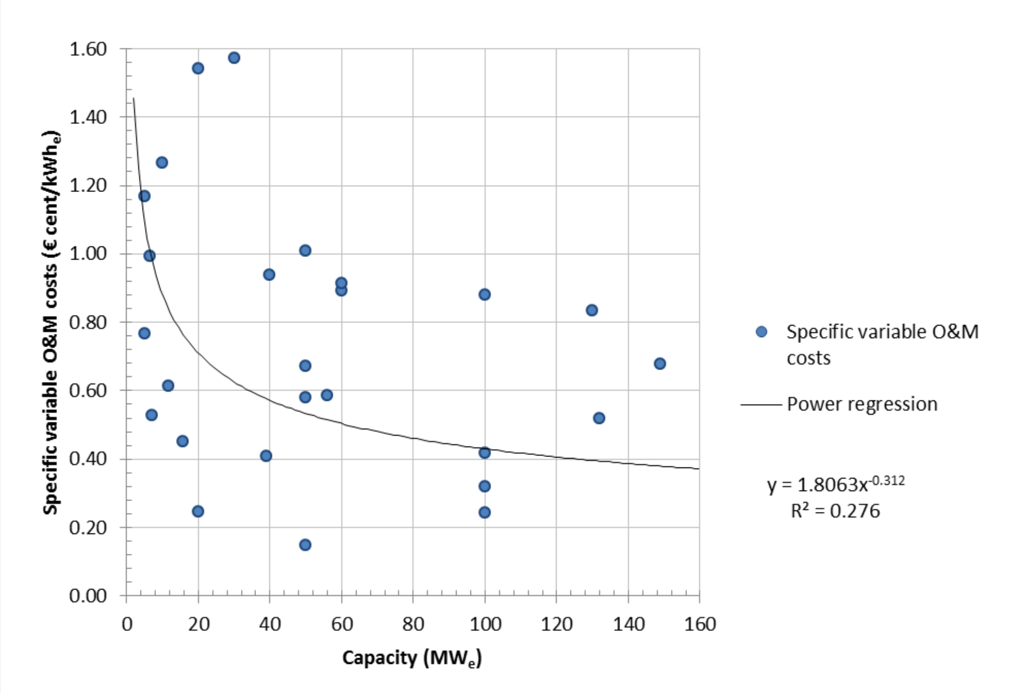


Figure 4.11: Specific variable O&M costs of a fluidised bed gasifier coupled to a combined cycle as a function of the electric capacity

The electric efficiency of a BIGCC plant based on fluidised bed gasification is also of major importance for describing the performance of this conversion technology. Relevant data regarding the electric efficiency are abundant and appear in nearly all analysed studies. Accordingly, the dependence of this parameter on scale is illustrated without difficulty in the plot of Figure 4.12 by representing its trend line. For this aim, a large array of data on electric efficiency for different capacities is represented, while their best fit is constructed on the basis of a logarithmic regression adjustment technique. The logarithmic behaviour of this best fitting curve is expressed by an asymptotic approximation that reaches a maximum efficiency of 47% for the largest power output (160 MW_e). Electric efficiency is also affected by uncertainty, although to a minor extent and notably for scales below 50 MW_e. For this capacity domain, [EPA 2007] refers to three BIGCC plants of 6.6 MW_e, 11.6 MW_e and 39 MW_e that present quite low electric efficiencies with respect to the calculated trend line. In

[22] [Yassin et al. 2009] corroborates this claim exclusively for variable O&M costs.

the same vein, [Do et al. 2014] simulates five BIGCC plants with capacities ranging from 0.8 MW_e to 46.2 MW_e that are equally associated with lower efficiencies. Thus, both studies contribute greatly to the uncertainty of this parameter, albeit the origin of the deviation from trend values is not apparent.

On another level, mention should also be made of the tiny bio-based heat output that arises during the operation of BIGCC power plants – albeit it is not intended to be modelled. As fluidised bed gasifiers coupled to a combined cycle are mainly power-operated, no joint product in form of heat is cogenerated. But similarly to co-firing, waste heat of low grade could also be gained as a by-product for the case of the BIGCC technology. The latent heat of exhaust gases at around 90°C as well as the sensible heat of the cooling fluid – circulating within the refrigeration system at a temperature of roughly 20-30°C – could definitely be harnessed as a further energy source with the objective of improving the process's performance.

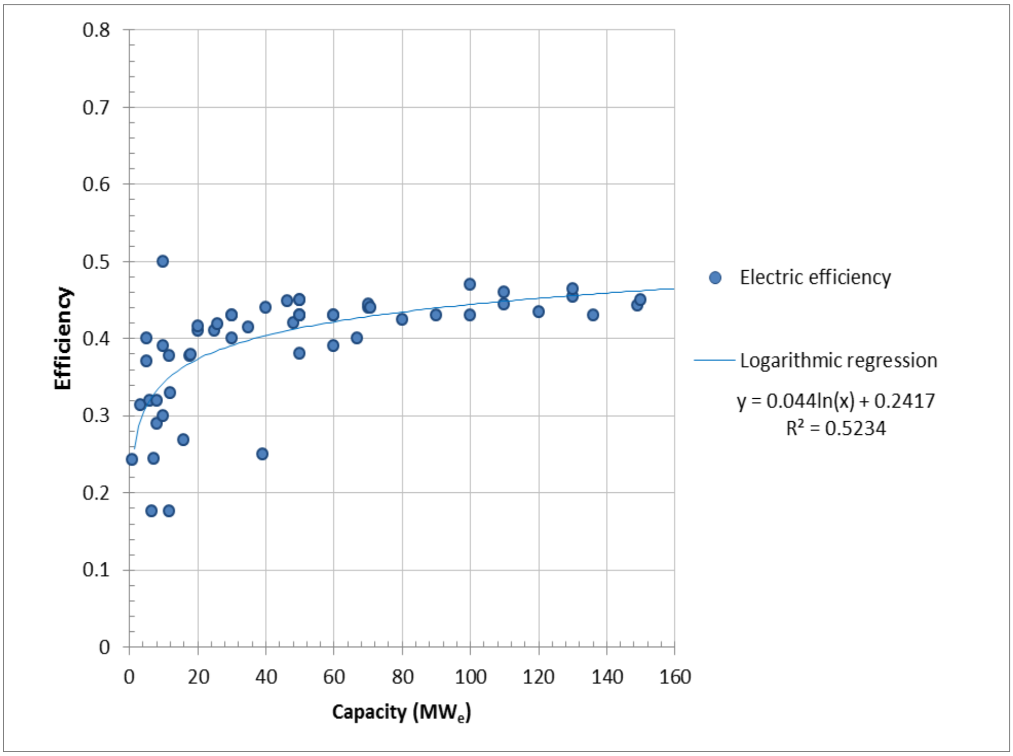


Figure 4.12: Electric efficiency of a fluidised bed gasifier coupled to a combined cycle as a function of the electric capacity

4.5. Tabulation of techno-economic parameters for the selected technologies

The dependence of the four techno-economic parameters (capital costs, variable and fixed operating costs, electric/total efficiency) on the electric capacity as displayed in Figures 4.1-12 for the three preselected technologies (co-firing, fluidised bed gasifier coupled to gas engine or combined cycle) are assessed via power/logarithmic regression techniques by creating trend lines based on techno-economic data derived from an array of studies listed in Tables 4.1-3 below.

Table 4.1: Techno-economic features of co-firing for a 10% fraction of wood resources

Total capacity	**Specific capital costs**	**Specific fixed O&M costs**	**Specific variable O&M costs**	**Electric efficiency**	**Reference**
MW	*€/kW$_e$*	*€/kW$_e$*	*€cent/kWh$_e$*	*%*	
5	502	78.58	0.71	-	[EPA 2007]
12	265	99.54	0.70	27.5	[McIlveen-Wright et al. 2011]
25	113	81.92	0.58	28.2	[McIlveen-Wright et al. 2011]
30	-	48.33	0.98	30	[Ortiz et al. 2011]
50	305	-	-	31	[Faaij 2006]
60	171	26.82	0.24	-	[EPA 2007]
100	285	44.53	0.40	35	[USDOE 2004]
150	299	46.85	2.29	33.3	[Royo et al. 2004]
200	305	-	-	39	[Faaij 2006]
200	352	55.07	0.50	-	[O’Connor et al. 2011]
200	576	90.16	0.82	-	[Energi 2012]
215	188	56.43	0.36	32.8	[Zhang 2010]
360	463	72.41	0.66	36	[Obernberger 2003]
400	173	26.26	0.49	33.2	[Boardman et al. 2013], [IRENA 2012]
400	544	85.06	0.77	-	[Energi 2012], [IRENA 2012]
500	353	55.20	0.49	40	[Bohnenschäfer et al. 2007]
550	200	79.35	0.67	32.8	[Skone 2012]
650	-	30.06	0.41	34.1	[Nderitu 2014]
700	181	28.32	0.56	-	[Wiegmann et al. 2008]
800	89	16.55	0.26	40	[Lüschen et al. 2010]
800	318	49.70	0.45	-	[Ehrig et al. 2013], [IRENA 2012], [IRENA 2013]

Table 4.2: Techno-economic features of fluidised bed gasifier coupled to gas engine

Bio-based capacity	**Specific capital costs**	**Specific fixed O&M costs**	**Specific variable O&M costs**	**Electric / total efficiency**	**Reference**
MW	*€/kW$_e$*	*€/kW$_e$*	*€cent/kWh$_e$*	*%*	
0.25	2,931	175.87	2.39	22 / 70	[Austermann et al. 2007]
0.8	7,537	908.08	-	25 / 60	[Do et al. 2014]
0.8	-	452.22	-	-	[Do et al. 2014], [IRENA 2012]
1.7	9,598	116.26	1.17	-	[RENET 2007], [Bolhàr-Nordenkampf et al. 2003]
1.73	4,280	256.78	-	25.4 / 70	[Rabou et al. 2001]
1.8	8,110	405.48	-	25 / 60	[Difs et al. 2010]
2	5,656	282.78	0.08	25 / 81.3	[NNFCC 2009], [Simader 2004]
2.2	4,601	276.05	-	27 / -	[Zeymer et al. 2009]
2.6	5,532	307.29	-	25 / 60	[Do et al. 2014]
2.6	-	331.92	-	-	[Do et al. 2014], [IRENA 2012]
4	1,688	100.33	2.15	27.2 / 71.2	[EPA 2007]
5	5,703	342.20	3.21	27 / 93.7	[Frombo et al. 2009], [IRENA 2012]
5	-	-	0.99	-	[Kalt et al. 2011]
5.5	2,962	177.73	-	28 / 87	[NNFCC 2009]
4.5	3,759	225.56	1.43	29 / -	[NNFCC 2009]
5.9	1,519	91.13	-	30.2 / 63.8	[Gard 2008], [Sánchez 2006]
5.45	3,174	190.46	-	30 / 82.4	[VTT 2009]
5.4	4,922	246.09	-	-	[Roos 2010]
6.8	3,307	198.44	0.89	23.3 / -	[Yassin et al. 2009]
7.7	3,066	132.22	-	25 / 60	[Do et al. 2014]
7.7	-	183.98	-	-	[Do et al. 2014], [IRENA 2012]
8	2,410	144.59	-	26 / -	[VTT 2009]
10	2,460	147.59	-	25.9 / 75	[Rabou et al. 2001]
14.6	2,471	148.24	0.56	24.7 / -	[Yassin et al. 2009]
15	1,954	97.71	-	30 / 70	[Austermann et al. 2007]
15.4	2,694	79.91	-	25 / 60	[Do et al. 2014]
15.4	-	161.62	-	-	[Do et al. 2014], [IRENA 2012]

Table 4.3: Techno-economic features of fluidised bed gasifier coupled to combined cycle

Bio-based capacity	**Specific capital costs**	**Specific fixed O&M costs**	**Specific variable O&M costs**	**Electric efficiency**	**Reference**
MW	*€/kW$_e$*	*€/kW$_e$*	*€cent/kWh$_e$*	*%*	
0.8	-	-	-	24.3	[Do et al. 2014]
3.2	5,905	525.94	-	31.4	[Do et al. 2014]
5	3,808	228.47	-	-	[IRENA 2012]
5	6,478	388.69	-	-	[IRENA 2012]
5	6,172	370.31	0.77	37	[Caputo et al. 2005]
5	5,076	304.57	1.17	-	[Gómez et al. 2010]
5	5,518	331.05	-	40	[Faaij 2006]
6.6	2,994	120.34	0.99	17.6	[EPA 2007]
7.2	3,261	195.67	0.53	24.4	[Yassin et al. 2009]
8	6,096	365.75	-	29	[Pang et al. 2006]
8	6,564	393.85	-	32	[Peacocke 2008]
10	4,691	257.99	1.27	39	[Caputo et al. 2005]
10	4,034	212.42	-	30	[Balat et al. 2009]
10	3,862	221.89	-	50	[Faaij 2006]
11.6	2,494	100.85	0.61	17.6	[EPA 2007]
11.7	2,766	150.38	-	37.8	[Do et al. 2014]
12	3,119	171.55	-	33	[Pang et al. 2006]
15.8	2,322	127.71	0.45	26.8	[Yassin et al. 2009]
17.8	3,786	200.67	-	37.8	[VTT 2009]
17.9	3,832	203.12	-	37.9	[Klimantos et al. 2009]
20	3,703	196.27	1.54	41	[Caputo et al. 2005]
20	2,303	123.35	0.25	41.6	[NC 2007]
25.9	2,023	123.35	-	41.9	[Do et al. 2014]
30	3,251	165.78	1.57	43	[Caputo et al. 2005]
30	978	49.88	-	-	[NNFCC 2009]
30	1,834	93.52	-	40	[Balat et al. 2009]
30	3,091	157.64	-	43	[Uddin 2004]
39	1,701	85.05	0.41	25	[EPA 2007]
40	2,963	148.13	-	44	[Caputo et al. 2005]
40	2,720	136.01	0.94	44.5	[Gómez et al. 2010]
42	1,484	74.22	-	-	[NNFCC 2009]
46.2	1,722	62.92	-	44.9	[Do et al. 2014]
48	2,674	133.69	-	42.1	[Klimantos et al. 2009]
50	2,534	126.70	-	45	[O’Connor 2011]
50	2,715	135.78	-	45	[Caputo et al. 2005]

Bio-based capacity	**Specific capital costs**	**Specific fixed O&M costs**	**Specific variable O&M costs**	**Electric efficiency**	**Reference**
MW	*€/kW$_e$*	*€/kW$_e$*	*€cent/kWh$_e$*	*%*	
50	2,075	51.87	0.67	43	[Wetterlund et al. 2010]
50	2,075	41.49	0.15	43	[Kalt et al. 2011]
50	1,663	41.58	1.01	38	[Marbe et al. 2004]
50	1,882	94.07	-	43	[Difs et al. 2010]
50	1,736	86.79	0.58	45	[Overend 2000]
56	1,283	64.13	0.59	-	[Sofia et al. 2014]
60	2,409	113.21	0.91	39	[Gómez et al. 2010]
60	1,407	35.18	0.89	43	[Marbe et al. 2004]
60	2,106	98.99	-	43	[Uddin 2004]
66.7	2,360	106.19	-	40	[Klimantos et al. 2009]
70	-	-	-	44.0/44.5	[Dornburg et al. 2001]
70.6	2,080	93.58	-	44	[Klimantos et al. 2009]
80	2,575	110.71	-	42.5	[Nussbaumer 2007]
80	856	36.80	-	-	[Dornburg et al. 2001]
80	906	38.96	-	-	[Dornburg et al. 2001]
90	2,476	106.46	-	43	[Nussbaumer 2007]
90	805	34.63	-	-	[Dornburg et al. 2001]
90	856	36.80	-	-	[Dornburg et al. 2001]
100	2,066	88.86	0.88	43	[Gómez et al. 2010]
100	1,901	49.54	0.32	-	[Jianbang et al. 2006]
100	1,433	41.88	0.42	47	[Gustavsson et al. 2003]
100	1,353	58.18	-	-	[Tsakomakas et al. 2012]
100	-	-	0.24	-	[IRENA 2012]
110	785	33.77	-	44.5	[Dornburg et al. 2001]
110	755	32.47	-	46	[Dornburg et al. 2001]
120	2,377	102.20	-	43.5	[Nussbaumer 2007]
130	1,910	80.22	0.83	46.5	[Gómez et al. 2010]
132	1,117	46.89	-	-	[Sofia et al. 2014]
136	1,377	57.84	-	43	[Uddin 2004]
149	1,104	40.83	0.68	44.3	[Rhodes et al. 2005]
150	-	-	-	45	[Gómez et al. 2010]
200	-	-	-	46	[Gómez et al. 2010]
250	1,190	40.47	-	55	[Gustavsson et al. 2003]
431	1,167	37.35	0.12	48.2	[Jin et al. 2009]
442	1,065	34.10	0.11	49.5	[Jin et al. 2009]

5. Development of a model for the optimisation of bioenergy systems

In this chapter, a singular optimising energy system model is created in order to assess the capacity expansion planning for an array of identified technologies converting biomass into bioenergy. The modelling approach developed for such a research analysis consists in a bottom-up model named BIOSPHERE (Bioenergy Optimisation Software for Production Pathways at High Energy and Resource Efficiency), which is based on the already existing PERSEUS model (Program Package for Emission Reduction Strategies in Energy Use and Supply). BIOSPHERE performs an optimisation of the value chain of a specific biomass resource by minimising the subsystem expenditures via analysing the corresponding bioenergy system from the viewpoint of the investors of each specific utilisation pathway. A set of auxiliary conditions involving the energy and material flow balance of the system as well as the restriction on process utilisation are already present in PERSEUS. On the contrary, the maximum amount of annually installed capacity along with a novel constraint on profitability is implemented in the existing source code thus creating the new BIOSPHERE model. The latter restriction is based on the fulfilment of the principle of profitability. This provides the possibility of separately assuring the cost-effectiveness of individual investments for each particular utilisation pathway. Thus, the cost assessment of a bioenergy system can be carried out from the viewpoint of the investor of each utilisation pathway for the entire economic life of a bio-based power plant. The resulting BIOSPHERE model can then be used for investigating the effect of remunerations on the total energy system or even a specific bioenergy subsystem within any particular region in consistency with the fulfilment of profitability constraints for each separate utilisation pathway.

5.1. The profitability of utilisation pathways

Due to the higher production costs of bioenergy versus other energy sources originating from nuclear or fossil resources but also on account of the lower level of remunerations received for bioenergy production in contrast to other renewable energies such as photovoltaic or wind power, investments in the bioenergy sector account for a lower share in the total energy market as against conventional or other renewable energy sources. In this regard, comparatively higher remunerations must be granted to investors with the aim of promoting bioenergy generation and thus compensating the higher expenses incurred throughout the entire value chain from resource harvesting to conversion into bioenergy. Biomass in general and wood resources in particular presents elevated harvesting and densification costs – as shown in chapters 2 and 3 – in addition to variable transport expenses as well as occasionally certain conditioning costs. The processes involved are rather expensive due to the low efficiencies registered throughout the stages of utilisation pathways as well as the low heating values and the geographical dispersion over the region.

On the other hand, the usual methodology employed for the analysis of energy systems consists in optimising the whole system from a unique point of view considered as an external observer. In this sense, some studies are performed according to which a bioenergy or energy system is modelled from the standpoint of a unique observer. For instance, [König 2009] carries out a techno-economic analysis of all mature energy generating utilisation pathways of Germany’s bioenergy system from the point of view of a unique observer. In the same vein, the research study [Rosen 2008] optimises the energy system of the 15 EU states equally from a general point of view.

However, it is observed that the critical point in relation to the modelling of each utilisation pathway is not so much the analysis of the whole system as the consideration of each specific utilisation pathway from the viewpoint of a specific observer: the plant operator. Thereby, new observers representing each utilisation pathway and hence each power plant operator can be introduced for a more appropriate analysis of the bioenergy system with the aim of independently assessing each conversion pathway. According to this approach based on separately analysing every utilisation pathway, the respective observer will register those incomes (i.e. remunerations) and expenses incurred at the power plant and its supply chain. This will allow evaluating the profitability not for the whole system but exclusively for each utilisation pathway from the standpoint of each plant operator (observer).

When investors have to make a decision about the installation of a bioenergy power plant, they are faced with the prerequisite to comply with the principle of profitability. This is associated with the fact that the net present value of each utilisation pathway must be greater than or equal to zero in order to perform profitable investments by reaching a certain level of profit. This principle can be translated to a further statement, whereby remuneration for bioenergy generation has to at least cover the sum of the expenditures incurred throughout the entire utilisation pathway – i.e. the corresponding bio-based power plant and its supply chain from the source to the point of conversion. By satisfying this condition separately, it is also intended to prevent profitable utilisation pathways from compensating for other non-profitable ones by setting an individual upper limit to the sum of costs. This compensation may occur when all utilisation pathways are analysed together in the context of an energy system analysis.

This inequation needs to be satisfied for investments in bioenergy on account of the elevated expenditures incurred throughout the entire utilisation pathway – irrespective of the type of resource to be transformed into bioenergy (e.g. wood residues, liquid manure,…etc.). Nevertheless, this requirement is in general easily complied with in utilisation pathways based on conventional energy generation (i.e. fossil and nuclear). The same applies to most renewable energies such as hydro, photovoltaic, wind and geothermal. This is basically due to the more suitable level of remunerations received as compared to those granted to other immature and relatively expensive energy vectors such as bioenergy (highly efficient bio-based power generation), solar thermal and ocean energies. In the case of fossil and nuclear energy, the fulfilment of the prior condition is associated with the high energy density of the respective primary energy carriers. This attribute facilitates their exploitation and subsequent transportation to the energy conversion unit. For both aforementioned groups of renewable energy sources with the exception of bioenergy, the basic resource (i.e. watercourse, radiation, wind, hot water, waves and tides) is free and has then no costs assigned. Besides, there is also no need for this amount of energy to be either collected or transported to the conversion facility. Therefore, the only expenses arising in these utilisation pathways are those related to the energy generation process itself (i.e. prime mover) at the corresponding conversion units. In general, the fulfilment of the principle of profitability for utilisation pathways of any kind of energy source is exclusively correlated to the possibility of properly adjusting profits or even reducing production costs.

The array of the previously explained issues introduces the prerequisite of profitability in bioenergy systems as an aspect that has to be analysed separately for any individual investment in a particular utilisation pathway. Leveraging the already existing structures of the PERSEUS model, a novel model (BIOSPHERE) is developed with the aim of integrating this mathematical restriction in its source code in order to deal with energy systems in general or focus on bioenergy subsystems in particular like that involving wood resources.

5.2. Literature review

The topic concerning the optimisation of bioenergy systems has experienced increasing interest in recent years and is therefore addressed in a lot of research studies published all around the world. The identification of the manner, in which certain types of biogenic resources such as wood resources – as well as cereals or liquid manure – are converted into power, heat or biofuels, is the main objective of these publications. These endogenous resources usually grow scattered across the surface of any targeted territory along the time axis. In consequence, the spatiotemporal determination of the stages concerning the most optimal bio-based utilisation pathways is the first step to be performed in the framework of the present analysis. For this purpose, an appropriate optimising energy system model has then to be devised so that the most cost-efficient design may be ascertained and finally implemented.

5.2.1. Overview of existing studies

Research studies dealing with the optimisation of bioenergy systems are reviewed in this section in order to identify the main topics. Some differences, common points as well as strengths and weaknesses that are identified within the studies are critically commented. The following list of research studies represents a selection of the most important contributions found through literature searching. Hereunder, they are listed according to their corresponding author while their most important contributions are highlighted for each analysis. Although the list is not intended to be comprehensive, it provides a strong enough indication of the type of analysis that researchers from across the world are carrying out with the aim of identifying an optimal solution for the proposed problem.

Aksoy et al. 2011 Four bio-refinery technologies were studied for feedstock allocation, optimum facility location, economic feasibility, and their economic impacts on Alabama. The studied technologies are: (1) circulated fluidized bed gasification of woody biomass for Fischer-Tropsch fuels and power production; (2) simultaneous saccharification and fermentation of paper sludge for ethanol production; (3) direct spouted bed gasification with air and steam of woody biomass for power; and (4) direct combustion of woody biomass for power production.

Bai et al. 2012 The rapid expansion of the biofuel industry diverts a large amount of agricultural crops as energy feedstocks and, in turn, affects farm land allocation, feedstock market equilibrium and agricultural economic development in local areas. In this paper, a game-theoretic model is proposed in order to incorporate farmers' decisions on land use and market choice into the biofuel manufacturers' supply chain design problem. The models determine the optimal number and locations of bio-refineries, the required prices for these refineries to compete for feedstock resources, as well as farmers' land use choices between food and energy.

Bowling et al. 2011 This paper presents a systematic approach for the optimal production planning and facility placement of a bio-refinery. A structural representation is first developed to include sources of biomass feedstock, distributed pre-processing hubs and centralized processing facilities to produce desired products and by-products. An optimisation formulation is developed to determine the optimal supply chain, size, operational strategies, and location of the bio-refinery and pre-processing hub facilities. The model considers the optimal selection of different configurations considering the specific location configuration (centralized and/or distributed), selection of biomass and processing facilities to determine the maximum profit.

Corsano et al. 2011 A MINLP optimisation model for a sustainable design and corresponding analysis of sugar/ethanol supply chains on the basis that bioethanol is one of the most appropriate solutions for short term gasoline substitution. A detailed model for ethanol plant design is embedded in the supply chain model and therefore plant and supply chain designs are simultaneously obtained. The simultaneous optimisation of these elements allows the evaluation of several compromises among design and process variables.

Kim et al. 2011 This paper presents a model for the optimal design of biomass supply chain networks under uncertainty with the aim of producing bio-fuels. The supply chain network covers the south-eastern region of the United States and includes biomass supply locations and amounts, sites and capacities for two kinds of fuel conversion processing, and the logistics of transportation from the locations of forestry resources to the conversion sites and then to the final markets. The problem is exposed to a high level of uncertainty originating in supply amounts, market demands, market prices, and processing technologies.

Natarajan et al. 2012 Two gasification-based biomass conversion technologies, methanol and combined heat and power (CHP) production, are assessed for commercialization in this study. Spatial information on forest resources, sawmill residues, existing biomass-based industries, energy demand regions, possible plant locations, and a transport network of Eastern Finland is fed into a geographically explicit Mixed Integer Programming model to minimise the costs of the entire supply chain. The model generates a solution by determining the optimal number, locations, and technology mix of bioenergy production plants. Scenarios were created with a focus on biomass and energy demand, plant characteristics, and cost variations.

Paulo et al. 2015 The present study analyses the design of the distribution network of residual forestry biomass with the aim of producing bioelectricity in the Portuguese context. A mixed integer linear programming (MILP) model is developed and applied in order to optimize the design and planning of the bioenergy supply chain. While minimizing the total supply chain cost a series of energy production facilities with a given capacity and location is defined. The model also includes the optimal selection of biomass potentials, the transportation modes and links that must be established for biomass transportation and products delivers to markets.

Schmidt et al. 2010 This article presents a spatial explicit optimisation model that assesses new biomass conversion technologies for fuel, heat and power production and compares them with woody pellets for heat production in Austria. Biomass integrated gas combined cycle plants (BIGCC) as well as ethanol and methanol production based on woody biomass feedstock are considered. The spatial distributions of biomass supply and energy demand are included in the modelling process. Many model parameters that describe new bioenergy technologies are uncertain, because some of the technologies are not commercially developed yet. Monte-Carlo simulations are used to analyse model parameter uncertainty.

Walther et al. 2012 A multi-period MIP-model is presented to identify an integrated location, capacity and technology planning as well as the design of production networks for second generation synthetic bio-diesel with a view to making an important contribution to sustainable mobility. The approach is applied to the region of Niedersachsen, Germany. Network configurations are developed for this region considering different scenarios and different risk attitudes of interest groups.

You et al. 2012 This paper addresses the optimal design and planning of biomass-to-liquids (BTL) supply chains under economic and environmental criteria. The supply chain consists of multisite distributed-centralized BTL processing networks. The economic objective is measured by the total annualized cost, and the measure of environmental performance is the life cycle greenhouse gas emissions. A bi-criterion, multi-period, mixed-integer linear programming model is proposed that takes into account diverse conversion pathways and technologies, feedstock seasonality, biomass degradation and government incentives. The model simultaneously predicts the optimal network design, facility location, technology selection, capital investment and production planning. The proposed approach is illustrated through a county-level case study for the state of Iowa.

Yue et al. 2014 A multi-objective optimisation model for the sustainable design and operation of bioelectricity supply chain networks is proposed for the analysis of their economic, environmental and social impacts. The proposed model covers the cradle-to-gate life cycle of bioelectricity including biomass cultivation and harvesting, feedstock pre-treatment, energy conversion and bio-power generation as well as transportation and storage. The problem is formulated as a multi-objective mixed-integer linear fractional programming (MILFP) problem. The geographical dispersion and seasonality of biomass supply are captured and handled by the spatial and multi-period features of the model.

Zhang et al. 2011 This study introduces a two-stage methodology to identify the best location for biofuel production based on multiple attributes. Stage I uses a Geographic Information System approach to identify feasible biofuel facility locations. The approach employs county boundaries, a county-based pulpwood distribution, a population census, city and village distributions, and railroad and state/federal road transportation networks. In Stage II, the preferred location is selected using a total transportation cost model. The methodology is applied to the Upper Peninsula of Michigan to locate a biofuel production facility supplied with woody biomass.

In virtue of the complete list of research studies included in following Table 5.1, it can be concluded that no study deals with the most important topics addressed in this dissertation. In general, these contributions are research studies that also analyse regions although, in some cases, without subdividing them into smaller spatial units such as districts or communities. Other times, they only deal with the modelling of a single supply chain independently of the interaction with other utilisation pathways within the same region. Moreover, the studies found do not only refer to electricity production but also to the production of heat, biofuel or even biochemical products. In any case, all the studies report on the identification of the spatial location of bioenergy power plants.

Specifically, aspects such as the modelling of the different types of wood resources as well as their corresponding logistic chains are not dealt with in the reported studies. In relation to conversion technologies, these studies do not go into depth on the type of conversion process for the specific case of electricity production. In this sense, both combustion or gasification techniques are used without generally entering into a techno-economic comparison analysis between both technologies. On the other hand, remunerations are not modelled through a restriction like the one previously proposed on the basis of the principle of profitability. In contrast, such remunerations are exclusively considered in the sum of revenues in order to calculate benefits. Summarising, no studies were found in line with the aspects that are intended by this work. Thus, it can be asserted that this literature review is only relevant for analysing the methodological approach employed in the construction of the model.

5.2.2. Methodological approaches to the optimisation of value chains

Hereunder, Table 5.1 compiles the set of the identified publications that focus on the optimisation of specific bioenergy value chains. They are equally selected from among a number of studies found in academic databases and journals. In this regard, each study is characterised on the basis of certain model features that relate to the chosen mathematical modelling approach, the consideration or not of spatial and/or temporal description as well as the utilisation of wood residues as a biogenic resource.

Table 5.1: Methodological characterisation of the selected research studies

Model characteristics	**Simulation**	**LP**	**MILP**	**NLP**	**Heuristics**	**Stochastic**	**Multi-period**	**Location allocation**	**Wood residues**
Aksoy et al. 2011			X					X	X
Bai et al. 2012				X				X	
Bowling et al. 2011			X						
Caputo et al. 2005	X								X
Celli et al. 2008					X				
Corsano et al. 2011				X				X	
De Mol et al. 1997	X		X					X	X
Frombo et al. 2009		X							X
Frombo et al. 2009b			X					X	
Gómez et al. 2010	X								X
Hamelink et al. 2005	X								X
Kim et al. 2011			X			X		X	X
König 2009		X					X		X
Leduc et al. 2008			X					X	
Morrow et al. 2006		X						X	
Natarajan et al. 2012			X					X	X
Panichelli et al. 2008		X						X	X
Paulo et al. 2015			X					X	
Perpiñá et al. 2009		X						X	X
Poudel et al. 2016				X				X	
Reche et al. 2008					X				X
Schmidt et al. 2010	X		X			X		X	X
Schwaderer 2012			X					X	X
Sokhansanj et al. 2006	X								X
Tatsiopoulos et al. 2003		X					X	X	
You et al. 2012			X				X	X	X
Yue et al. 2014			X				X	X	X
Zhang et al. 2011		X						X	X
Walther et al. 2012			X				X	X	X
Parrilla 2018			X					X	X

Regarding the mathematical modelling approach, some studies refer to simulation models that allow reproducing the resource flow distribution by also considering the expenses incurred through the processes of the targeted value chain. In contrast, a major amount of publications involves programming models including a series of equation systems, constraints as well as an objective function (total system costs or profits) that must eventually be optimised. Among the employed types of programming approach, the linear programming (LP) and the mixed integer linear programming (MILP) are the most frequently implemented techniques. Whereas the former is usually used for the analysis of supply chains feeding into predefined conversion units, the latter is rather oriented towards the description of process units deployed across the studied area by introducing discrete variables for quantifying the number of such units. Additionally, a few studies, which are dedicated to the production of biofuels, also apply the nonlinear programming (NLP) method. This approach aims at either nonlinearly modelling some reactions such as those of fermentation [Corsano et al. 2011] or solving certain equation systems including the nonlinear functions *argmax*/*argmin* (arguments of the maxima/minima) for finding the most optimal site of given processes (see [Bai et al. 2012] and [Poudel et al. 2016]).

By contrast, a few research studies also tackle the optimisation of bioenergy systems by implementing approximation methods such as heuristics. These are capable of finding near optimum solutions for quite complex problems in short periods of time [Ghaderi et al. 2016]. In this regard, both publications introducing heuristic approaches in the list of representative studies of Table 5.1 address the optimisation problem by means of genetic algorithms (GA) and particle swarm optimisation (PSO) techniques. Whereas genetic algorithms are based on the laws of natural selection for achieving the best solution, the PSO methodology imitates the social behaviour of certain organisms while trying to improve a candidate solution [Kennedy et al. 1995].

A further aspect that may be applied to programming models and that is employed in some of the selected studies is stochasticity. Contrary to a classical deterministic approach, a stochastic treatment of a bioenergy system allows the impact derived from uncertainty of input data to be minimised. Nevertheless, few research studies apply stochastic analysis for appropriately modelling certain magnitudes such as the potentials and costs of biomass, the parameters describing the diverse technologies as well as the energy market demands or the prices of final energy carriers. In relation to this, a considerably higher use of the stochastic approach is carried out by those analyses dealing with the optimisation of single supply chains, where no spatial determination of processes involved is required.

Additionally, a decisive aspect involving the description of bioenergy systems is the inclusion or not of the spatial and temporal dimension. Whereas the chronological evolution of any energy system is easily addressed by means of a multi-period approach where years and/or seasons may be contemplated, the exploration of the spatial dimension for finding the optimal location of any process involved will imply further analysis. On the one hand, the infinite number of possible sites for a given process within a region supposes a significant hindrance that must be overcome via its reduction to a limited but high enough amount of divisions or basic units. The introduction of these units, which are designated as districts [Fleischmann et al. 1988], gives rise to the well-known districting problem that is characterised by assigning a specific node to each district. According to [Laporte et al. 2015], two solution approaches can be identified for this problem, namely the utilisation of a mathematical programming model and the use of heuristics. Whereas the latter encompasses algorithms for the determination of the shortest path between the nodes of a graph (e.g. Dijkstra algorithm for GIS-based analysis [Höhn et al. 2014]), the mathematical modelling approach introduces the more frequently employed location allocation methods as well as the set partitioning procedures[23] [Laporte et al. 2015]. The use of heuristics for solving the districting problem is applied to territory planning problems in some studies such as [Minciardi et al. 1981], [Chou et al. 2006] and [Bender et al. 2016] beyond the optimisation of energy systems [Bergey et al. 2002]. As observed in Table 5.1, this technique is not widely used in studies that focus on finding an optimal location for the processes involved in a bio-based utilisation pathway.

5.2.3. Methodological approaches to the modelling of remunerations

A number of support policies for the development and promotion of renewable energies can be considered. Among others, a first category can be identified, which comprises price-based support instruments such as feed-in tariffs (FIT) and feed-in premiums (FIP). Accordingly, governments regulate electricity prices while the market decides on the quantity of produced electricity [Ragwitz et al. 2011]. A second group relates to quantity-based support policies such as quota obligations with tradable green certificates (TGC) and tendering schemes. These mechanisms leave it up to the market to decide the level of electricity price whereas governments fix the permitted amount of electricity production – the quotas [Ragwitz et al. 2011]. The price-based instruments FIT and FIP as well as the quantity-based procedures consisting in TGC and auctions must necessarily be taken into account in the context of the optimisation of energy systems in order to ensure profitability of energy generation processes. These support schemes can be either endogenously or exogenously integrated into the energy system models. Whereas an endogenous approach allows modelling such mechanisms by introducing tariffs, premiums as well as certificate prices or those remunerations originating from auctions as negative costs in the objective function of the model, an exogenous procedure permits the minimum volume of FIT and FIP schemes as well as the quota obligations based on TGC or tenders to be reproduced in a simple manner by means of targeted constraints. Thereby, tariffs and premiums in price-based support policies (FIT, FIP) as well as quotas in quantity-based schemes (TGC, tenders) can be appropriately reproduced because such magnitudes are fixed by governments. But undefined amounts such as the resulting volume in price-based mechanisms (FIT, FIP) or those prices arising by virtue of the implementation of quantity-based instruments (TGC, tenders) can equally be modelled by treating such uncertainty via scenario-based analyses. At any rate, the use of an exogenous

[23] Set partitioning methods can be employed to generate suitable candidate districts by means of a heuristic. Subsequently, adequate districts are selected from the set of proposed candidates [Laporte et al. 2015].

approach for modelling the resultant volumes of renewable energies in the framework of an energy system analysis is not in general a complicated task. Conversely, the endogenous procedure proposed for describing prices as negative costs is more complex but not extremely difficult either. However, this technique could equally be substituted with a more advanced exogenous methodology by introducing a mathematical constraint according to which the sum of costs incurred throughout the whole electricity production chain is restricted by the corresponding electricity price or granted remuneration. The introduction of this restriction in an energy system model is the great challenge to overcome within this dissertation so as to identify the most cost-efficient processes and discard the others due to their comparatively higher production costs or lower granted remunerations.

There have been several attempts to model the previously introduced price- and quantity-based support instruments on the basis of endogenous or exogenous approaches. However, this is not a widespread area of research, which results in a scarce list of encountered studies addressing such topic. Hereunder, a literature review is presented with the following studies as the most relevant contributions to this subject.

Huber et al. 2007 This paper carries out an economic analysis of renewable energy price support mechanisms in the Irish electricity generation sector. The focus is set on the assessment of the effect of quota obligations, feed-in tariffs and competitive tender schemes on the Irish energy system. The Green-X model is implemented in order to identify the potential and costs of renewable energies in Ireland until 2020 by exogenously modelling not only the quotas of the quantity-based support instruments but also the minimum volume of FIT.

Rosen 2008 An endogenous approach for modelling FIT with the PERSEUS model is integrated into the energy system model of EU-15 by introducing tariffs as negative variable cost. It carries out the subtraction of FIT as negative costs endogenously within the objective function but this is only applied to renewables and not to conventional energy sources, which is not completely correct. Anyhow, this technique is more adequate for renewable energy sources other than biomass, as bioenergy in contrast to the rest of renewables includes fuel costs that may jeopardise its overall cost-effectiveness.

Shin et al. 2012 This paper models the electricity system in Malaysia with a mixed integer linear programming (MILP) approach in GAMS. They minimise total system costs whilst satisfying electricity demand and CO_2 reduction targets. They consider renewable electricity generation technologies where FIT are endogenously modelled as negative variable costs relating to each unit (kWh) of electricity generation. The authors do not reflect on the robustness of this approach. As in the case of [Rosen 2008], the subtraction of electricity prices in the objective function is exclusively carried out for energy renewables (including bioenergy) while costs related to conventional sources remain incorrectly unchanged.

Götz et al. 2012 This author has made probably the most significant contribution to the problem of modelling FIT in energy system models in their work with the TIMES model generator. They endogenously model FIT and electricity retail prices as negative costs associated with specific capacities of renewable and conventional energy processes, while they report on the exogenous modelling of quantity-based support schemes such as tradable green certificates and tendering procedures. As a result, the effects of such support instruments on both the payment (tariffs) and the demand side (surcharge included in electricity prices) are assessed. The authors have to convert tariffs into capacity-specific remunerations that involve converting FIT in ct/kWh into capacity payments in ct/kW by using fixed full load hours. Through surcharges on electricity prices, which vary according to the sector, the reapportionment of the FIT payments can be accounted for. According to [Götz et al. 2012], in certain energy system analyses conducted by [UBA 2009] and [IER et al. 2010], the effects of feed-in tariffs on the development of the German energy system were taken into account in a simple way by exogenously setting minimum volumes for the electricity produced from the different types of renewable energies by means of appropriate constraints.

5.2.3.1. The unsuitability of implementing the endogenous approach

[Rosen 2008] and [Shin et al. 2012] apply the referenced endogenous approach exclusively to those remunerations granted to renewable energies. Thus, the rest of the processes based on conventional energy sources show the full amount of costs occurring throughout their corresponding utilisation pathways. Under these circumstances and when minimising the corresponding objective function, the optimising energy system model will select the renewable energy processes showing artificially lower costs than their competing conventional energy producers. But this effect is unrealistic as the costs assigned to a renewable energy-based utilisation pathway are in general higher than those of mature conventional technologies. As a result, it becomes apparent that the same methodology should be performed for the conventional energy producers by subtracting remunerations as negative costs from the incurred expenses in the objective function of the energy system model. On the contrary, [Götz et al. 2012] appropriately applies such a technique to all energy generations processes regardless of the type of energy carrier.

Prices or remunerations arise at almost any stage of every utilisation pathway within an energy system. In consequence, there may be more than one agent receiving remunerations throughout the entire utilisation pathway of a power plant: namely the fuel producer, the fuel transporter, the fuel processor or the grid operator. Shortly, as many stages as the whole supply chain possesses from the source up to the final consumer where remunerations arise in exchange for a new energy product. Therefore, the systematic subtraction of remunerations from the costs incurred in each of these stages within the objective function might also be a possible procedure that would be in line with the endogenous approach based on negative costs. Actually, [Götz et al. 2012] implements this methodology in the energy system analysis for both the tariff and the price interfaces thus harmonising and correcting the original method employed by [Rosen 2008] and [Shin et al. 2012]. However, this is not a correct solution for the intended cost minimisation analysis although it is more realistic than only applying such a technique to a single interface between e.g. plant and grid operator or grid operator and end consumer. In this connection, the minimisation of a function consisting in the sum of costs incurred within each stage minus the remunerations received from each of the next downstream agents would actually serve as a sort of profit maximisation unlike the originally proposed cost minimisation analysis. Thereby, the aim of [Götz et al. 2012] is to determine the most economic energy generation pathways although it ends up yielding the most profitable outcome for the targeted energy system. By means of such endogenous technique, quite expensive energy generation processes that may be assigned accordingly high remunerations could be incorrectly selected by the optimising energy system model as part of the most profitable but not the most cost-efficient solution.

When remunerations granted to plant operators are deducted from costs within an objective function, the whole sum of costs arising at the power plant and in its supply chain throughout the upstream stages together with the sum of respective benefits obtained by each stage are equally removed if remunerations are higher than the entire amount of costs and upstream benefits. In the case that remunerations are lower than such sum of costs and benefits, the profitability of the processes involved is not assured. As a result, such processes cannot be selected by the model as they are not profitable for the respective plant operators. This translates to the fact that the endogenous approach does not give rise anymore to a profit maximisation but results in an erroneous outcome that must be avoided by identifying such lack of profitability in advance. In this regard, it must also be avoided that profitable utilisation pathways might offset other non-profitable ones, even though the minimised objective function might give a negative value as indication of being a good profit maximisation. When profitability is satisfied by means of high enough remunerations, the remaining quantity after the subtraction of remunerations from the corresponding sum of costs and benefits for each plant operator and its supply chain is a negative amount corresponding to the profit achieved by each plant operator with a negative sign. As previously indicated, the minimisation of such a negative magnitude is nothing more than a profit maximisation like that implemented by [Götz et al. 2012].

In virtue of the foregoing, such a composed objective function expressed as the total system costs plus certain – depending on the chosen method not all – remunerations implemented as negative costs unfortunately leads to either an unusable magnitude – if the endogenous approach is only allowed for renewable energies – or the identification of the maximum profit for the total system – when such methodology is exclusively applied to all interfaces provided that profitability of the processes involved is guaranteed. Both outcomes differ from the initially intended minimisation of the objective function originally expressed as the sum of total expenses. For this reason, the endogenous approach introduced by the negative costs methodology fails to minimise the total system costs and cannot be considered as a suitable procedure for reducing expenditures. In addition to this, if the sum of costs incurred in a utilisation pathway becomes considerably high, it might end up being higher than its remunerations. Given that situation, the power plant in question would anyhow be installed and operated despite the lack of profitability. In order to overcome this issue, the profitability of utilisation pathways within an energy system has to be guaranteed even if it does not really need to be maximised so as to maintain the goal of reducing expenses. Therefore, profitability has to be preserved but not via a profit maximisation or as a result of applying such endogenous approach. To attain that objective, an exogenous methodology in the form of a simple constraint outside the objective function will ensure profitability while simultaneously generating the most cost-efficient solution.

5.3. Fundamentals

5.3.1. The PERSEUS model

PERSEUS is an energy and material flow model that stands for Program Package for Emission Reduction Strategies in Energy Use and Supply. It was developed in the nineties at the Institute of Industrial Production (IIP) of the Karlsruhe Institute of Technology (KIT) on the basis of the EFOM[24] model ([Eßer-Frey 2012], [Kunze 2015]). A family of different PERSEUS models for diverse fields of application (power plant expansion planning, environmental policy support, energy markets) has been developed since then trying to solve different research questions in relation to building energy systems. In this respect, PERSEUS has proved to be a successful optimisation model employed in many research projects carried out in recent decades. These models are based on a techno-economic approach that optimises the future expansion of a given energy system at different spatial aggregation levels (regional, national, European). In this regard, the basic energy and material flow model PERSEUS includes two essential aspects that permit analysing such an energy system: the energy and material balancing and the temporal expansion planning via further unit commissioning. The former ensures that the energy inflows and outflows are appropriately traded off at the different processes or nodes within the whole energy system. Regarding the latter, the model enables identifying to what extent a given energy system can be extended in the coming years for meeting new energy demand requirements.

The PERSEUS model minimises the total expenditures of a given energy system for an exogenously determined energy demand throughout a time frame of multi-periods constituted of several years. The objective function contains the sum of the whole expenditures of the entire energy system, discounted to the base year and calculated from the viewpoint of the whole system. Together with the minimisation of the objective function, a number of techno-economic and environmental constraints have to be satisfied.

The model is made up of an equation system containing significant variables such as the process level *PL*, the flow level *FL* connecting all different processes and the capacities of the

[24] EFOM [Finon 1974] stands for Energy Flow Optimisation Model and was developed in the early seventies at the Institute Economique et Juridique de l'Energie in Grenoble (France) to support the decision making process in the area of energy policy [Eßer-Frey 2012]. A further improvement of this model led to the EFOM-ENV model (Energy Flow Optimisation Model–Environmental), which was carried out in Belgium for the European Commission in the mid-nineties in order to address the new challenges derived from environmental burdens [Krzemien 2013].

conversion plants. This equation system encompasses energy and material balance equations along with inequations introducing capacity, resource and demand-related restrictions. These capacity constraints permit the commissioning, decommissioning as well as the repowering of existing power plants in any determined period of time to be modelled. This mathematical construct can be complemented with further restrictions or auxiliary conditions in line with new energy or environmental policy-related framework conditions. This energy system model includes an energy demand to be satisfied by means of conversion of several resources into different energy carriers. For that purpose, diverse conversion technologies are implemented via processes that are inserted within the structure of the system for energy generation.

The optimisation algorithm employed in the group of PERSEUS models is usually the linear programming (LP) as well as the mixed-integer linear programming (MILP) approach, even though other algorithms are also available depending on the kind of solver. The PERSEUS model is implemented in GAMS (General Algebraic Modelling System) to solve large mathematical optimisation problems by means of diverse solvers.

5.3.1.1. Temporal dimension

It is worth noting the relevance of the temporal dimension in the PERSEUS model. The temporal differentiation of any energy system is described by a multi-period approach. Accordingly, the optimising energy system model is arranged in such a way that the time frame is limited to a maximum time span of sixty years, albeit it can be expanded so long as needed. Thereby, all processes of an energy system can be described for each period of time $t \in PER$ in which their activity occurs or is planned to take place. These periods are in turn constituted by a number of time slots, where the power demand is specifically defined. Thus, determining the temporal development of a specific process involves describing its techno-economic behaviour in each time slot for any period of the analysed time span. The chronological evolution of a technological process ranges from the time in which it is brought into operation through to the end of its economic lifetime. Besides, new processes equipped with upgraded and more mature technologies can additionally be integrated into the system as of a certain time after the base year. Likewise, the inputs or potentials of energy resources as well as the power demands of a specific energy system can be modelled on the basis of their temporal evolution so as to include possible variations induced by future energy/environment policies as a consequence of e.g. the effects of climate change. As a result, knowing the time progression of all aforementioned issues enables making projections of a given energy system for a certain space of time.

5.3.1.2. Data structure

Any energy system modelled with PERSEUS is characterised by a structure representing a digraph (directed graph), where the vertices or nodes are constituents making up the whole network [Eßer-Frey 2012]. The edges of each digraph as well as the entire network represent energy flows established between the different processes of the system. Besides this graph nature, a hierarchical data structure constituted of sectors, producers, units and processes is defined according to the corresponding four aggregation levels (see Figure 5.1) [Frank 2003].

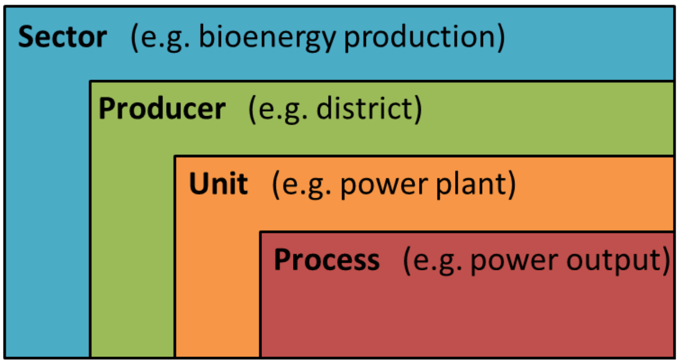


Figure 5.1: Hierarchical data structure of the PERSEUS model

The sectors $sec \in SEC$ are the top aggregation level and serve to shape the data structure by grouping the producers. Each producer $prod \in PROD$ is allocated to a unique sector and represents a node within the network of digraphs. In this context, producers are connected to one another through energy and material flows FL (edges of the directed graph). These flow levels FL transport a range of energy carriers $ec \in EC$ thus forming the entire network of the system. At the level of the units $unit \in UNIT$, energy and material conversion technologies are implemented by means of assigning a whole scale or total capacity to the corresponding unit. In this way, units may involve several different processes $p \in PROC$ with diverse technologies. These processes form the lowest hierarchical level and contain all techno-economic and environmental parameters characterising each technology. In this manner, a unit consisting of various processes allows consuming and generating different energy carriers $ec \in EC$ at different periods of time as well as at different costs.

In the definition of the hierarchy, a convention is used according to which each subordinate element must be assigned to one superordinate one, so that each process must exactly be assigned to one unit, each unit exactly one producer, and each producer exactly one sector. Conversely, an element of a given aggregation level can contain an arbitrary number of elements of the immediately subordinate level [Frank 2003].

5.3.2. Selection of the suitable modelling approach

The choice of a suitable modelling approach enables ensuring that an optimal solution within the entire feasible region of the intended problem can be found. For this purpose, certain considerations about the model design are to be made, concretely in relation to the linearity of the model – i.e. whether the problem is linear or non-linear. Whereas the equation system of the PERSEUS model presents a linear behaviour, any further complementing constraint might impose a non-linear relationship between variables. A first attempt was made when reproducing the intended bioenergy system by means of non-linear structures. But this task was considerably difficult to cope with although most decision variables were implemented by means of real variables. In this regard, [Kunze 2015] reports that non-linear problems even implemented with real variables may become rather difficult to be solved due to extremely high computing times that might lead to a non-convergence of the model.

The decision variables describing the energy system can be implemented on the basis of either a discrete or continuous modelling approach depending on whether certain magnitudes are respectively defined as integer or just as real decision variables. The former option implies the difficulty of giving rise to an increase in the model size as compared to the latter. The reason for this is that a single mixed integer problem (MILP) can generate several linear programming (LP) sub-problems that may be very compute intensive and thus require significant amounts of physical memory (RAM) [GAMS-CPLEX]. From all existing decision variables available in the PERSEUS model, only the magnitude representing the installation of new power plants must be discretely modelled by means of an integer variable. The required capacity expansion planning involves the erection of new units on the basis of an integer variable *Com* that indicates the amount of facilities to be commissioned in each period of time. Thereby, this magnitude must be necessarily modelled according to a discrete approach with the assistance of appropriate integer variables.

As a result, the inclusion of integer variables into the linear equations of the model requires the use of a specific optimisation technique based on a mixed-integer linear programming (MILP) approach. The PERSEUS model incorporates the CPLEX solver on the basis of the simplex algorithm for solving linear programming problems. This solver may also implement both the branch-and-bound and branch-and-cut procedures to solve problems with integer variables. The former approach performs a branching and bounding process consisting in partitioning the entire set of feasible solutions into smaller and smaller subsets and subsequently estimating how good the best solution in these subsets can be by discarding unsuitable bounds obtained from LP relaxations as possible optimal solutions [Hillier et al. 2015]. Whereas this method permits relatively small problems to be solved, many important problems of higher dimension could not be resolved until a new algorithm based on the branch-and-cut approach enabled big problems with thousands or even hundreds of thousands of variables to be solved [Hillier et al. 2015]. This technique generates cutting planes that introduce new constraints into the original problem with the aim of reducing the feasible region for the LP relaxation and thus accelerating the search process [Hillier et al. 2015]. For both approaches, the simplex algorithm looks for a solution for the LP relaxation by disregarding integer constraints until a final solution is found that fully satisfies the integer constraints [GAMS-CPLEX]. On the other hand, the quality of the mixed integer solution obtained with a branch-and-bound or a branch-and-cut algorithm can be inferred by determining the deviation of the integer solution from the optimal solution for the LP relaxation through the Relative Optimality Criterion (OPTCR).

5.4. Methodological development of the BIOSPHERE model

Leveraging the existing structures of the PERSEUS model, a new and more advanced tool can be constructed in order to techno-economically reproduce and analyse not only the wood resources-based bioenergy system of Baden-Württemberg but also any possible bio-based subsystem of the total energy system of a particular region. The outcome is the BIOSPHERE model (Bioenergy Optimisation Software for Production Pathways at High Energy and Resource Efficiency), which is based on a multi-period mixed integer linear programming (MILP) approach. The model includes an objective function and an array of auxiliary conditions derived from the PERSEUS model. These conditions involve the issue of energy and material flow balance as well as a number of restrictions on capacity and process utilisation. Besides, a further set of constraints relating to the previously introduced principle of profitability for discrete investments is developed as a significant methodological advance. BIOSPHERE performs an optimisation of the value chain of a specific biomass resource for bioenergy generation in a certain geographic area by minimising the total subsystem expenditures incurred over a determined period of time. The resulting model is a bottom-up approach conceived as an energy and material flow model as its precursor PERSEUS, which is equally coupled to a basis of endogenously and exogenously given input data.

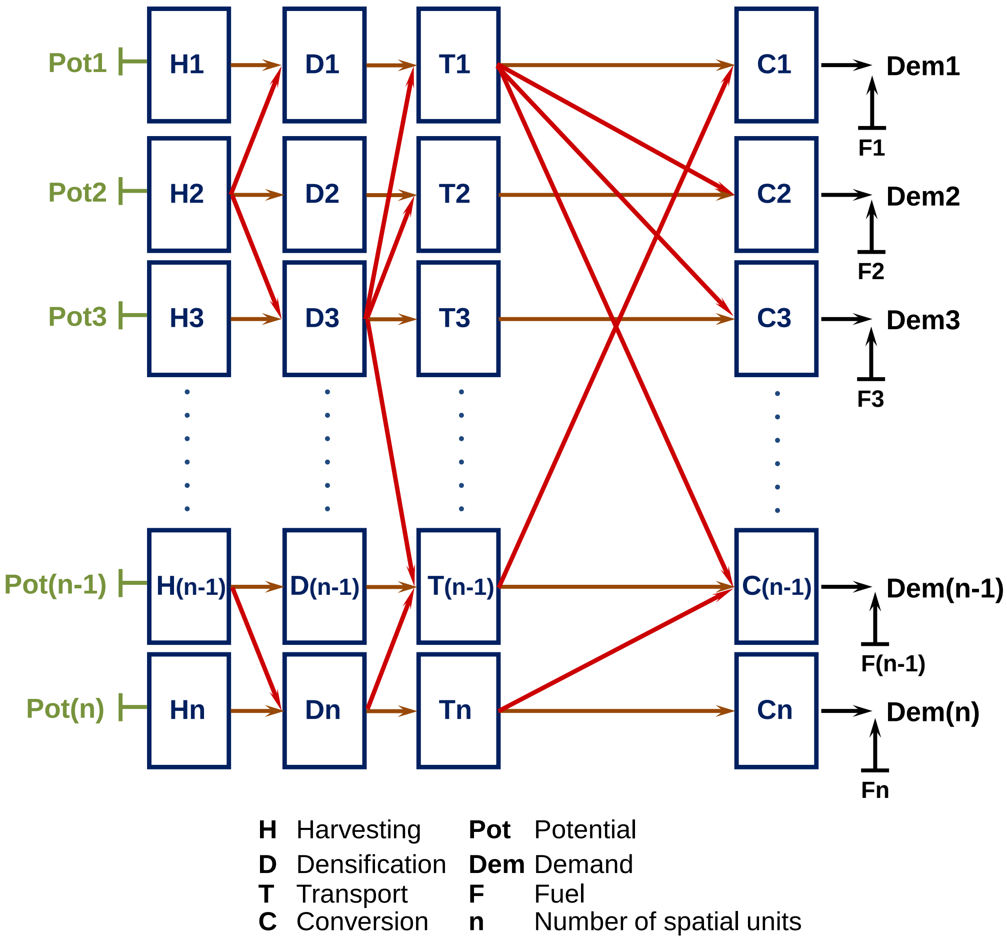


Figure 5.2: Structure of the BIOSPHERE model as a grid of producers connected by energy flows for a bioenergy system composed of n spatial units

Any value chain of a specific biomass resource may encompass a multiplicity of utilisation pathways consisting of a series of four consecutive stages corresponding to harvesting, densification, transport and conversion technologies. All competing utilisation pathways are described by any possible combination of four succeeding technological processes, which exhibit a specific capacity while being located within a certain spatial unit and defined for a given time frame. Based on the hierarchical data structure of PERSEUS (see Figure 5.1) – which is also employed for modelling with BIOSPHERE –, these four processes in all their technological diversity are consecutively contained in four producers, which in turn are arranged into four main sectors. In general, each bioenergy system consists of four technology sectors (harvesting *H*, densification *D*, transport *T* and conversion *C*) extending over a number *n* of spatial units or regional subdivisions $reg \in REG$. As a result, the graph structure of a bio-based subsystem can be represented by a composition of four columns and *n* rows resulting in an array encompassing *4n* producers linked to each other by energy flows as showed in Figure 5.2. In virtue of this structure, data characterising all possible bio-based utilisation pathways can be compiled into a database under the premise that such pathways compete with each other to become the most cost-efficient.

In the same way as the four technological processes, both the potential of biomass and the bioenergy demand of the bio-based subsystem are spatially and temporally differentiated over the targeted territory. Whereas the potentials of biomass are freely consumed, the bioenergy demand – behaving as a driving force for the model – has to be met by covering the full energy consumption of each spatial unit. Fulfilling this condition implies that in addition to bioenergy production an input of non-biogenic fuels *F* (see Figure 5.2) may be provided for satisfying the subsystem's demand in the event that not enough biomass resources might be converted into bioenergy. In this connection, the introduction of such non-biogenic input as a supplement is due to the fact that biomass potentials are limited and therefore they do not necessarily have to entirely cover the bioenergy demands of each spatial unit. The methodological implementation of such non-biogenic fuels unavoidably requires setting their costs greater than those of other competing bio-based utilisation pathways under consideration so that the cheapest bioenergy generation schemes can be chosen by BIOSPHERE. This way, a solution for a particular bioenergy system can be guaranteed, which in turn relates to the most cost-efficient allocation pattern of biomass resources to an array of selected bioenergy sinks spatially distributed across the analysed area.

A major issue that must be taken into account in the construction of BIOSPHERE relates to the integration of the spatial dimension into the existing PERSEUS model. The new optimising energy system model reproduces a series of interconnected technological processes for a broad spectrum of capacities at a given period of time. Therefore, including the spatial dimension entails properly linking the producers comprehending the pertinent technological processes within a spatial unit with those (producers) from the subsequent technology sector within the same or other spatial unit by means of proper flow levels *FL* (see Figure 5.2). In this regard, transport processes from different spatial units are assigned a certain amount of transport costs as a function of the distance between the corresponding regional subdivisions. This creates the necessary effect of spatial dimension in the sense that the higher the transport costs are the longer the distances between the harvesting and the densification processes and those located in the densification and conversion sectors are.

As the geographical area under analysis is divided into spatial units, the solution path is reduced to the analysis of the formerly referenced districting problem, which can be solved by means of a mathematical programming model based on a location allocation procedure (see literature review in section 5.2). This technique is characterised by assigning a node or centroid to each spatial unit of the analysed territory with the aim of reproducing the characteristics of its bioenergy system. According to this approach, certain magnitudes of the different spatial units (e.g. potentials of biomass resources and bioenergy demands) are allocated to a representative point – called centroid or node – situated in certain statistically or geometrically defined coordinates on the surface of the respective spatial unit, which is also designated as “district” [Chou et al. 2006]. Similarly, each of the four consecutive processes constituting a particular utilisation pathway across the four sectors of a bioenergy system – harvesting, densification, transport and conversion– are apportioned to each of the *producers* of Figure 5.2 and hence to their corresponding centroids or nodes acting as sittings within each spatial unit.

On another level, the present methodological development aims at building such a novel model by integrating two significant aspects that are common to every bioenergy subsystem. They basically consist in meeting the principle of profitability for discrete investments in the whole utilisation pathway as well as spatiotemporally estimating the cost components of electricity production costs incurred by a bio-based utilisation pathway – including bioenergy plant and supply chain over the catchment area – in a certain bioenergy subsystem under analysis. The former point relies on a specific methodological approach based on the principle of profitability that involves discretely modelling each individual investment having been separately made by a certain investor for a single utilisation pathway when considered as a whole. To this end, the costs induced in each utilisation pathway have to be assessed separately from those of the remainder in the analysed value chain via implementation of a suitable profitability constraint (see subsection 5.4.2). In this sense, any bioenergy subsystem is analysed from the viewpoint of the investors of each specific utilisation pathway in keeping with the principle of profitability for discrete investments. This approach is completely different from that applied to common energy system analyses (ESA), where the cost assessment is traditionally performed from the standpoint of a general investor for the total energy system by considering the sum of all its expenditures. With regard to the latter issue, the cost components of electricity production costs – whose sum must be lower than or equal to the remunerations according to the principle of profitability – can be spatiotemporally determined through a series of formulas that derive from a number of secondary conditions to be introduced in the following subsection 5.4.2. For this purpose, a set of auxiliary variables denominated *virtual flows* are introduced as support to calculate an array of decision variables relating to the energy and material contributions of all upstream processes of harvesting, densification and transport sectors within the corresponding supply chain to a given bio-based conversion process. Thereby, the costs components indicating the share of EPC attributable to the harvesting, densification, transport and conversion stages of a given utilisation pathway can be individually assessed and correlated to their sum – the EPC – and hence to the profitability constraint itself.

5.4.1. Techno-economic parameters of BIOSPHERE

On the basis of the hierarchical data structure of the PERSEUS model, which is also the data structure of BIOSPHERE, a list of parameters for modelling any bioenergy system is presented in Table 5.2. They permit modelling the processes, units and flows of a given energy system with a high level of detail. In this context, each parameter characterising a process *p*, a unit *u* or a flow level *FL* is defined for every period of time $t \in PER$. On the other hand, the hierarchical data structure of the BIOSPHERE model presents a certain particularity. This consists in the fact that every unit can uniquely contain one process $p \in PROC_u$. This premise is contrary to the rules of PERSEUS, where several processes are allowed to be included.

Some of the parameters included in Table 5.2 are assigned a major role within the framework of the modelling of the system. In this sense, some of them serve as limits to the activity level described by the processes *proc*, the units *unit* and the flow levels defined between two producers *prod*. Regarding the modelling of processes, the range of their activity level is controlled by means of the lower limit for the annual full load hours *FLH_MIN* on the one hand, and the upper limit for the annual full load hours *FLH_MAX*, on the other. Something similar occurs for the description of units, the capacity of which is modelled with the assistance of the lower and upper bound of installed power for each particular unit (i.e. parameters *MIN* and *MAX*). In addition, the activity level established between two specific producers can be exogenously modulated by modifying both parameters concerning the lower and upper limit of the energy and material flow, *FLMIN* and *FLMAX* respectively.

Table 5.2: Techno-economic parameters for the modelling of the processes, units and flows with BIOSPHERE (based on [Frank 2003])

	Parameter	Description
Process	EFFICIENCY	Efficiency of each process as a ratio of output to input (%)
	FLH_MAX	Upper limit for the annual full load hours (h/a)
	FLH_MIN	Lower limit for the annual full load hours (h/a)
	INT_CONS	Own consumption of a process as a share of the process level (%)
	COST_VAR	Specific variable operation and maintenance expenditures of a process (€/kWh)
Unit	AVAILABILITY	Power availability of a unit as a share of the available power at the rated power (%)
	MIN	Lower bound for the installed power of a unit (MW)
	MAX	Upper bound for the installed power of a unit (MW)
	RES	Installed power of a unit prior to the period of analysis (MW)
	LIFE_TEC	Technical life or time period in which a unit is available as of its commissioning (a)
	CAPACITY	Block size of discretely modelled units, only multiples of the block size are allowed (MW)
	CAP_MIN	Share of the total output power that must be provided at the very least (%)
	COST_INV	Specific investment of an energy or material conversion technology of a unit (€/kW)
	COST_FIX	Specific fixed operation and maintenance expenditures of an energy or material conversion technology within a unit (€/kW)
	EC_LIFE	Economic life (depreciation period) i.e. period of time considered for calculating the annuities of an investment in a unit (a)
Flow	F_EFF	Efficiency of an energy or material flow as the ratio of output to input (%)
	FLMAX	Upper limit for the activity level of energy or material flow (PJ)
	FLMIN	Lower limit for the activity level of energy or material flow (PJ)
	CTVAR	Specific variable expenditures of an energy or material flow (€/kWh)

5.4.2. Mathematical description

Based on the data structure and parameters laid down for the PERSEUS model, the mathematical description of the new model BIOSPHERE can be addressed by introducing four decision variables playing a significant role in the modelling of any bioenergy system: namely, the process level *PL*, the amount *Com* of commissioned units, the capacity *Cap* and the flow level between producers or nodes, *FL*. These variables are all equally defined for each period of time $t \in PER$ in a similar manner as in the case of the techno-economic parameters of BIOSPHERE.

The mathematical equation system that describes any bioenergy system is constituted of an objective function representing the sum of the total expenditures of the system. Moreover, this equation system also encompasses an array of techno-economic constraints involving the energy and material flow balancing at grid nodes along with a number of equations for modelling the capacities of units and a series of inequations introducing temporal capacity restrictions as well as constraints on process utilisation. A further restriction is also introduced on the basis of the previously explained principle of profitability, which has to be fulfilled for each specific power plant or investment carried out within each utilisation pathway.

5.4.2.1. Objective function

The optimisation model BIOSPHERE minimises all system expenditures provided that the power demand as an exogenous driver is satisfied in all spatial units of the analysed bioenergy system. For this purpose, an objective function is defined as the sum of the total expenditures (investment costs and variable and fixed operation and maintenance costs) discounted to the base year and calculated from the viewpoint of the whole system.

$$\min \sum_{t} \alpha_t \cdot \begin{bmatrix} \sum\limits_{prod_{exp,ec}} Fuel_{prod_{exp,ec},t} \cdot Cfuel_{prod_{exp,ec},t} + \\ \sum\limits_{i \in H,D,T} PL_{i,t} \cdot Cvar_{i,t} + \\ \sum\limits_{p \in C} PL_{p,t} \cdot Cvar_{p,t} + \\ \sum\limits_{u \in H,D,T,C} \left(Com_{u,t} \cdot CAPACITY_{u,t} \right) \cdot Cinv_{u,t} + \\ \sum\limits_{u \in H,D,T,C} Cap_{u,t} \cdot Cfix_{u,t} \end{bmatrix} \tag{5.1}$$

$t \in PER,\ prod_{exp,ec} \in PROD_{exp,ec},\ i \in SUPPROC,\ p \in GENPROC,\ u \in GENUNIT$

The first summand of Equation 5.1 contains the expenditures associated with the non-biogenic fuels required in the case that no biomass is consumed by bioenergy plants within each spatial unit for the supply of energy demand. These variables *Fuel* concerning non-biogenic resources are the unique flows within the whole system that are contributing to the total expenditures, as the remaining flows defined between nodes or producers are basically assigned neither costs nor efficiencies (i.e. efficiencies are equal to 100%). The second group of addends is made of two terms introducing the variable costs of all processes of the energy system. The first term adds up the variable costs generated by all processes belonging to the sectors of harvesting *H*, densification *D* and transport *T*. These processes produce diverse biogenic resources, which are finally converted into bioenergy by means of generation processes *p*. The second term precisely relates to the variable costs incurred by these generation processes in the sector *C*. Finally, the two remaining summands include the investment or capital costs as well as the fixed expenses generated by all the units $u \in UNIT$ of the bioenergy system. The former summand is expressed as the product of the specific investment costs by the yearly commissioned capacity, which is equal to the multiplication of the parameter *CAPACITY* (see Table 5.2) and the already introduced natural (integer) variable *Com*.

5.4.2.2. Energy and material flow balances

A central aspect in relation to the mathematical description of the model is the array of constraints concerning the balancing of all energy and material flows of the bioenergy system. These flows have to be balanced at each node of the structure of directed graphs (digraphs). As already explained, the nodes represent the different producers $prod \in PROD$ and take an equivalent role to the specific sectors within each spatial unit of the bioenergy system. As a result of balancing flows at each node, the sum of its inflows for every energy carrier must be consistent with its outflows while considering process efficiencies and thereby energy or material losses occurring at flows[25].

Satisfaction of demand

The exogenously determined bioenergy demand of all the spatial units of a bioenergy system constitutes the driver of the BIOSPHERE model. The satisfaction of this demand is assured by integrating a range of auxiliary conditions for each spatial unit. This constraint implies that the energy and material flows for each energy carrier going out from the nodes or producers belonging to the conversion sector *C* are greater than or equal to the bioenergy demand *Dem* registered at each spatial unit. The fulfilment of this restriction, as expressed in Equation 5.2, is accomplished through conversion of biomass into bioenergy, although the use of non-biogenic fuels is also possible, as a last resort, in order to assure model convergence.

$$FL_{prod_{exp,ec},t} + Fuel_{prod_{exp,ec},t} \geq Dem_{prod_{exp,ec},t} \tag{5.2}$$

$$\forall prod_{exp,ec} \in PROD_{exp,ec},\ \forall exp \in EXP,\ \forall ec \in EC,\ \forall t \in PER$$

According to the above constraint, the energy carrier's contributions from any producer *prod* within the conversion sector *C* of each spatial unit to the corresponding export producer *exp* (sink) plus a variable amount of a directly injected energy carrier from non-biogenic origin

[25] The BIOSPHERE model, similarly to PERSEUS, was not devised for considering the case of energy or material storage. However, certain studies like [Rosen 2008], [Eßer-Frey 2012] and [Heffels 2015] model the special case of pumped storage power plants by means of setting their capacities equal to zero throughout the periods of time in which power is stored and hence not generated.

must at least cover the demand for such energy carrier in each spatial unit or region (see Figure 5.2).

Upper bound for biogenic resources

The potentials *Pot* of biogenic resources for each spatial unit are equally exogenously given as in the case of the determination of bioenergy demands *Dem*. The difference between both restrictions is that the consumption of potentials shows a flexible behaviour that permits the biogenic resources to be utilised according to the needs established by the driving force of demand. This suggests that the biogenic resources may be fully consumed or also remain unexploited on the respective generation areas in each period of the modelled time horizon. Equation 5.3 reproduces the inflow of the biogenic potentials in the digraph structure of the analysed bioenergy system for each energy carrier of biogenic nature.

$$Pot_{imp_{prod,ec},t} \geq FL_{imp_{prod,ec},t} \tag{5.3}$$

$$\forall imp_{prod,ec} \in IMP_{prod,ec},\ \forall imp \in IMP,\ \forall ec \in EC,\ \forall t \in PER$$

Balance equations

An array of important mathematical relationships reproducing the physical shape of the bioenergy system is the set of energy and mass flow balances equations. The energy and material balancing is performed in each node (producer) of the digraph structure that represents the bioenergy system. The producer types *imp* and *exp*, which potentials and demands are exogenously allocated to, are equally regulated through the corresponding balance equations. Both Equations 5.4 and 5.5 give insight into the energy and material flow balance for each period of time $t \in PER$. The former equation represents the energy and material flow balance of the sum of flow levels transporting an energy carrier *ec* from all possible upstream producers *prod'* to the specific producer *prod*, where a set of processes $p \in C$ take the amount of *ec* for its conversion into other energy carrier.

$$\sum_{prod'_{prod,ec}} FL_{prod'_{prod,ec},t} = \sum_{p_{prod,ec}} \frac{PL_{p_{prod,ec},t}}{\eta_{p_{prod,ec},t}} \tag{5.4}$$

$$prod'_{prod,ec} \in PROD'_{prod,ec},\ p_{prod,ec} \in P_{prod,ec},\ \forall t \in PER$$

The latter equation takes into account any producer *prod* involving a group of processes $p' \in C$. All these processes generate an activity level for a specific energy carrier *ec*. These levels of activity are equivalent to the sum of a number of flow levels transporting the same energy carrier from *prod* to all possible downstream producers *prod'* at each period of time *t*.

$$\sum_{p'_{prod,ec}} PL_{p'_{prod,ec},t} = \sum_{prod_{prod',ec}} FL_{prod_{prod',ec},t} \tag{5.5}$$

$$prod_{prod',ec} \in PROD_{prod',ec},\ p'_{prod,ec} \in P'_{prod,ec},\ \forall t \in PER$$

The Equations 5.4 and 5.5 can also be applied to any process $i \in H, D, T$ from upstream sectors of C by simply substituting the process p with the process i.

5.4.2.3. Capacity equations

The capacity *Cap* of a unit is one of the decision variables with a major significance when trying to model a bioenergy system. Thereby, the model describes the evolution of all conversion capacities in the modelled time horizon on the basis of a bio-based technology portfolio. This capacity evolution permits the energy system expansion to be reproduced by considering the sum of the residual capacity *RES* plus the contribution of all commissioning and decommissioning processes. These processes are modelled by means of the integer variable *Com* for any bio-based unit at each period of time (see Equation 5.6). The contributions of the second summand of the equation refer to the capacity expansion developed at least since a period of time *t-LIFE_TEC*, where LIFE_TEC is the technical life (see Table 5.2).

$$Cap_{u,t} = RES_{u,t} + \sum_{t'=t-LIFE\_TEC}^{t} Com_{u,t} \cdot CAPACITY_{u,t} \qquad (5.6)$$

$$\forall u \in GENUNIT, \ \forall t \in PER$$

5.4.2.4. Annually installed capacity restriction

Occasionally, diverse restrictions on capacity expansion can be imposed for an entire region in the framework of new energy policy regulations. In this regard, a maximum annual capacity installation may be observed for a list of bioenergy technologies. As a result, such a restriction determines a cap on new installed power generation from biogenic resources. This quantity is usually fixed to a certain amount per year for the whole region. Aiming at adequately modelling a bioenergy system, the most important implications of current and future energy policies concerning limitation of bio-based power generation can be taken into account in order to not exceed the maximum permitted capacities. Therefore, the following Equation 5.7 introduces the annually installed capacity restriction for the energy system of a given territory. The corresponding upper limit for capacity expansion is expressed by an exogenously determined parameter *TotMaxCap*.

$$TotMaxCap_t \geq \sum_u Cap_{u,t} \qquad (5.7)$$

$$\forall u \in GENUNIT, \ \forall t \in PER$$

5.4.2.5. Process utilisation restriction

As referred to in Table 5.2, besides the activity level of flow levels and the capacity of units, the activity level *PL* of processes may also be constrained between a minimum and a maximum bound based on the lower and upper limit of annual full load hours, FLH_MIN and FLH_MAX respectively. Consequently, Equation 5.8 ensures that the bioenergy production of a process $p \in C$ during a period $t \in PER$ does not surpass an availability level determined by the product of the corresponding capacity by the maximum full load hours.

$$Cap_{u,t} \cdot FLH\_MAX_{p_u,t} \geq PL_{p_u,t} \tag{5.8}$$

$$p_u \in GENPROC,\ \forall u \in GENUNIT,\ \forall t \in PER$$

On the other hand, Equation 5.9 analogously makes reference to the determination of the lower bound of a process level $p \in C$. In this regard, the activity level of any bioenergy process within a bio-based unit during a period of time $t \in PER$ shows a lower limit that is defined by the multiplication of the unit's capacity by the minimum full load hours.

$$PL_{p_u,t} \geq Cap_{u,t} \cdot FLH\_MIN_{p_u,t} \tag{5.9}$$

$$p_u \in GENPROC,\ \forall u \in GENUNIT,\ \forall t \in PER$$

5.4.2.6. The profitability constraint

As stated in the first section of this chapter, it is necessary to introduce a new mathematical constraint in the existing optimising model. This restriction is based on the fulfilment of the principle of profitability for each implemented bio-based utilisation pathway when analysed from the viewpoint of the respective investor or plant operator. According to this premise, the sum of the discounted expenditures incurred within any utilisation pathway for a given bioenergy process $p \in C$ must not exceed the discounted remunerations granted for the corresponding investment during its economic life. In this connection, Equation 5.10 mathematically reproduces such a condition of profitability for each utilisation pathway. In the first place, the terms within both sides of the resulting inequation are discounted to the base year and added from the commissioning or investment period until the end of its economic life *EC_LIFE*. The left side of the inequation comprises the sum of the variable and fixed operation expenses as well as the investment costs of the corresponding bioenergy unit u_p together with the same set of expenditures incurred by the upstream units from the sectors of harvesting *H*, densification *D* and transport *T* (supply chain). These upstream units generate material flows that supply to the specific bioenergy unit of the intended utilisation pathway. Thus, every upstream process $i \in SUPPROC_p$ contributing to the bioenergy process *p* belongs to the corresponding units u_i of the sectors *H*, *D* and *T*; while *p* is equally part of every unit u_p in the sector *C*. In such a context, this quantity has to be less than or equal to the sum of remunerations *R* received during the economic life of this bio-based unit (see Equation 5.10).

$$\sum_t \alpha_t \cdot \left(\begin{array}{l} PL_{p,t} \cdot Cvar_{p,t} + \\ \left(Com_{u_p,t} \cdot CAPACITY_{u_p,t}\right) \cdot Cinv_{u_p,t} + \\ Cap_{u_p,t} \cdot Cfix_{u_p,t} + \\ \sum_{i \in H,D,T} PL_{i,p,t} \cdot Cvar_{i,p,t} + \\ \sum_{u_i \in H,D,T} \left(Com_{u_i,t} \cdot CAPACITY_{u_i,t}\right) \cdot Cinv_{u_i,t} + \\ \sum_{u_i \in H,D,T} Cap_{u_i,t} \cdot Cfix_{u_i,t} \end{array} \right) \leq \sum_t \alpha_t \cdot PL_{p,t} \cdot R_{p,t} \qquad (5.10)$$

$\forall p \in C,\ u \in BIOGENUNIT,\ t \in INVPER_u,\ i \in SUPPROC_p$

Besides the bioenergy process level $PL_{p,t}$, the integer number of commissioned bio-based units $Com_{u,t}$ and the corresponding capacity $Cap_{u,t}$, there is a further decision variable $PL_{i,p,t}$, which introduces the energy and material contributions of all upstream processes *i* from the harvesting, densification and transport sectors to a given bio-based conversion process *p* (see Figure 5.3). The determination of the costs of these contributions is of great importance in order to accurately evaluate the total expenditures of the supply chain and thus the profitability of each individual investment in a specific utilisation pathway. The costs incurred in stages before the bioenergy generation are assessed specifically for each upstream process so that only their real contributions are taken into account, while the rest are discarded.

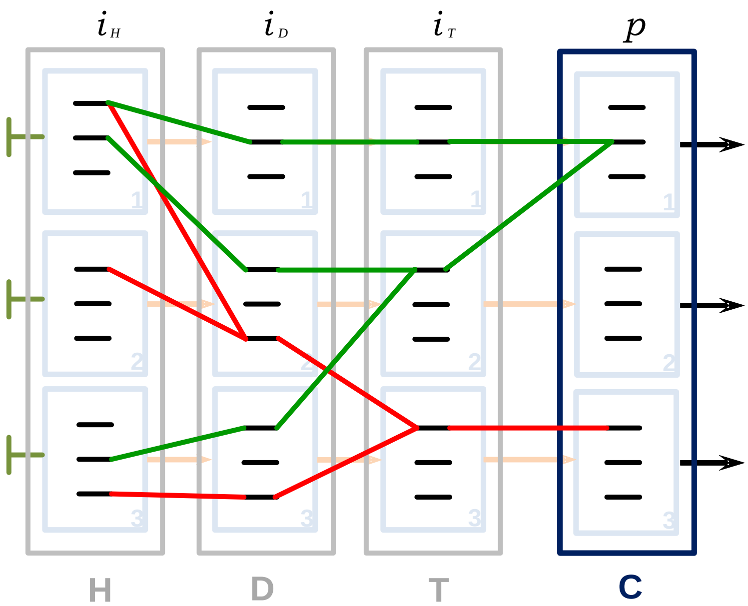


Figure 5.3: Graphic representation of two utilisation pathways (green/red) along with the material and energy contributions of consecutive upstream processes i within the harvesting, densification and transport sectors H, D and *T to two different bioenergy processes p in the conversion sector C*

However, integrating the profitability constraint of Equation 5.10 in the source code of the BIOSPHERE model requires the implementation of a set of auxiliary equations that link the decision variable $PL_{i,p,t}$ with both the process levels *PL* and (indirectly) the flow levels *FL* of the bioenergy system. These auxiliary equations fundamentally originate from three inherent aspects that characterise the analysed system: the sector-based hierarchical data structure, the efficiencies of the processes involved in each of the sectors as well as the predefined energy and material flows structure connecting each pair of producers $prod \in PROD$. In line with this, Equation 5.11 indicates that each upstream process level $PL_{i,t}$ from *H*, *D* and *T* sectors in any spatial unit can be broken down into the sum of all its energy and material contributions $PL_{i,p,t}$ to all bioenergy processes *p* located in the regional subdivisions $reg \in REG$ of the bioenergy system.

$$PL_{i,t} = \sum_{p} PL_{i,p,t} \qquad (5.11)$$

$\forall i \in SUPPROC,\ \forall t \in PER,\ p \in C_i$

Secondly, a triad of equations derived from the hierarchical structure of the bioenergy system as well as the efficiencies correlation between the four sectors *H*, *D*, *T* and *C* is presented. Each equation shows a mathematical interdependence between the sum of all contributions from upstream processes *i* of a given sector to a conversion process *p*, $PL_{i,p}$, and that of total contributions resulting from upstream processes *i* of the subsequent sector to the same conversion process while appropriately dividing the latter sum by their corresponding efficiency. Regarding the conversion sector *C*, no contributions to further sectors are defined for their processes as they serve as sinks of upstream processes originating from previous sectors within the supply chain. Accordingly, these contributions are substituted by the respective process level PL_p. The main idea underlying these equations is to carry out energy and material flow balances between consecutive sectors combined into pairs such as *H-D*, *D-T* and *T-C*. Equations 5.12-14 consequently introduce the resultant mathematical expressions for the targeted bioenergy system.

$$\sum_{i_H} PL_{i_H,p,t} = \sum_{i_D} \frac{PL_{i_D,p,t}}{\eta_{i_D,t}} \qquad (5.12)$$

$i_H \in H_p,\ i_D \in D_p,\ \forall p \in C,\ \forall t \in PER$

$$\sum_{i_D} PL_{i_D,p,t} = \sum_{i_T} \frac{PL_{i_T,p,t}}{\eta_{i_T,t}} \qquad (5.13)$$

$i_D \in D_p,\ i_T \in T_p,\ \forall p \in C,\ \forall t \in PER$

$$\sum_{i_T} PL_{i_T,p,t} = \frac{PL_{p,t}}{\eta_{p,t}} \qquad (5.14)$$

$i_T \in T_p,\ \forall p \in C,\ \forall t \in PER$

On the other hand, relating the contributions $PL_{i,p,t}$ with the flow levels FL between producers of different sectors requires the introduction of a set of auxiliary variables that are denominated virtual flows φ. They stand for the smallest indivisible energy and material flows that sequentially connect four consecutive processes of the respective *H*, *D*, *T* and *C* sectors, in this natural order. Thereby, every system's variable representing the activity level of an energy and material-related magnitude such as the process levels *PL*, the flow levels *FL* or the contributions $PL_{i,p}$ can be described by means of a linear function of the pertinent virtual flows. As an example, Figure 5.4 graphically illustrates the breakdown of contributions $PL_{i,p}$ – previously presented in Figure 5.3 – into the corresponding virtual flows φ.

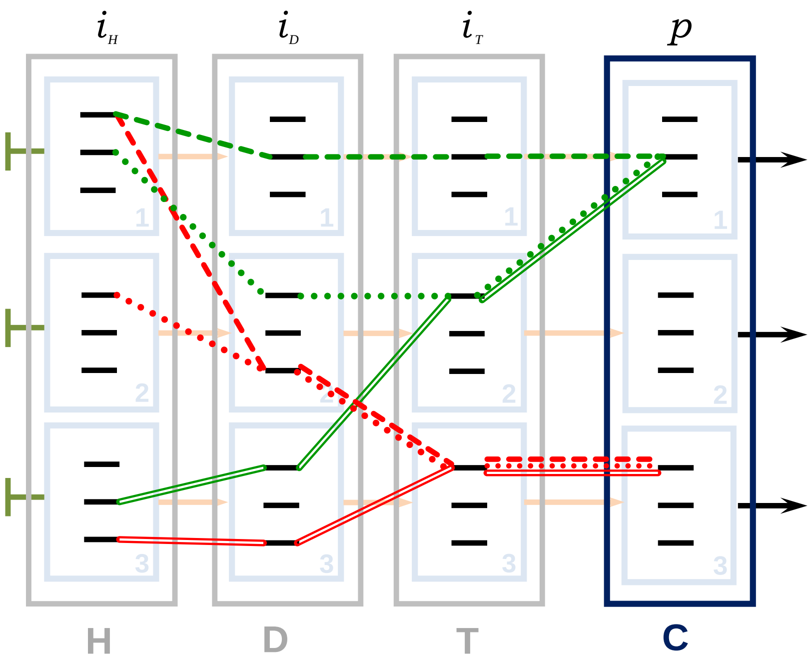


Figure 5.4: Breakdown of material and energy contributions into their corresponding virtual flows as the smallest indivisible flow units on the basis of the illustration presented in Figure 5.3

In this manner, the breakdown of the contributions $PL_{i,p}$ from the harvesting, densification and transport sectors – *H*, *D* and T – as a linear function of the suitable virtual flows $\varphi_{i,j,k,p}$ renders the third block of auxiliary equations (Equations 5.15-17). This is obtained by appropriately multiplying the virtual flows by the efficiencies of the corresponding processes. In this regard, it is worth noting that the virtual flows $\varphi_{i,j,k,p}$ represent an activity level determined by the amount of energy registered by the processes in the harvesting sector *H*.

$$PL_{i_H,p,t} = \sum_{i_D} \sum_{i_T} \varphi_{i_H,i_D,i_T,p,t} \tag{5.15}$$

$\forall i_H \in H_p,\ i_D \in D_p,\ i_T \in T_p,\ \forall p \in C,\ \forall t \in PER$

$$PL_{i_D,p,t} = \sum_{i_H}\sum_{i_T}\varphi_{i_H,i_D,i_T,p,t}\cdot\eta_{i_D,t} \tag{5.16}$$

$i_H \in H_p,\ \forall i_D \in D_p,\ i_T \in T_p,\ \forall p \in C,\ \forall t \in PER$

$$PL_{i_T,p,t} = \sum_{i_H}\sum_{i_D}\varphi_{i_H,i_D,i_T,p,t}\cdot\eta_{i_D,t}\cdot\eta_{i_T,t} \tag{5.17}$$

$i_H \in H_p,\ i_D \in D_p,\ \forall i_T \in T_p,\ \forall p \in C,\ \forall t \in PER$

As previously indicated, the flow levels *FL* between producers of different sectors cannot be directly expressed as a (linear) mathematical function of the contributions $PL_{i,p,t}$ or even of the activity levels of processes from the whole utilisation pathway, $PL_{i,t}$ or $PL_{p,t}$. A manner to indirectly establish this relationship is the use of the auxiliary variables $\varphi_{i,j,k,p}$ or virtual flows. They allow creating the fourth set of auxiliary equations that is made up of Equations 5.18-20. In keeping with this, each flow level *FL* connecting consecutive nodes from permitted pairs of sectors *H-D*, *D-T* and *T-C* within one or two spatial units *reg, reg'* $\in$ *REG* for a specific energy carrier $ec \in EC$ is reproduced for every period of time $t \in PER$ as a linear combination of the same set of virtual flows formerly employed in Equations 5.15-17. Similarly to the previous block of equations, the multiplying factors of the resultant linear combinations are the efficiencies η of the processes located in the densification and transport sectors, *D* and *T*.

$$FL_{H_{reg}D_{reg',ec},t} = \sum_{i_{H_{reg},ec}}\sum_{i_{D_{reg'},ec}}\sum_{i_T}\sum_{p}\varphi_{i_{H_{reg},ec},i_{D_{reg'},ec},i_T,p,t} \tag{5.18}$$

$\forall H_{reg}, D_{reg'} \in BIOPROD;\ \forall ec \in EC;\ i_{Hreg,ec} \in P'_{Hreg,ec};\ i_{Dreg',ec} \in P_{Dreg',ec};\ i_T \in T;\ p \in C;\ \forall t \in PER$

$$FL_{D_{reg}T_{reg',ec},t} = \sum_{i_H}\sum_{i_{D_{reg},ec}}\sum_{i_{T_{reg'},ec}}\sum_{p}\varphi_{i_H,i_{D_{reg},ec},i_{T_{reg'},ec},p,t}\cdot\eta_{i_{D_{reg},ec},t} \tag{5.19}$$

$\forall D_{reg}, T_{reg'} \in BIOPROD;\ \forall ec \in EC;\ i_H \in H;\ i_{Dreg,ec} \in P'_{Dreg,ec};\ i_{Treg',ec} \in P_{Treg',ec};\ p \in C;\ \forall t \in PER$

$$FL_{T_{reg}C_{reg',ec},t} = \sum_{i_H}\sum_{i_D}\sum_{i_{T_{reg},ec}}\sum_{p_{C_{reg'},ec}}\varphi_{i_H,i_D,i_{T_{reg},ec},p_{C_{reg'},ec},t}\cdot\eta_{i_D,t}\cdot\eta_{i_{T_{reg},ec},t} \tag{5.20}$$

$\forall T_{reg}, C_{reg'} \in BIOPROD;\ \forall ec \in EC;\ i_H \in H;\ i_D \in D;\ i_{Treg,ec} \in P'_{Treg,ec};\ p_{Creg',ec} \in P_{Creg',ec} \subset C;\ \forall t \in PER$

5.5. Enumeration of the most significant aspects of BIOSPHERE

BIOSPHERE (Bioenergy Optimisation Software for Production Pathways at High Energy and Resource Efficiency) as a multi-period mixed integer linear programming approach is a bottom-up model conceived as an energy and material flow tool. It is characterised by the following features:

1. Minimisation of the objective function including total system expenditures for a given time frame
2. Set of auxiliary conditions
    a. Energy and material flow balance
    b. Restrictions on capacity and process utilisation
3. Profitability constraints for separate utilisation pathways
    a. Plant operator within a utilisation pathway is considered as an observer
    b. Remunerations must cover expenses incurred in each utilisation pathway
    c. 4 sets of auxiliary equations including variables that describe the virtual flows are required for calculating:
        i. the energy and material contributions of all upstream processes within the supply chain to a given bio-based conversion process,
        ii. the cost components and
        iii. thus the electricity production costs
4. Database describing 4*n* nodes with spatiotemporal differentiation
    a. 4 technology sectors (harvesting, densification, transport, conversion) containing processes defined by a 4-tuple (location, time, technology, capacity)
    b. *n* spatial units
    c. Potential of biomass, input of non-biogenic fuels and energy demand
        i. Biomass potentials are freely consumed and converted into bioenergy
        ii. Non-biogenic fuels *F* are set at higher costs than bioenergy production and consumed according to the method of last resort
        iii. Energy demand is the exogenous driver of the model
        iv. Bioenergy production and non-biogenic fuels *F* must satisfy the subsystem's demand

5. Nodes are connected to each other by energy flows
6. The solution represents the optimal allocation of biomass resources to an array of bioenergy sinks distributed across the analysed area. It includes:
    a. Electricity production costs of the most cost-efficient utilisation pathways
        i. Spatial variation of production costs over catchment areas
    b. Cost components regarding harvesting, densification, transport and conversion
    c. Matrix solution for each utilisation pathway. It is made up of four partial solutions (process) within each technology sector
        i. Each partial solution refers to a process together with its 4-tuple (location, time, technology, capacity)

6. Modelling of the wood resources-based bioenergy system of Baden-Württemberg

Modelling a bioenergy system based on the conversion of wood resources into power requires a number of specific measures for integrating an array of different sets of input data. In the first place, the district is chosen as the most appropriate spatial unit for modelling the federal state of Baden-Württemberg. Apart from this level of spatial aggregation, also a temporal restriction is selected for the modelling of the bioenergy subsystem, according to which only a unique period of time is considered for this study. Furthermore, the data structure describing the existing free potentials as well as the different logistic chains of wood chips produced from forest residues and landscape wood raw material must be properly harmonised so as to create an integrated data base. The resultant correlation between the free potentials and the respective unit costs of wood chips gives rise to a set of ten different types of chipped wood resources-based on the variety of the harvested tree (coniferous or deciduous), the type of ownership (small or large owner) and the steepness of slope in forest and landscape areas (lower or higher than 50%). Each type of chipped wood resources presents an annual free potential that is linked to a specific unit cost. Different unit costs result from the application of two cost allocation methods on the basis of regarding wood resources either as a by-product or a joint product. In addition, the methodology for the spatial allocation of the bioenergy demands and the free potentials of wood resources to each district is described as well as the manner in which the technologies in the different sectors – specifically, the existing coal-fired power plants in Baden-Württemberg – are modelled. In this regard, the employed methodological approach for simulating the preselected conversion technologies on the basis of a cost minimisation analysis of the whole utilisation pathway is presented. Finally, two different methodologies for the modelling of the remunerations by gradually varying their magnitude are introduced in order to identify new bioenergy configurations.

6.1. The district as the most appropriate level of spatial aggregation

The previously developed BIOSPHERE model includes the possibility of modelling the spatial dimension of a bio-based system by partitioning it into a number of spatial units that are connected with each other. In addition, the geographic particularities of the region of Baden-Württemberg including an administrative division into 35 districts and 9 urban districts recommend analysing the remaining free potentials of wood resources at a simple district level. However, data availability regarding the free and consumed technical potentials of wood resources at lower aggregation levels such as a municipality or a community is reduced and in general quite deficient. Consequently, the district is selected as the most adequate level of spatial aggregation. This enables determining in detail the spatial distribution of free potentials of wood resources as well as any other techno-economic feature that might be characterised over the spatial dimension.

Since the analysed federal state is divided into spatial units that are equated with its administrative districts, the intended analysis takes the shape of the well-known districting problem. As explained in subsection 5.2.2 of the previous chapter, the solution for this problem can be found via the implementation of a location allocation technique with the assistance of a programming model such as BIOSPHERE. Based on this methodology, the potentials of wood resources as well as the bioenergy demands of the districts of Baden-Württemberg can be apportioned to a centroid (or node) that represents such magnitudes within each administrative unit. In the same vein, the four technological processes within the harvesting, densification, transport and conversion sectors of any utilisation pathway are accordingly assigned to the centroids of their respective districts. In this connection, the processes of harvesting and densification are allocated to the district that generates the wood resources. In contrast, the stage of conversion remains in the target district where bio-based power and heat are consumed on the basis of an existing demand. Finally, a transport process is established between the former and the latter districts for the haulage of wood chips to the targeted power generation unit.

On another issue, transport distances across the districts of Baden-Württemberg are calculated by means of an application based on Geographic Information Systems (GIS) in order to estimate the length (km) of the routes between the centroids or nodes concerning the potentials of wood resources and those including the sites of conversion plants. Indeed, this assessment includes the consideration of all combinations among the 44 districts of the federal state from their source of wood resources up to their sinks in the target districts. The journeys between the centroids of any two districts are selected according to two specific criteria. On the one hand, the shortest route among both nodes has to be chosen but, on the other hand, the required time to drive along a specific journey must also be regarded. As a result, the latter criterion gives rise to a greater utilisation of the regional network of highways and major roads over other routes of the secondary road system of the federal state.

6.2. Temporal restriction

Although the temporal differentiation of the BIOSPHERE model is described on the basis of a multi-period approach, the intended modelling of the wood resources bioenergy system of Baden-Württemberg is accomplished for a single year as the time component is not considered in the present study. The rationale for the choice of this approach is that the objective of this study is mainly the spatial analysis of the arising utilisation pathways within the targeted bioenergy subsystem. Precisely because technologies are separately analysed (see subsection 6.7.2), such a temporal assessment would only make sense for projecting the evolution of costs over certain periods of time. However, the electricity production costs and their components can equally be estimated for any bioenergy configuration by applying to it a sensitivity analysis according to the changes experienced in each time frame. This way, the temporal development of potentials of wood resources or even of energy and bioenergy demands in the framework of future energy and environment policies – as a result of e.g. the effects of climate change – could also be taken into account.

The same applies to the time slots within the selected year in which power or heat demand should be specifically defined. They are not modelled in this analysis because it is irrelevant to introduce into the model the seasonal variations of the free potentials of wood resources – as the aim is to estimate the location, technology and capacity and not the logistic issue over the year – or even of the load profile of the districts' demand – as this would only equate to the total demand and not the bio-demand of the analysed bioenergy subsystem (see section 6.5).

6.3. Modelling of the logistic chains for harvesting wood resources

The modelling of the different logistic chains for harvesting both types of wood resources – forest residues and landscape wood raw material – by converting them into wood chips (see section 3.5) is a major task to be carried out when generating the required input data for the analysis of the wood resources-based bioenergy system of Baden-Württemberg. The following subsection describes the manner in which the four logistic chains of wood chips derived from forest residues for both presented cost allocation procedures – as a by-product and a joint product – are techno-economically modelled by means of classifying them into two simplified harvesting systems for each apportionment technique. The second subsection equally regards the modelling of the logistic chains of wood chips generated from wood raw material. Similarly, two further harvesting systems are techno-economically described.

6.3.1. Production of wood chips from forest residues

Once the total unit costs of wood chips produced from forest residues are estimated for each of the four logistic chains in section 3.5, they could then be introduced into the database of the model as input data for each of both cost allocation procedures. However, the identified four logistic chains for harvesting of forest residues are simplified into two standard logistic chains. This is carried out by means of two apportionment techniques, according to which a minimal cost scenario for chipped forest residues as a by-product and a maximal cost scenario involving wood chips exclusively considered as a joint product are generated. In such a context, both cost allocation procedures exhibit two markedly different levels of total unit costs according to the specific description accomplished in subsection 3.5.1. Thereby, analysing forest residues as a by-product or even their resulting wood chips leads to the identification of two different rates of total unit costs for two simplified harvesting systems. These harvesting systems are operated by either small private forest owners (SPFO) or large (private or public) forest owners (LFO). The former equates to the motor-manual harvesting system of small private forest owners while the latter relates to a weighted average of the remaining logistic chains (partly, highly and fully mechanised harvesting techniques) of larger private or public forest owners. Thus, the total unit costs of LFO are obtained from the simplification of these three logistic chains by means of unifying them into only one harvesting system. The resulting total unit costs are expressed as a weighted average on the basis of the forest areas where each logistic chain should be applied. In this respect, [ForstBW 2013] provides the share of woodlands in Baden-Württemberg that belongs to small private forest owners (up to 50 ha.), who implement the motor-manual harvesting method for producing wood chips from forest residues harvested by SPFO. This fraction accounts for around 23.5% of total forests, whereas the remaining contribution (circa 76.5%) is linked to those woodlands managed by larger (public or private) forest owners (LFO) with the assistance of the weighted three logistic chains. The estimation of the total unit costs of wood chips produced by LFO is carried out by considering the portion of woodlands with a steepness of slope higher than 50% [Kappler 2008]. This magnitude is associated with the weight of the highly mechanised logistic chain with respect to that of both the partly and fully mechanised harvesting methods. As the share of sloped forest areas higher than 50% accounts for 6.2% for the entire federal state, then the partly and fully mechanised logistic chains may be weighted as a whole by a rough[26] coefficient of around 0.938. Regarding these two logistic chains, the different slope restriction of 50% and 30%[27], respectively, as well as the weak penetration rate of the fully mechanised logistic chain in the forests of Baden-Württemberg [Wippel et al. 2015] do not shed much light on which should be the correct weighting for the respective costs of each harvesting system. As a result, the same weighting coefficient was assumed for both the partly and fully mechanised techniques when calculating the total unit costs for chipped forest residues gained by LFO. This way, more emphasis is therefore given to the fully mechanised harvesting method with respect to the partly mechanised logistic system as it could supposedly become in a future time – maybe the next decade.

Employing a similar methodology to that used for calculating the total unit costs of both types of wood chips (SPFO and LFO) evaluated by using the by-product allocation procedure, the unit costs of further categories of wood chips may also be estimated for forest residues when analysed as a joint product. Likewise, the total unit costs of the four logistic chains for harvesting forest residues as a joint product can be simplified into two different rates of total unit costs that give rise to two types of wood chips. Specifically, those made up of chipped forest residues that are exclusively generated by the highly mechanised logistic chain in woodlands with a steepness of slope higher than 50% (S>50F) and a second class that corresponds to a weighted average of the remaining harvesting techniques (motor-manual as well as partly and fully mechanised systems). This second category of harvesting systems are mostly implemented in lower sloped forest areas than 50% (S<50F). Consequently, the total unit costs of the S<50F chip type are derived from the weighting of total unit costs of the corresponding three harvesting systems by means of unifying them into a unique average procedure. In this sense, leveraging the data provided by [ForstBW 2013] with regard to the portion of forests harvested with the motor-manual procedure by small private forest owners

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[26] This approximation is considered under the assumption that woodlands managed by SPFO are homogenously distributed between both slope classes for steepness above and below 50%.

[27] [Kappler 2008] indicates that approximately 77% of Baden-Württemberg's woodlands with a maximum slope of 50% (partly mechanised harvesting method) shows a steepness not higher than 30%, which is thus appropriate for the wheeled vehicles implemented in the fully mechanised logistic chain.

allows the contribution of this logistic chain to the unit total costs of the S<50F chip type to be assessed. Meanwhile, the other summand that contributes to the total expenditures of S<50F results from the consideration of both the partly and the fully mechanised logistic chains as an integrated whole. In such a way, the same weighting coefficient is assigned to both harvesting systems on account of the rationale already applied to the determination of the by-product allocation-based total unit costs of LFO chipped forest residues.

On the other hand, mention is to be made of the inaccuracy resulting from the combination of data regarding the forest areas harvested by small private forest owners [ForstBW 2013] and those data dealing with the portions of woodlands for the whole array of different slopes [Kappler 2008]. The problem arises from the fact that the share of forests harvested by the motor-manual technique of small private owners also includes plots of forests categorised into the class of woodlands including a slope higher than 50%. The same, but the other way around, is reported when analysing the unit costs of wood chips as a joint product, as the portion of terrains with a slope higher than 50% equally encompasses plots exploited with motor-manual harvesting methods by small private forest owners. In any case, even though this represents a source of error, it can be regarded as a rather small deviation from real values. This is basically because the share of sloped woodlands higher than 50% accounts for a quite small rate of around 6.2% for the whole of Baden-Württemberg [Kappler 2008]. Moreover, the portion of forest areas being exploited by small private forest owners amounts to circa 23.5% of total forests in the federal state, thus resulting in a small error of around 1.4% of the woodlands involved. This imprecision is considered insignificant when it comes to considering the total unit costs of several logistic chains that have to be unified into a single simplified harvesting system. In fact, the corresponding total unit costs are quite alike and this reduces the impact of the error incurred by weighting.

Table 6.1: Total unit costs of the four types of wood chips produced from forest residues according to both cost allocation procedures either as a by-product or as a joint product

Cost allocation	Type of wood chips	€/m^3 l	€/t
By-product	***SPFO***	11.26	34.86
	LFO	10.22	31.67
Joint product	***S<50F***	17.28	53.52
	S>50F	28.96	89.70

SPFO Small private forest owner

LFO Large (private or public) forest owners

S<50F Steepness of slope lower than 50% in forest areas

S>50F Steepness of slope higher than 50% in forest areas

Summarizing, the total unit costs that serve as input data for the modelling of the bioenergy subsystem are presented in Table 6.1. It comprises the total expenditures for the four introduced types of wood chips obtained from forest residues regarded as a by-product (SPFO and LFO) and as a joint product (S<50F and S>50F). All four types are expressed in *€/*m^3 *l* and *€/t* FW (35% MC) as a weighted value for all districts of Baden-Württemberg.

6.3.2. Production of wood chips from landscape wood raw material

Similarly to the modelling of the logistics chains of chipped forest residues, the harvesting of landscape wood raw material can also be modelled although in a more direct manner than the former. Due to its specific typology as a resource growing on succession areas, landscape wood raw material is the result of harvesting the full tree by implementing only two logistic chains – namely the partly and highly mechanised harvesting systems – that are operated by a large corporation. As there is no final outcome consisting of by-product and main product, or even of two joint products, but a unique final product as a whole (the full tree), costs are assigned to the entire tree or bush and then no specific cost allocation has to be applied. This differs from the case of forest residues, which are regarded as a by-product or joint product.

The identified harvesting systems for collection and densification of landscape wood raw material show two different total unit costs (see section 3.5). These costs clearly depend on the steepness of slope of the landscape areas involved. As a result, two different types of wood chips are defined for modelling purposes: S<50L for chips produced by the partly mechanised logistic chain for a steepness of slope lower than 50% and S>50L for the outcome of the highly mechanised harvesting system with a slope above 50%. In comparison to the modelling of logistic chains for forest residues, the identification of total unit costs for both types of wood chips obtained from landscape wood raw material does not require any weighting as there is exclusively two logistic chains with markedly different costs. In this regard, Table 6.2 shows the total unit costs of both types of wood chips, S<50L and S>50L, which are generated by the partly and highly mechanised logistic chains, respectively. Both total unit costs are tabled in two columns expressed in *€/*m^3 *l* and *€/t* FW (35% MC) as a weighted cost for all districts of the federal state.

Table 6.2: Total unit costs of the two types of wood chips obtained from landscape wood raw material by assigning costs to the entire harvested tree as a whole

Cost allocation	Type of wood chips	*€/*m^3 *l*	*€/t*
Unique product	***S<50L***	20.90	64.74
	S>50L	29.64	91.82

S<50L Steepness of slope lower than 50% in landscape areas

S>50L Steepness of slope higher than 50% in landscape areas

6.4. Correlation of free potentials and total unit costs of wood chips

The identification and characterisation of the four types of wood chips from forest residues for both cost allocation procedures as well as those types originating from landscape wood raw material gives rise to the possibility of determining their corresponding free potentials. The idea behind this approach is that each specific sort of wood resource of the bioenergy system of Baden-Württemberg exhibits an exogenously given resource input. In this vein, the different types of wood chips and therefore their total unit costs, on the one hand, and the corresponding free potentials, on the other, are closely correlated. The following Figures and Tables within this section aim then to shed light on this correlation by focusing on the cost potential distribution at district level for each of the six sorts of wood chips.

Table 6.3: Total unit costs per unit loose volume and unit mass for the four types of wood chips obtained from forest residues as a by-product

Type of wood chips	€/m^3 l	€/t
SPFO coniferous	11.26	41.38
SPFO deciduous		26.12
LFO coniferous	10.22	37.59
LFO deciduous		23.72

Until the last section, the total cost of wood chips per unit loose volume was systematically converted into total costs per unit mass by taking advantage of the weighted average (0.323 t/m^3 l FW 35% MC)[28] of bulk densities for both softwood and hardwood, i.e. both coniferous and deciduous wood resources, respectively. However, special attention should be given to the fact that a separate consideration of the coniferous and the deciduous share of wood resources will reproduce completely different costs per unit mass in line with the selected wood variety and hence its bulk density. In this respect, [FNR 2014] indicates the bulk density of the coniferous wood type (softwood) at circa 0.272 t/m^3 l FW (35% MC) and that of deciduous option (hardwood) with a value of around 0.431 t/m^3 l FW (35% MC). As a result, two dissimilar total costs per unit mass of chipped forest residues are identified for both coniferous and deciduous wood resources. This is the case of those wood chips gained from forest residues as a by-product or a joint product, whose total unit costs are tabulated in Tables 6.3-4. On the contrary, landscape wood raw material is made up of a heterogeneous mixture of tree varieties with a diverse fraction of coniferous and deciduous species growing in copses and groves within succession areas. As a consequence, the prior weighted average of both bulk densities for softwood (coniferous) and hardwood (deciduous) is employed for landscape wood raw material as an acceptable assumption instead of separately considering

[28] The weighted average of the bulk densities of softwood (coniferous) and hardwood (deciduous) is calculated on the basis of the respective free potentials that are harvested in all the forests of Baden-Württemberg [ForstBW 2013].

each wood variety. As this wood resource represents a mixture of both wood types, then the corresponding total unit costs turn out to be the same as those of Table 6.2. However, since each district actually exhibits a specific weighted average of the bulk density (t/m^3 l) on account of the different proportion of softwood (coniferous) and hardwood (deciduous), then the total unit costs of wood chips when they are converted into €/t FW (35% MC) vary from one district to another (see Table 6.8). The actual proportion of coniferous and deciduous wood resources within the harvested landscape wood raw material in each district is unfortunately unknown. Nevertheless, it can roughly be derived as an assumption based on the ratio between both wood types showed by forest residues according to data published by [ForstBW 2013].

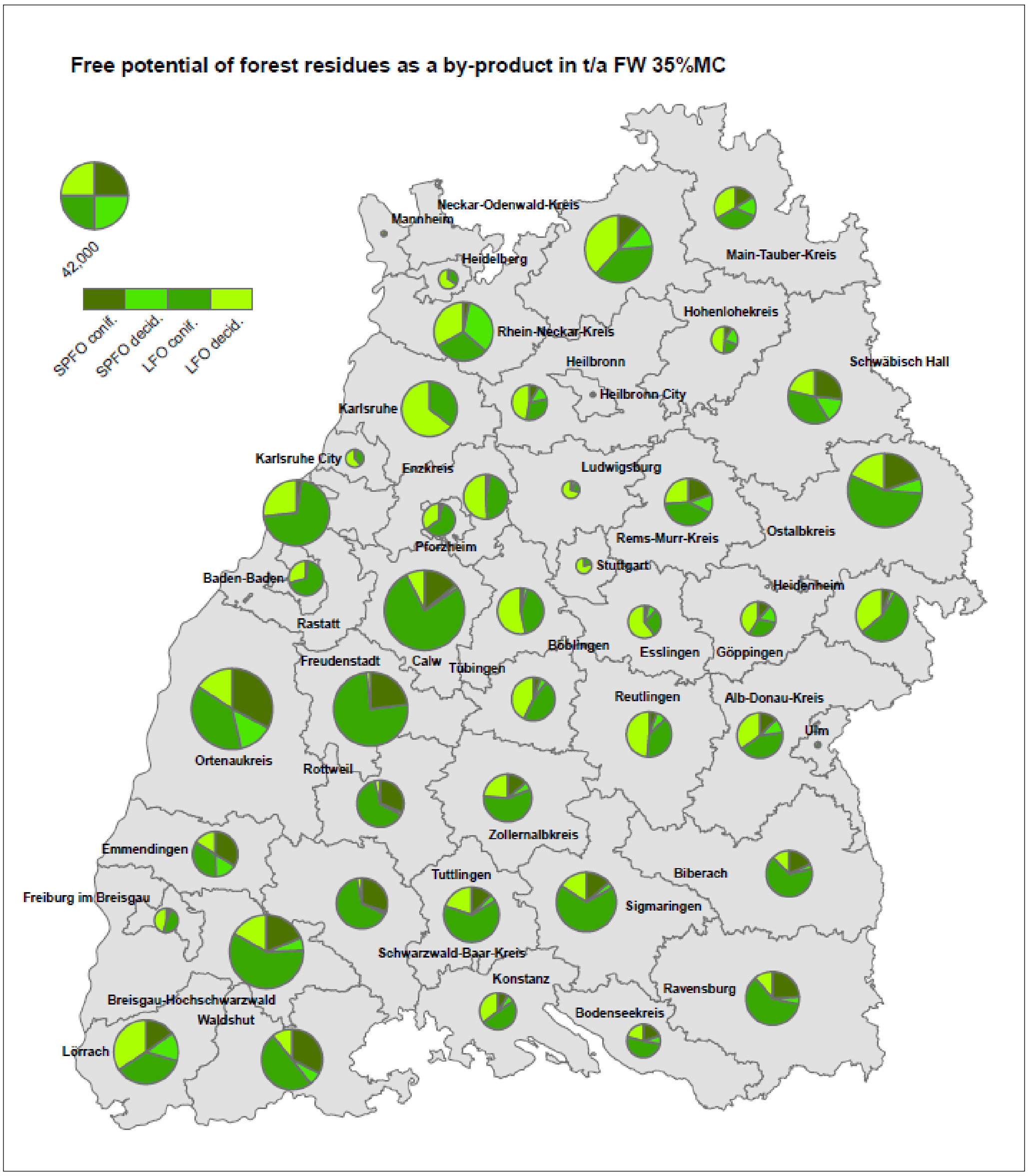

Figure 6.1: Annual free potentials of the coniferous and deciduous fractions of both SPFO and LFO chipped forest residues regarded as a by-product in each district of Baden-Württemberg

As mentioned, the total unit costs referred to unit loose volume and unit mass for wood chips produced from forest residues are illustrated in Tables 6.3-4 for coniferous and deciduous species. Concretely, both coniferous and deciduous fractions of the following types of wood chips are characterised: namely, SPFO and LFO for forest residues analysed as a by-product in addition to both S<50F and S>50F wood chip types that result from regarding such wood resources as a joint product. By contrast, Table 6.2 exclusively makes reference to both S<50L and S>50L chip types produced from landscape wood raw material, regardless of allowing for the different species or even their respective densities. This is because these types of wood chips consist of a mix of coniferous and deciduous wood varieties with the same weighted bulk density for the whole federal state of Baden-Württemberg.

Table 6.4: Total unit costs per unit loose volume and unit mass of the four types of wood chips obtained from forest residues as a joint product

Type of wood chips	€/m³ l	€/t
S<50F coniferous	17.28	63.53
S<50F deciduous		40.09
S>50F coniferous	28.96	106.48
S>50F deciduous		67.20

Turning to the issue of the correlation between total unit costs and their respective free potentials, the latter parameters still must be appropriately calculated so that they can be related to the already available costs. In this regard, besides the corresponding total unit costs, each of the six identified types of chipped wood resources is assigned a free potential for each portion of coniferous or deciduous wood classes. These potentials are distributed all over the territory of Baden-Württemberg at district level as represented in Figures 6.1-3. For each district of the federal state, Tables 6.6-8 tabulate these free potentials for both coniferous and deciduous fractions of all types of wood chips derived from forest residues either as a by-product or as a joint product as well as those free potentials for the two types of wood chips originating from landscape wood raw material.

For forest residues converted into wood chips and being analysed as a by-product, Figure 6.1 depicts the spatial distribution of forest residues for each district of the federal state by categorising forest areas into two classes based on [ForstBW 2013]. This partition includes those areas exploited by small private forest owners and, on the other hand, the woodlands belonging to large (public or private) forest owners. Both classes respectively relate to both types of wood chips, SPFO and LFO, although a second classification into coniferous and deciduous wood types permits generating four categories of free potentials of forest residues (see Table 6.3). With regard to the produced amount of potential, some urban districts such as Ulm, Mannheim and Heilbronn City render quite small free potentials for the corresponding types of wood chips on account of the reduced district's surface as well as their marked urban nature. Such conditions strongly determine the available forest areas in certain districts of Baden-Württemberg.

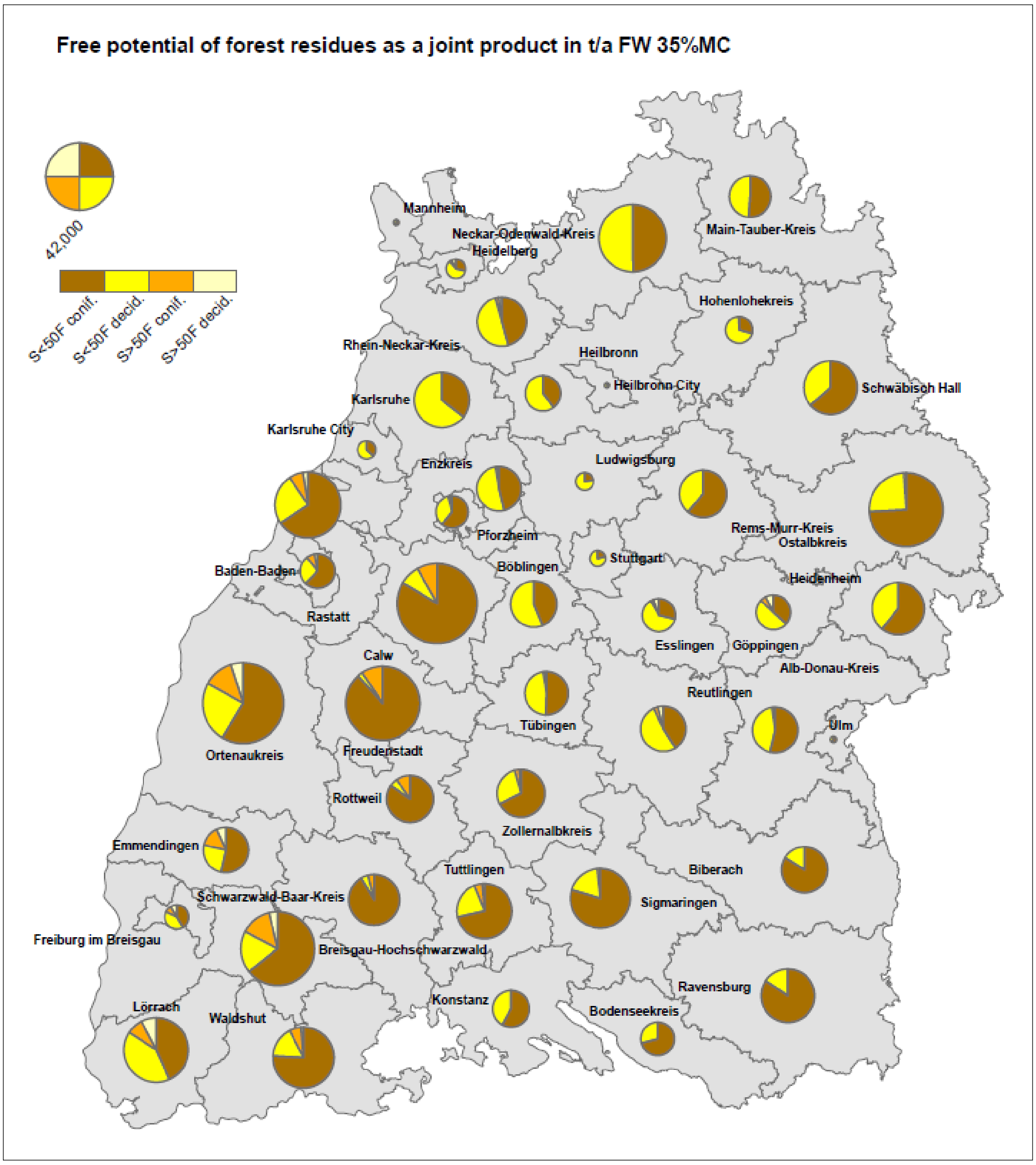

Figure 6.2: Annual free potentials of the coniferous and deciduous fractions of both S<50F and S>50F chipped forest residues regarded as a joint product in each district of Baden-Württemberg

In a similar fashion to the case of wood chips produced from forest residues regarded as a by-product, the free potentials of chipped forest residues that are considered as a joint product can also be unambiguously correlated to the total unit costs of both coniferous and deciduous fractions of the S<50F and S>50F wood chip types. In this respect, Figure 6.2 illustrates the spatial distribution of the four types of wood chips with the assistance of [Kappler 2008] by leveraging the portion of woodlands with a slope below and above 50% for both S>50F and S<50F types, respectively. The study [ForstBW 2013] additionally provides suitable data for estimating the free potentials of the coniferous and deciduous portions of both types of wood chips. In relation to the generated amount of free potentials, the urban districts of Ulm, Mannheim and Heilbronn City are also characterised by very small free potentials of forest residues as a joint product due to the same reasons outlined for the case analysed under the by-product cost allocation method.

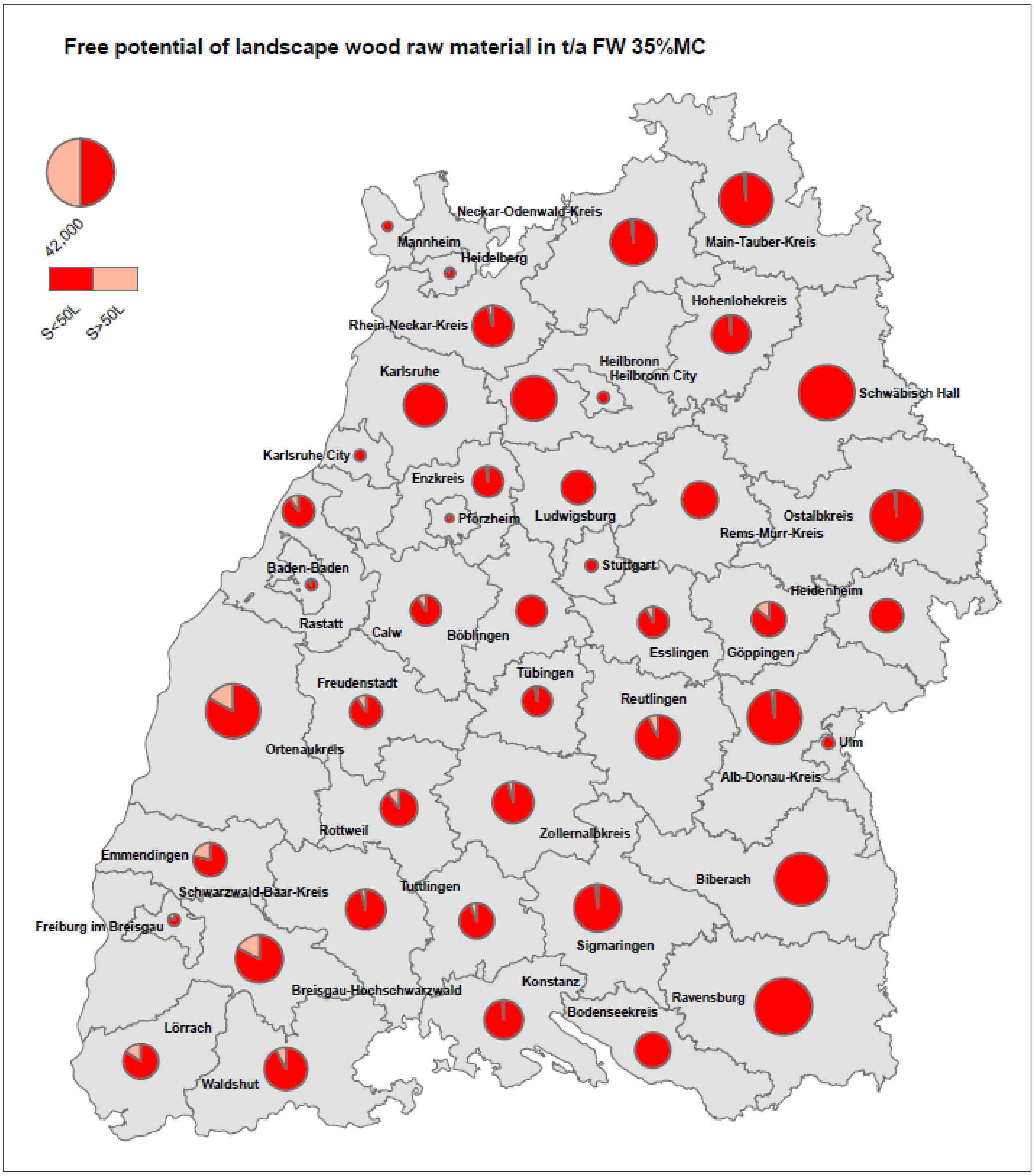

Figure 6.3: Annual free potentials of both S<50L and S>50L chipped landscape wood resources in each district of Baden-Württemberg

In contrast to the calculation of total unit costs, the source of error reported in subsection 6.3.1 does not appear when determining the free potentials of all types of wood chips derived from forest residues or landscape wood raw material. This inaccuracy happens only when data regarding forest areas that are harvested by small and large forest owners as well as data addressing the shares of forest areas with steepness of slopes below and above 50% are combined in order to weight the total unit costs of several logistic chains. Such a problem is related to the risk that certain forest areas exploited by the motor-manual technique of small private owners and some woodlands showing a steepness of slope lower or higher than 50% might be counted twice. In any case, this error factor was not considered relevant in the case of estimating total unit costs. By contrast, using the fractions of coniferous and deciduous forest areas at district level for calculating the respective portions of all types of wood chips – SPFO, LFO, S<50F and S>50F – for the by-product and joint product approach clearly leads to a certain inaccuracy. However, this is the only possible methodology for ascertaining the corresponding coniferous and deciduous shares due to the lack of data delimiting these fractions for the free potentials of each of the four types of wood chips. Anyway, the source of error should not be of importance when aiming at calculating the final production costs of bioenergy. In this regard, the portions of coniferous and deciduous forest residues at district level are rigorously kept constant when adding up the respective fractions of the two types of wood chips for each cost allocation procedure.

As for defining the pertinent free potentials of landscape wood raw material for the corresponding S<50L and S>50L wood chip types, their calculation proves to be quite direct due to considering the resource as a mixture and not as a specific amount of either coniferous or deciduous species. Both S<50L and S>50L are associated with those succession areas and forest boundaries with a steepness of slope lower and higher than 50%, respectively. By determining both fractions for each district of Baden-Württemberg – with the assistance of surface data provided by [Kappler 2008] – the illustration of the spatial distributions of both types of wood chips is presented in Figure 6.3. In terms of quantity of resource, the lower overall free potential of landscape wood raw material as compared to that of forest residues also entails a lesser generation of both types of wood chips at district level and, as a consequence, an increased number of urban districts showing extremely tiny free potentials for this wood material. Not only the three urban districts identified in both cost allocations methods for forest residues, namely Ulm, Mannheim and Heilbronn City, but also the rest of the existing nine urban districts of Baden-Württemberg render rather minor free potentials. This is owing to the small district's surface and the limited amount of agricultural areas in favour of urban spaces.

6.5. Modelling of energy demands

Modelling the power and heat demands of the wood resources-based bioenergy system of Baden-Württemberg requires identifying the real dimension of such magnitudes at district level. As the targeted bioenergy system that is intended to be analysed is actually a subsystem of the total energy system of the federal state, it becomes apparent that the exogenously given demand of such bioenergy subsystem would definitely be a sort of bio-based demand resulting from the expectations of the consumed amount of both bioenergy products originating from wood resources. In line with this premise, such bio-based demands could be defined in the framework of a set of energy policy measures aiming at establishing a certain level of bioenergy production from wood resources arising in each district. This is the case in which the wood resources-based bioenergy demands are identified as a result of a series of objectives to be met in the context of a specific bioenergy policy. But this kind of bio-based demands will end up turning out to be an inaccurate methodological technique for modelling the demands of such a bioenergy subsystem. The reason behind this assertion relates to the fact that expensive bioenergy produced to entirely satisfy districts' bio-based demands and thus close some existing "bioenergy gaps" might be substituted with other cheaper non-biogenic energy sources of the total energy system. Accordingly, the well-founded purpose to quantify demands by estimating such artificial amounts of bio-based demands requires the use of a methodology that can be qualified as absolutely unsuitable with a view to describing the targeted subsystem with the highest levels of accuracy. It can be concluded that no wood resources-based bioenergy demands can be exogenously declared for a model reproducing the corresponding bioenergy subsystem within the total energy system of Baden-Württemberg.

In the absence of such bio-based demands at district level, a possible solution to this problem is resorting to the use of the total energy demand of Baden-Württemberg and hence the total demands registered in each of its administrative units. Under these conditions, the model describing the proposed bio-based subsystem does not exhibit its own exogenous driver at the demand side anymore. As a substitute, the driver assigned to the energy system of the federal state and being associated with its total energy demand level is identified for this purpose. In virtue of the use of this methodology, the amount of bioenergy production in each district does not cover the respective total demands. Instead, non-biogenic energy contributions – fuels F introduced in section 5.4 – supplement the bio-based energy generated from wood resources up to the real level required by energy consumers in each administrative unit. In the event of modelling demands by using not total energy demands but the discarded option of bio-based demands, the input of non-biogenic energy carriers would only come into action if there were not enough wood resources for covering bioenergy demands at district level. Generalising for both cases, a bio-based subsystem such as that of Baden-Württemberg can be exogenously driven regardless of whether bio-based demands or total demands are only satisfied with wood resources or even with an additional contribution of non-biogenic sources.

Thereby, both types of bioenergy demands – power and heat bio-based demands – are modelled on the basis of the real amounts of both total demands at district level. As the bioenergy subsystem accounts in general for a small portion of the entire energy system of Baden-Württemberg, total heat and power demands serve as a proper ceiling for both bioenergy demands. In this regard, the lack of bioenergy demands is not a critical issue, as they can be modelled by resorting to the higher total demands of the whole energy system. Finally, data on total power demands for every district of Baden-Württemberg during the year 2017 are taken from [Eßer-Frey 2012]. This study accomplishes a projection of power demand at district level for this federal state from 2005 up to 2035. In the same vein, the values of total heat demands at district level are assessed on the basis of industry's demands for heat at the same spatial aggregation level according to the source [Blesl et al. 2011]. These data on total heat demand from the industrial sector are increased by an assumed factor of 2.0 so as to coarsely add the heat demand contributions of service and household sectors to the heat demand of industry for each specific district.

6.6. Spatial allocation of the free potentials of wood resources and the energy demands

A major issue, when it comes to modelling the free potentials of forest residues and landscape wood raw material as well as the energy demand for each district in Baden-Württemberg, consists in identifying a representative spatial location for both magnitudes within each of the respective districts. A procedure aiming at the determination of the spatial allocation for both the free potentials and the energy demands to a specific site within each district of Baden-Württemberg is performed on the basis of the methodology introduced in section 6.1. Under this approach, each specific techno-economic feature defined for a given district is apportioned to a certain geographic point (centroid or node), which serves as a representative site for the attributes under consideration thus simplifying the modelling of the bioenergy system.

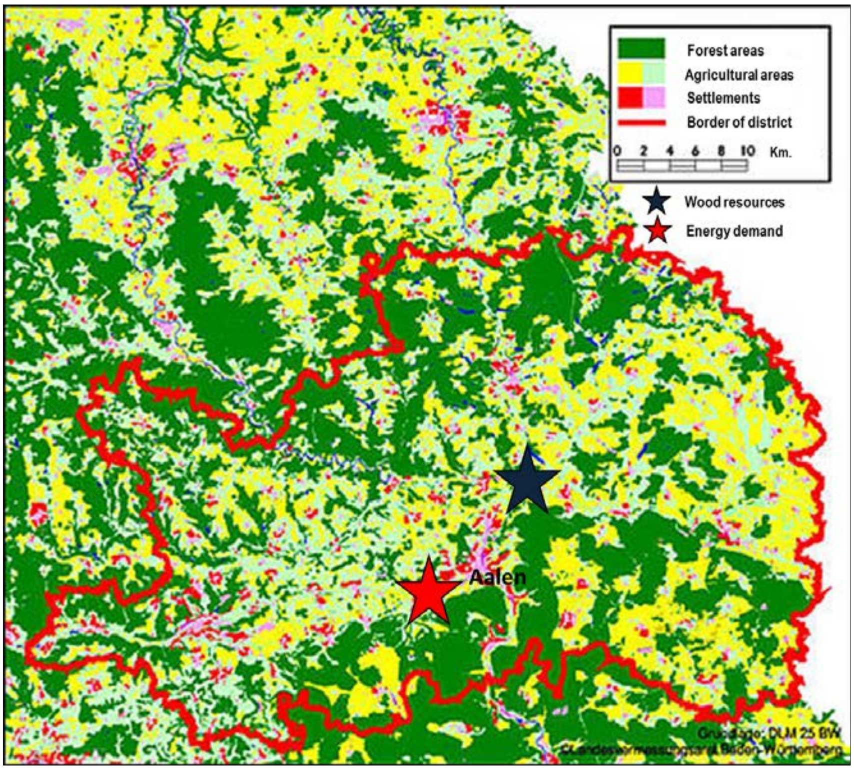

Figure 6.4: District of Ostalbkreis together with the location of both centroids involving the free potentials of wood resources and the energy demands (based on [LVABW 2011])

As wood resources are made up of forest residues and landscape wood raw material, a common centroid is determined within each district by considering the relative weight of the corresponding forest and agricultural areas for each administrative unit. In this vein, the spatial allocation of total wood resources to a specific geographic point is carried out through a thorough visual inspection of an array of suitable maps, which – like that of Figure 6.4 for Ostalbkreis – include the necessary information concerning both different kinds of vegetation zones for each district of Baden-Württemberg. In contrast to the estimation of transport distances between districts, the determination of the spatial location of the common centroids for both wood resources within a specific district is not performed on a surface basis via the use of Geographic Information Systems (GIS). The grounds for this relates to the different specific yields of both forest residues and landscape wood raw material. This actually leads such a tool to generate an invalid outcome on account of the different weights of forest and landscape/agricultural resources regardless of their forest and landscape surface.

With regard to both types of bioenergy demand – power and heat (in the case of CHP facilities) –, the capital cities of the districts of the federal state are taken as the sites for the required centroids representing the spatial location of the districts’ bioenergy demands, which in turn act as energy sinks of the streams of wood resources. Just prior to these sinks, these flows of forest residues and landscape wood raw material are appropriately converted into bioenergy after having been harvested, densified and transported. The selection of the districts’ capital cities relates to a rationale underlying higher levels of energy efficiency without substantial losses in the transmission of power and heat. These areas show not only the highest concentration of population but also the greatest industrial rate within each district.

6.7. Modelling of technologies

The BIOSPHERE model provides a partial solution in the form of an array constituted of four combined 3-tuples (location, technology, capacity) that relate to the four technology sectors of harvesting, densification, transport and conversion – respectively H, D, T and C in Figure 5.2 – within the wood resources-based bioenergy system of Baden-Württemberg. This matrix describes in detail the most optimal utilisation pathways within the value chain of wood resources on the basis of efficient and mature enough technologies for harvesting, densification, transport and conversion. This way, a series of preselected technologies for each sector of the bioenergy system is thoroughly identified. Concretely, this selection encompasses the motor-manual as well as the partially, highly and fully mechanised harvesting systems, the process of chipping as a necessary densification method after drying the raw material, a means of transport consisting of a truck with two containers and lastly three different power generation units based on the most cost-effective conversion techniques co-firing, FBG+E and BIGCC. In addition, mention should also be made of the storage of wood resources, which is integrated into the techno-economic modelling of the power plants as a phase prior to conditioning. In general, each technology sector also determines the diverse sorts of bioenergy carrier that serve either as an input or output of the processes involved. Thereby, wood resources are first transformed into chips and subsequently into electricity and/or heat respectively as primary and secondary bioenergy carriers, which are closely related to the consumption practices in each district.

A further aspect that requires being modelled for each preselected technology is the respective capacity. The same technology can be implemented as a process in a broad spectrum of possible capacities ranging from very small to extremely large scales. In consequence, a multiplicity of different bioenergy production patterns can occur in such a way that they may vary from highly decentralised to fully centralised energy systems. Thus, a centralized process with a high capacity can convert a large amount of wood resources into bioenergy, whereas the same quantity of raw material has to be separately transformed by a large number of decentralised processes with lower scale. The size of the processes making up a utilisation pathway depends on the volume of resources that can sequentially be harvested, densified, transported and converted into bioenergy. Particularly, the capacity of each of these processes, and therefore indirectly the consumption and production of the corresponding bioenergy carriers, is scaled to the available amount of its energy inputs within the respective catchment area and consistent with the dimension of its corresponding bioenergy demands.

Anyhow, some differences arise when it comes to modelling the diverse processes for each of the four technology sectors. Although the processes of harvesting, densification and transport exhibit a certain scale-effect (see chapters 2 and 3), the corresponding spectrum of feasible capacities for these technologies is not actually modelled. This derives from the fact that the whole expenses incurred by the three aforementioned technologies are usually expressed in the form of variable costs. On account of the limited data availability on costs published by the consulted research studies, these variable costs encompass not only the real variable operating costs but also integrate both capital expenses and fixed operating costs. Conversely, the capital costs as well as the fixed and variable share of O&M costs are well enough documented for most processes of the conversion sector. In this sense, the power output capacity of conversion processes unavoidably requires the consideration of all possible sizes for conducting a proper optimisation-based analysis of a targeted bioenergy system. As a result, their capacities and therefore also the complete conversion technologies can be accordingly modelled.

Moreover, determination of the location for each proposed technology completes the solution that allows describing each process within any utilisation pathway of a bioenergy system. With the aim of modelling the spatial location of processes, a similar methodology to that employed for ascertaining the spatial allocation of the free potentials of wood resources and the bioenergy demands at district level is carried out. The processes of harvesting and densification are allocated to a centroid calculated for the different potentials of wood resources through a common location determined by forest and agricultural areas within each raw material generating district. Both processes are consecutively implemented before wood resources are hauled away from both forest and landscape areas in the source district. Besides, each conversion process is assigned to the node linked to the spatial allocation of bioenergy demands at the respective districts' capital cities. As the stage of conversion is performed at the nearest possible sites to demand in the referenced urban settlements, then higher rates of efficiency are achieved when transforming wood resources into bioenergy at reduced levels of power and heat losses. This assumption is particularly important in the case of combined heat and power cogeneration units, where heat cannot be easily stored or conveyed to other places and has to be consumed in the surroundings of the heat producing facility in the shortest possible period of time. Finally, the remaining processes of transport are set up in such a manner that they establish a connection between both previously mentioned centroids – those calculated for the potentials of wood resources and the bioenergy demands –and in consequence also between both respective source and target districts.

6.7.1. The coal-fired power plants of Baden-Württemberg

Modelling the processes based on co-firing within the wood resources-based bioenergy system of Baden-Württemberg requires compiling an updated list of all coal power plants registered in the region. The list exhibited in Table 6.5 is the starting point for the selection of the final set of coal power plants that can be transformed into co-firing based power generation units with a 10% share of wood resources with respect to total energy input (see subsection 4.1.4). The most implemented coal feeding technology is dust firing, which predominates especially in large-scaled coal-fired power plants. However, a few medium and small scale coal power plants in a range between 10 and 30 MW_e do not apply this technology based on pulverised coal combustion but a concept based on fluidised bed combustion coupled to a steam turbine with even higher co-fire rates. In this connection, [McIlveen-Wright et al. 2011] is the sole consulted research study that expressly reports on the required techno-economic parameters of two power plants of 12 and 25 MWe working with this kind of technology, while the rest deals with the more conventional dust firing system. As for the case of Baden-Württemberg, a few coal-fired power plants fitted with a fluidised bed combustion system are located in some districts of the federal state (see Table 6.5): concretely in Pforzheim (26.9 MW_e), Stuttgart-Gaisburg (22.6 MW_e) and Oberkirch with a capacity of 18.5 MW_e that specifically co-fires recyclable materials on the basis of circulating fluidised bed combustion [BNA 2018].

Although most of these coal power plants can be retrofitted by installing specific co-firing based feeding systems for wood resources, not all power plants presented in Table 6.5 will be available for upgrading in the upcoming years. In this regard, the coal-fired power plants of Pforzheim and Oberkirch respectively fire biogenic and other non-recyclable wastes at high co-fire rates. Therefore, they are intentionally excluded from undergoing further sustainability requirements as compared to the rest of the existing coal-fired power plants. On the other hand, Block 7 in Mannheim and both units WAL 1 and WAL 2 in Walheim are put in cold reserve with the aim of coping with power shortages [Miekley et al. 2014] and therefore they cannot be adapted to the co-firing mode either. As a result, 12 already existing coal-fired power plants from the aforementioned list in Table 6.5 – with locations in the districts of Esslingen, Heilbronn, Karlsruhe, Mannheim, Stuttgart and Ulm – will be suitable to be equipped with the co-firing technology in case of including this bio-based technology into the modelling of the targeted bioenergy system.

Table 6.5: List of the existing coal power plants in Baden-Württemberg [BNA 2018]

Location	**Power plant**	**District**	**Start-up**	**Technology**	**Secondary fuel**	**Capacity (MW_e)**
Altbach	ALT HKW 1	Esslingen	1985	dust firing	oil	433
Altbach	ALT HKW 2	Esslingen	1997	dust firing	gas	336
Heilbronn	HLB 7	Heilbronn	1985	dust firing	-	778
Karlsruhe	RDK 7	Karlsruhe	1985	dust firing	-	505
Karlsruhe	RDK 8	Karlsruhe	2014	dust firing	-	842
Mannheim	Block 6	Mannheim	2005	dust firing	-	255
Mannheim	Block 7	Mannheim	1982	dust firing	-	425
Mannheim	Block 8	Mannheim	1993	dust firing	-	435
Mannheim	Block 9	Mannheim	2015	dust firing	-	843
Oberkirch	n/s	Ortenaukreis	1986	circulating FBC	residual waste	18.5
Pforzheim	n/s	Pforzheim	1990	FBC	substitute fuel, petroleum products, sewage sludge	26.9
Stuttgart-Gaisburg	GAI DT 14	Stuttgart	2009	FBC	-	22.6
Stuttgart-Münster	MÜN DT 12	Stuttgart	1982	dust & grate firing	waste	45
Stuttgart-Münster	MÜN DT 15	Stuttgart	1984	dust & grate firing	waste	45
Ulm	HKW Magirusstr.	Ulm	1978	n/s	natural gas, heating oil	20.7
Walheim	WAL 1	Ludwigsburg	1964	dust firing	-	96
Walheim	WAL 2	Ludwigsburg	1967	dust firing	-	148

6.7.2. Cost minimisation-based simulation of utilisation pathways

The BIOSPHERE model is made up of an array of interconnected technological processes arranged over the four sectors of a utilisation pathway: namely harvesting, densification, transport and conversion. As explained in section 5.4, all these processes may become part of the solution of the targeted bioenergy subsystem provided that the selected consecutive processes constitute the most cost-efficient combination of any four successive stages as a sum of supply chain and conversion process. This structure can be used for modelling the whole set of all feasible utilisation pathways existing within the bioenergy system in question.

Naturally, each utilisation pathway presents different specific electricity production costs as the sum of all expenses incurred throughout the entire supply chain and the final conversion stage. As BIOSPHERE incorporates a modelling approach based on a cost minimisation algorithm, only the most economical utilisation pathways will be chosen as part of the final solution. Thus, the selected conversion processes are implemented a specific number of times so as to completely deplete the available wood resources. On the contrary, the rest exhibiting higher EPC but maybe – hence subject to some uncertainty – comparatively higher rates of profitability will be automatically excluded from a deeper techno-economic analysis. In order to prevent this outcome, a new analytical methodology is introduced. This consists basically in focusing exclusively on the specific conversion process together with all its possible locations and its whole spectrum of capacities, which translates to fixing the type of technology and varying only two elements from the 3-tuple involving the single solution of each conversion process. This methodological approach enables the simulation of each specific utilisation pathway to be conducted against the backdrop of the minimisation of its total costs. As a consequence, the analysed bioenergy system definitely loses a degree of freedom in relation to the possibility of realising a comprehensive assessment of the whole subsystem including all conversion processes. However, such methodology generates much more information – especially in relation to more expensive utilisation pathways – when the analysis is performed separately for each of the conversion technologies under consideration. In this regard, mention should also be made that this simulation approach can exclusively be carried out by introducing the non-biogenic energy contributions (fuels *F*) indicated in section 5.4. In practice, the simulated utilisation pathway only generates a portion of the required district's bioenergy demand, while the rest needed for covering the entire bio-demand is supplied by the corresponding inputs of non-biogenic resources.

The employed analytical methodology indeed implies the elimination of a direct competition among different technologies. Nevertheless, the diverse possible utilisation pathways for conversion of wood resources into power can be individually simulated in a first stage and then directly compared so as to ascertain the most cost-efficient options. After comparing the entire array of possible utilisation pathways and subsequently identifying a set including the least-cost ones, these preselected bio-based conversion options along with their corresponding locations and capacities could already be integrated into a conventional energy system analysis (ESA). In this context, a relatively reduced number of highly detailed bio-based utilisation pathways belonging to the wood resources-based bioenergy subsystem can now compete and interact with the rest of the non-biogenic conversion paths originating from fossil and nuclear sources as well as other renewables.

6.8. Modelling of remunerations

The remunerations granted to the selected bio-based power plants can be modelled through a fundamental procedure by eliminating the effect of the respective profitability constraints via setting high enough values for these parameters – i.e. higher than the breakeven point obtained for each of these remunerations. A further approach aiming at modelling the remunerations consists in the progressive lessening of their magnitude below each resulting breakeven point for any utilisation pathway or in general for the whole wood resources-based bioenergy subsystem in order to identify potential cost reductions. This methodology should permit gaining insight into a wide range of techno-economic configurations with different spatial arrangements and hence lower electricity production costs. For this purpose, remunerations in the framework of this approach are conceived as the minimum amount of incomes received by plant operators for the production of bioenergy so that the incurred production costs can at least be covered without any profit margin (breakeven point). In essence, the focus of both types of modelling will be on the formation of the EPC of each utilisation pathway and not on the benefit achieved by the respective investor for each power facility.

6.9. Implementation of BIOSPHERE

The BIOSPHERE model is implemented in GAMS (General Algebraic Modeling System), concretely in GAMS version 24.5. Besides, version 12.6.2 of the CPLEX solver is used. On the other hand, input data management is easily accomplished by means of a Microsoft Access relational database, which provides for reliable input data handling as well as completely automated connection to the source code written in GAMS. The model results are generated in GAMS data exchange (GDX) files, which can be subsequently transferred to Microsoft Excel for better data management. The additional use of geographic information systems (GIS) for representation and visualisation of georeferenced results is finally performed with ArcGIS. On another issue, the existence of an integer variable within the linear mathematical equations of the proposed model imposes the use of an optimisation algorithm on the basis of a mixed-integer linear programming (MILP) approach.

Owing to the reasons stated in section 6.2, only one optimisation period is implemented for the calculations carried out with the BIOSPHERE model. Under these conditions, the model is made up of approximately 64,000 equations (14 blocks) including around 10 million variables (5 blocks), of which 36 are discrete variables. This number of variables is due to the high amount of combinations that can be established among the different districts in relation to the process of allocating the free potentials of wood resources to the bio-based power plants. Furthermore, the matrix contains around 61 million non-zero elements. Anyhow, the size of the linear optimisation problem and hence the number of equations and variables strongly depends on the selected number of spatial units and technology process involved in the model.

The BIOSPHERE model requires a physical memory of around 40 GB RAM for solving the proposed problem of the given wood resources-based bioenergy system with the assistance of a computer with a processor of 3.0 GHz. The proposed integer programming problem is solved by using the branch-and-bound technique without causing an increase in computation time, which would definitely have led to the implementation of the more sophisticated branch-and-cut approach. Under such conditions, the required computing times range from 4 hours for the case of co-firing forest residues to a maximum of 20 hours in the scenarios based on both CHP and BIGCC technologies, when forest resources along with landscape wood raw material are converted into bioenergy. In any case, modelling such a bioenergy system implies finding a balance between the desired level of detail (i.e. low aggregation level with comprehensively described processes) and the computational effort in terms of computing time and physical memory (RAM) requirements.

6.10. Excursion: Political framework conditions in Baden-Württemberg

Most important elements of the energy policy framework of the wood resources-based bioenergy system of Baden-Württemberg are analysed under the perspective of a context exclusively aiming at power generation. Thus, the novel bidding scheme of the German bioenergy legislation along with its corresponding amendments is considered as the basis for modelling the revenues achieved from the sales of power as well as heat in the case of CHP technologies. Against this backdrop, production of bio-based power can be financed by means of collecting subventions or wholesale prices in addition to market premiums. Moreover, a further possibility may also lead to the consideration of heat retail prices from heat cogenerated in CHP facilities as a by-product of the primary process aiming at power production. As a result, two major laws for the development of the targeted bioenergy system along with some of their most techno-economic characteristics are summarised below in order to gain insight into certain important aspects for modelling the corresponding political framework conditions.

The approval of the **German Renewable Energy Act 2017** (GREA) [EEG 2017] implied switching the funding from administratively set feed-in tariffs to competitive auctions so as to drive down costs and equally increase the market integration of renewables by means of a faster response to market development [BMWE 2017]. Auctions are conceived as a support scheme for expansion of renewable energies with the aim of reaching higher realisation rates under the framework of GREA. This tendering system applies to most renewable energy sources as a market instrument for their promotion in the German energy transition. In the light of this context, 3 or 4 auction rounds per year are conducted by the Federal Network Agency (Bundenetzagentur) on specific dates, which together with the tender volume of auctions and the maximum market premium are set by law. Subsequently, all stakeholders must bid in auctions for tender volumes with the aim of receiving the market premium from the grid operator. The amount of the market premium is assessed through the subtraction of the average technology-specific market value from the stipulated reference value of the renewable energy under consideration. If the market premium is awarded, it will be paid for 20 years starting with the commissioning of the project. Thereby, the total remuneration that the investors receive is made up of a market premium granted by the grid operator as well as an equivalent amount to the electricity wholesale price that could be gained on the spot market. In the specific case of biomass, the installation of power capacities below 150 kW_e is exempted from the requirements imposed by the GREA, although this capacity range is still eligible under the feed-in tariff scheme. Furthermore, the tendered volume for biomass is 150

MW_e in 2017 and 200 MW_e in subsequent years according to [EEG 2017]. As a consequence, the commissioning and operation of bio-based power plants in the context of the GREA entails the introduction of a specific analysis framework for new forms of energy generation.

On the other hand, highly efficient combined heat and power (CHP) cogeneration plants in Germany are promoted by the **Combined Heat and Power Act 2016** (CHPA) [KWKG 2016] in order to combat climate change by increasing cost-effectiveness and flexibility of the cogeneration processes involved. For this objective, CHP cogeneration can utilise up to 90% of primary energy input by recovering significant amounts of low temperature heat. In addition, this act sets out an appropriate regulatory framework for the promotion of certain techniques such as district heating/cooling and heat/cold storage that are not especially cost-effective. In particular, this regulation provides specific support for low-carbon technologies such as existing gas-fired CHP plants when they are directly connected to district heating systems. Thus, greater levels of flexibility are reached through the installation of electricity and heat storage systems that enable reacting more readily to the fluctuating volumes of renewables and power demand. Besides, additional certainty is likewise offered to investors and stakeholders through the CHPA so as to accomplish all aforementioned objectives. This is possible via a support mechanism based on the payment of a bonus (or fixed premium), which is awarded to CHP plants for the electricity generated by newly constructed, modernised or upgraded cogeneration plants running on fossil (except coal and lignite) and renewable fuels. As a condition, plant operators must prove via an expert's report that heat is generated via combined heat and power cogeneration processes. In a similar manner to the GREA, a transition from a feed-in tariff to a bidding scheme is already initiated. Towards the end of 2017, the use of auctions for funding CHP plants with a power output capacity between 1 and 50 MW_e was introduced. Equally, installed capacities over 50 MW_e will also be entitled to receive premiums provided that no unfair competition is created over smaller-scaled CHP plants. In this manner, the fixed premium is granted in addition to the market price for a limited period of time – varying between 10,000 and 60,000 full load hours – on the condition that electricity is fed into a public supply grid. A total tender volume of 200 MW_e will be auctioned yearly up to 2021.

6.11. Tabulation of free potentials and total unit costs of chipped wood resources

The free potentials of the coniferous and deciduous share of the four types of wood chips derived from forest residues when regarded as a by-product and a joint product in each of the 44 districts of Baden-Württemberg are displayed in Tables 6.6-7 below. Similarly, the free potentials as well as the total unit costs of both types of wood chips produced from landscape wood raw material for each district are additionally tabulated in Table 6.8. The amounts of chipped wood resources are quantified in tonnes FW at 35% moisture content.

Table 6.6: Free potentials of the coniferous and deciduous fractions of both types of chipped forest residues as a by-product at district level

	Free potential *(t/a FW 35% MC)*			
	SPFO coniferous	***SPFO deciduous***	***LFO coniferous***	***LFO deciduous***
Stuttgart	5	19	472	1,796
Böblingen	449	576	8,203	10,521
Esslingen	387	844	2,778	6,051
Göppingen	1,324	1,812	3,367	4,607
Ludwigsburg	65	222	584	2,013
Rems-Murr-Kreis	4,118	2,610	8,561	5,427
Heilbronn City	3	13	40	162
Heilbronn	1,009	1,541	3,610	5,515
Hohenlohekreis	610	1,467	1,358	3,266
Schwäbisch Hall	7,029	4,032	9,908	5,684
Main-Tauber-Kreis	2,581	2,480	5,598	5,378
Heidenheim	1,239	803	14,125	9,150
Ostalbkreis	10,017	3,342	28,160	9,395
Baden-Baden	196	85	7,556	3,262
Karlsruhe City	22	38	1,073	1,850
Karlsruhe	146	265	9,943	18,055
Rastatt	955	360	28,313	10,659
Heidelberg	29	61	1,084	2,255
Mannheim	0	0	153	126
Neckar-Odenwald-Kreis	4,970	4,993	16,015	16,088
Rhein-Neckar-Kreis	991	1,078	9,801	10,662
Pforzheim	218	126	5,983	3455
Calw	8,401	821	45,884	4,483
Enzkreis	250	277	8,447	9,338
Freudenstadt	11,569	285	38,119	939
Freiburg im Breisgau	180	175	2,532	2,466
Breisgau-Hochschwarzwald	9,530	2,739	29,697	8,535
Emmendingen	6,369	2,977	6,518	3,047
Ortenaukreis	19,950	8,307	23,039	9,594
Rottweil	6,320	420	12,883	855
Schwarzwald-Baar-Kreis	7,238	359	15,555	771
Tuttlingen	3,527	1,108	17,980	5,646
Konstanz	1,128	815	6,149	4,442
Lörrach	5,799	5,493	13,947	13,212
Waldshut	11,126	2,431	17,044	3,724
Reutlingen	1,060	1,335	7,359	9,267
Tübingen	925	853	8,141	7,509
Zollernalbkreis	2,861	1,184	12,156	5,032
Ulm	25	16	187	121
Alb-Donau-Kreis	2,374	1,947	8,162	6,696
Biberach	3,554	677	13,034	2,481
Bodenseekreis	2,051	842	5,264	2,162
Ravensburg	6,412	1,185	16,070	2,971
Sigmaringen	4,499	1,060	22,209	5,234

Table 6.7: Free potentials of the coniferous and deciduous fractions of both types of chipped forest residues as a joint product at district level

	Free potential *(t/a FW 35% MC)*			
	S<50F coniferous	***S<50F deciduous***	***S>50F coniferous***	***S>50F deciduous***
Stuttgart	475	1,811	1	5
Böblingen	8,646	11,088	7	9
Esslingen	2,901	6,318	265	576
Göppingen	4,073	5,574	618	846
Ludwigsburg	646	2,224	3	11
Rems-Murr-Kreis	12,613	7,996	66	42
Heilbronn City	43	175	0	0
Heilbronn	4,595	7,020	23	36
Hohenlohekreis	1,936	4,656	32	77
Schwäbisch Hall	16,784	9,628	153	88
Main-Tauber-Kreis	8,055	7,739	124	119
Heidenheim	15,287	9,903	78	51
Ostalbkreis	37,623	12,552	555	185
Baden-Baden	6,913	2,984	839	362
Karlsruhe City	1,094	1,887	0	0
Karlsruhe	10,060	18,267	29	53
Rastatt	26,482	9,970	2,786	1,049
Heidelberg	982	2,043	131	273
Mannheim	153	126	0	0
Neckar-Odenwald-Kreis	20,574	20,668	410	412
Rhein-Neckar-Kreis	10,324	11,230	469	510
Pforzheim	5,955	3,439	246	142
Calw	49,430	4,829	4,854	474
Enzkreis	8,474	9,368	223	247
Freudenstadt	44,882	1,106	4,806	118
Freiburg im Breisgau	2,222	2,164	490	477
Breisgau-Hochschwarzwald	32,405	9,313	6,822	1,961
Emmendingen	10,106	4,724	2,781	1,300
Ortenaukreis	35,710	14,870	7,279	3,031
Rottweil	17,183	1,140	2,021	134
Schwarzwald-Baar-Kreis	21,844	1,083	949	47
Tuttlingen	20,200	6,344	1,307	410
Konstanz	7,163	5,175	113	82
Lörrach	16,619	15,743	3,127	2,962
Waldshut	26,020	5,685	2,151	470
Reutlingen	7,812	9,836	608	765
Tübingen	8,821	8,136	245	226
Zollernalbkreis	14,371	5,949	646	268
Ulm	211	137	0	0
Alb-Donau-Kreis	10,290	8,440	247	203
Biberach	16,584	3,157	4	1
Bodenseekreis	7,256	2,980	58	24
Ravensburg	22,382	4,137	101	19
Sigmaringen	26,173	6,169	534	126

Table 6.8: Free potentials and total unit costs of both types of chipped landscape wood raw material at district level

	Free potential (t/a FW 35% MC)		**Total unit costs** (€/t FW 35% MC)	
	S<50L	***S>50L***	***S<50L***	***S>50L***
Stuttgart	1,495	4	52.53	74.50
Böblingen	8,993	7	57.84	82.04
Esslingen	8,255	753	54.86	77.81
Göppingen	9,791	1,485	57.44	81.47
Ludwigsburg	10,584	52	52.89	75.01
Rems-Murr-Kreis	12,593	65	62.64	88.84
Heilbronn City	1,326	1	52.32	74.20
Heilbronn	19,117	98	56.78	80.53
Hohenlohekreis	13,722	228	54.39	77.14
Schwäbisch Hall	28,386	259	63.35	89.84
Main-Tauber-Kreis	25,976	399	59.73	84.72
Heidenheim	10,418	53	62.49	88.62
Ostalbkreis	24,445	360	67.04	95.08
Baden-Baden	1,169	142	65.33	92.66
Karlsruhe City	1,241	0	56.09	79.55
Karlsruhe	16,491	49	55.81	79.15
Rastatt	8,655	911	66.25	93.96
Heidelberg	975	130	55.09	78.14
Mannheim	971	0	60.83	86.28
Neckar-Odenwald-Kreis	19,535	389	59.43	84.29
Rhein-Neckar-Kreis	14,968	680	58.90	83.54
Pforzheim	670	28	63.30	89.77
Calw	7,950	781	73.04	103.60
Enzkreis	8,665	228	58.80	83.39
Freudenstadt	8,712	933	75.78	107.48
Freiburg im Breisgau	1,140	251	59.64	84.59
Breisgau-Hochschwarzwald	17,433	3,670	67.97	96.41
Emmendingen	8,327	2,291	64.78	91.88
Ortenaukreis	22,634	4,614	65.58	93.00
Rottweil	11,309	1,330	74.15	105.16
Schwarzwald-Baar-Kreis	14,297	621	74.78	106.06
Tuttlingen	10,769	697	67.42	95.63
Konstanz	13,886	219	61.71	87.53
Lörrach	9,759	1,836	59.83	84.86
Waldshut	15,649	1,294	69.55	98.65
Reutlingen	17,038	1,326	57.96	82.20
Tübingen	8,121	226	60.01	85.12
Zollernalbkreis	15,064	678	65.62	93.06
Ulm	1,461	4	62.48	88.61
Alb-Donau-Kreis	26,586	639	60.82	86.26
Biberach	25,890	6	70.27	99.67
Bodenseekreis	11,560	92	65.67	93.14
Ravensburg	30,175	136	70.42	99.88
Sigmaringen	20,482	418	69.14	98.05

7. Model-based analysis of the wood resources-based bioenergy system of Baden-Württemberg

In this chapter, the BIOSPHERE model is used to analyse the wood resources-based bioenergy system of Baden-Württemberg. In the first place, a number of scenarios are defined with the aim of describing a set of different framework conditions so that the decision-making of stakeholder groups and investors can be supported. Such scenarios are composed of a combination of an array of wood resource and bio-based technology-related simple scenarios that individually introduce the particular techno-economic context of the entire value chain of wood resources. This way, such scenarios make it possible to deal with the uncertainty involved in the techno-economic analysis of the targeted bioenergy system. This step consists in the assessment of such scenarios for specific levels of remunerations above and below the original breakeven point. The spatial distribution of the selected bio-based power plants as a solution in the form of a 3-tuple (location, technology, scale) together with the cost contributions of every district within the respective catchment area to the specific electricity production costs of each power plant is determined. In this sense, the breakdown of the specific amount of both electricity production costs and harvesting costs for each power plant into its cost components is presented. For this purpose, the latter costs are split according to two different criteria based on the contributions of different harvesting stages and those resulting from the produced types of wood chips.

7.1. Definition of scenarios

The aim of the present model-based analysis is to identify through which kind of utilisation pathway and at what cost the existing free potentials of wood resources from the different districts of the bioenergy subsystem of Baden-Württemberg can be spatially allocated to a given bio-based power plant fitted with a specific technology for a broad spectrum of power output capacity so as to attain the highest level of cost-effectiveness. The location, technology and scale of each of the processes comprised in the selected utilisation pathway together with its electricity production costs and the breakdown into their cost components, besides the district-specific electricity production costs over the bioenergy plant's catchment area, are to be determined. As already stated, the optimisation of the value chain of wood resources is to be exclusively performed for power generation purposes. In contrast, heat acts as a by-product of the bio-based conversion process, exclusively for the technology based on fluidised bed gasification coupled to a gas engine. With this aim, the modelling of such a bioenergy subsystem requires taking into account a number of significant aspects that might lessen the accuracy of the intended analysis. These issues are linked to some indeterminacy, which has to be identified and subsequently integrated in the modelling of the system. But this is not a simple task, as it unavoidably involves the need to ascertain various criteria around which different structural settings may arise in the framework of the actual energy transition. Some major aspects are analysed hereunder in order to set the course for identifying the required set of scenarios.

In the first place, there exists some structural uncertainty that derives from a particular level of subjectivity, which is associated with the decision-making involved in the appropriate selection of a conversion technology. This structural uncertainty can be treated by means of a scenario-based approach on the basis of a specific criterion that relates to the type of conversion process. From a methodological point of view, each utilisation pathway is separately simulated via these scenarios against the backdrop of the minimisation of its total costs by fixing its specific conversion technology and correspondingly leaving the respective locations and capacities free. Therefore, the technology-based scenarios can be correlated with each of the most cost-effective bio-based conversion technologies that were previously preselected in section 4.3 as a result of a comprehensive techno-economic analysis pursued for all feasible conversion paths of wood resources into power. These techniques are three suitable combinations of converter system and prime mover: namely a fluidised bed gasifier coupled to a gas engine (FBG+E) working as a CHP process, the co-firing option relying on the utilisation of the already existing coal-fired power plants within the borders of Baden-Württemberg as well as a fluidised bed gasifier connected to a combined cycle – equally designated as a biomass integrated gasification combined cycle (BIGCC). The FBG+E includes a prime mover acting as a combined heat and power cogeneration process, which exhibits small and medium scales up to a maximum capacity of 20 MW_e thus allowing for decentralised bioenergy production patterns. In relation to the second technological option, the fact that the current owners of existing coal-fired power plants might not be interested in extra investments in their not always profitable facilities gives rise to the possibility of choosing any of the other two alternative techniques. While the selection of co-firing is anyhow attributed to its reduced investment costs, the BIGCC technology becomes the right choice on account of its higher electric efficiency for the entire spectrum of power output capacities – albeit especially in more cost-effective large-scaled power plants. As these settings only relate to the type of conversion technology, they are designated as *simple scenarios*, which together with others to be defined should permit the analysis of the targeted bioenergy subsystem.

A further criterion can be introduced, which is equally associated with the lack of knowledge and the state of ignorance – and therefore with some structural uncertainty. This element serves as a firm foundation for ascertaining the sort of cost allocation procedure used for assessing the total unit costs of chipped forest residues – i.e. whether these resources are regarded as a by-product or as a joint product. The dimension of total unit costs incurred by chips production is equally subject to a certain level of structural or qualitative uncertainty, which has to be equally coped with via a scenario-based approach. This methodology introduces two different states that relate to both the by-product and the joint product cost apportionment methods introduced in chapter 3. Thereby, both costs allocation techniques induce the creation of two extra *simple scenarios* that can be coupled with the three previously defined ones regarding the type of conversion technology. Moreover, any other cost allocation method based on an intermediate state of distributing the sales value between forest residues and timber could be derived from an appropriate linear combination of both proposed simple scenarios.

Another major aspect, which involves the potential of wood resources, also exhibits a relatively important level of vagueness. This indeterminacy originates from the lack of knowledge that underlies the structural uncertainty linked to the feasibility of harvesting certain potentials of wood resources. Concretely, it deals with landscape wood raw material and the imprecision associated with the social and political acceptance with respect to valorising such a natural resource. For this reason, two further *simple scenarios* are proposed in order to complement the two prior ones involving both kinds of cost allocation to forest residues. One *simple scenario* refers to the exploitation of landscape wood raw material from copses and groves located in succession areas and forest boundaries, whereas the opposite option based on not harvesting such resources on account of promoting values of respect and conservation of natural environments represents the other one.

Table 7.1: Set of simple scenarios together with the final list of compound scenarios

Simple scenario	**Description**
CHP	Combined heat and power cogeneration based on FBG+E
Cofi	Co-firing technology
BIGCC	Biomass integrated gasification combined cycle based on FBG
ByPro	Production of chips from forest residues as a by-product
JointPro	Production of chips from forest residues as a joint product
NonLaW	Without exploitation of landscape wood raw material
LaW	With exploitation of landscape wood raw material
Compound scenarios	
CHP/ByPro/NonLaW	
CHP/ByPro/LaW	
CHP/JointPro/NonLaW	
CHP/JointPro/LaW	
Cofi/ByPro/NonLaW	
Cofi/ByPro/LaW	
Cofi/JointPro/NonLaW	
Cofi/JointPro/LaW	
BIGCC/ByPro/NonLaW	
BIGCC/ByPro/LaW	
BIGCC/JointPro/NonLaW	
BIGCC/JointPro/LaW	

In accordance with all the above mentioned premises, Table 7.1 illustrates the set of seven (3+2+2) *simple scenarios* that serve as the basis to construct the final scenarios that are to be employed within this study. The technological settings (CHP, Cofi and BIGCC) are first combined with the forest residues-based simple scenarios (ByPro and JointPro). Secondly, the outcome is further matched with those simple scenarios linked to the possibility of harvesting landscape wood resources (NonLaW and LaW). In this way twelve (3x2x2) *compound scenarios* are established in order to conduct a comprehensive model-based analysis of the wood resources-based bioenergy subsystem of Baden-Württemberg for power generation purposes.

7.2. Scenarios based on the CHP technology

The CHP technology simple scenario creates a perfect background in order to attach it to the wood resources-related simple scenarios with a view to analysing the corresponding bioenergy subsystem of Baden-Württemberg. This technology simple scenario is matched with two further simple scenarios by relying upon the selected cost allocation methods employed for assessing the total unit costs of chipped forest residues when regarded either as a by-product or as a joint product. Furthermore, the utilisation or not of landscape wood raw material as a wood resource for conversion into power is contemplated as two added simple scenarios that will permit the complete analysis to be achieved. Each of the four resulting compound scenarios reproduces dissimilar conditions regarding the implemented technology and the supplied free potential of wood resources for conversion into bio-based power. In addition, CHP plants are also awarded retail price derived incomes for the combined generation of heat. This bioenergy is produced by combined cogeneration of heat and power in efficient and cost-effective fluidised bed gasifiers coupled to a gas engine (FBG+E) with a maximum power output capacity of 20 MW_e. In this connection, Table 7.2 – relying on data from Figures 4.5-8 – illustrates the most relevant techno-economic characteristics of the specific technology FBG+E for three specific capacities (5, 10 and 20 MW_e) from the entire spectrum involved in the modelling of the targeted bioenergy subsystem. As the availability of such CHP plants accounts for 90% on average according to [EPA 2007] and [Do et al. 2014], a maximum amount of full load hours on the order of 7,500 h/a is therefore assumed for the modelling of this technology. In virtue of this precept, lower full load hours will only be reached by the selected power plants when the existing free potentials of wood resources are depleted and no further bioenergy can be generated.

Furthermore, this particular methodological approach for the FBG+E technology results in four compound scenarios (see Table 7.1). These scenarios are applied to the wood resources-based bioenergy subsystem of the federal state while eliminating the effect of the profitability constraints by ineluctably complying with it at high enough remunerations – i.e. higher than the EPC obtained at the breakeven point. This way, the largest amount of bioenergy can be generated as the whole amount of wood resources is converted into power. Hereafter, the resultant solutions of the modelling of this conversion technology for the targeted bioenergy subsystem are presented and accordingly illustrated.

Table 7.2: Techno-economic features of power plants based on a fluidised bed gasification process connected to a gas engine as a function of their scale

Bio-based capacity	**Specific capital costs**	**Specific fixed O&M costs**	**Specific variable O&M costs**	**Electric efficiency**	**Availability**
MW	*€/kW$_e$*	*€/kW$_e$*	*€cent/kWh$_e$*	*%*	*%*
20	2,364	119.67	0.81	27.7	90
10	2,841	149.49	0.88	27.1	90
5	3,413	186.74	0.96	26.5	90

7.2.1. Energy conversion of wood chips derived from forest residues as a by-product

The CHP/ByPro/NonLaW scenario based on the utilisation of the FBG+E technology for conversion of wood chips produced from forest residues as a by-product renders a solution characterised by a spatial distribution of a number of conversion units with the most cost-efficient power output capacity of 20 MW$_e$. Six such bio-based power plants are selected over the entire territory of Baden-Württemberg for this scenario. They are correspondingly located in the capital cities of six districts: Mosbach (Neckar-Odenwald-Kreis), Aalen (Ostalbkreis), Calw, Freudenstadt, Emmendingen and Sigmaringen (see Figure 7.1).

According to Table 7.2, the technology option of a fluidised bed gasification process coupled to a gas engine presents an availability of 90% and can therefore be operated at a maximum rate of 7,500 full-load hours per year. On this basis, the selected bioenergy plants yield specific electricity production costs (EPC) ranging from 10.09 €cent/kWh$_e$ in Neckar-Odenwald-Kreis to a maximum value of 10.45 €cent/kWh$_e$ in both plants of Emmendingen and Freudenstadt. Figure 7.1 illustrates two representative catchment areas out of the six ones that belong to each selected conversion unit. Both the catchment zone of Ostalbkreis and Emmendingen are a good example of the set of the six selected power plants and describe to a large extent the techno-economic aspects of each individual facility. Each area of influence consists of a number of districts that provide the corresponding power plant with forest residues for conversion into bioenergy. The districts included in the catchment area of the plant installed in Aalen (Ostalbkreis) are correspondingly assigned a district-specific production cost (DSEPC), which ranges between 9.97 €cent/kWh$_e$ in Heidenheim and 11.32 €cent/kWh$_e$ in Rems-Murr-Kreis. On the other hand, those DSEPC of the districts within the catchment area of the conversion unit placed in Emmendingen vary from 10.12 €cent/kWh$_e$ in Emmendingen district itself to 11.03 €cent/kWh$_e$ in Waldshut. The respective DSEPC of an area of influence can be weighted according to their bioenergy contribution to the power plant thus resulting in the specific electricity production cost (EPC) for each bio-based unit. The district of Rems-Murr-Kreis within the catchment area of the power plant located in Aalen registers a markedly high DSEPC for its distance from the conversion place, which is due to the exclusive contribution of 4,104 t FW of the relatively expensive chip type involving coniferous SPFO. Another particularity within the Ostalbkreis's catchment area is the district of Heidenheim, where a comparatively low DSEPC is displayed owing to the higher proportion of the more economical wood variety of deciduous forest resources with respect to the expensive sort of coniferous residues in a ratio of 2 to 3, respectively. This proportion is substantially higher than that of other administrative units in the vicinity such as Ostalbkreis. It is also important to highlight that forest residues originating in forest areas are transported to the bio-based conversion unit of each catchment area by means of the regional network of highways and major roads. In this regard, the highways 5, 6, 7, 8 and 81 together with their secondary roads permit the supply of wood resources to each of the six FBG+E-based power plants in their respective areas of influence.

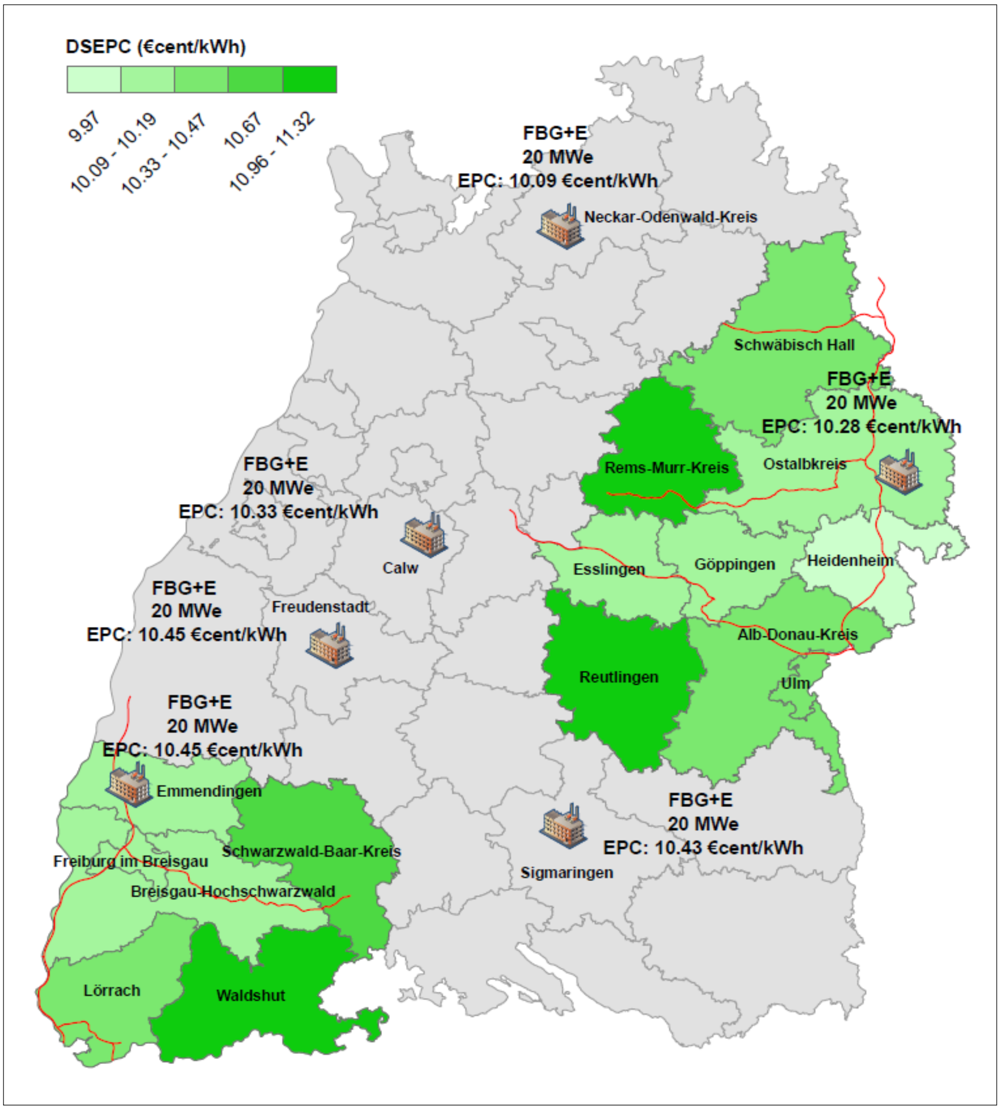

Figure 7.1: Location of the six FBG+E-based power plants with the respective electricity production costs along with two representative catchment areas illustrating the district-specific electricity production costs in the corresponding administrative units

On another issue, the specific electricity production cost (EPC) of a representative FBG+E-based power plant (Emmendingen) with a power output capacity of 20 MW_e is displayed in Figure 7.2 broken down into their cost components harvesting, transport as well as the annuity and the fixed and variable O&M costs. The investment and operation-related share of the bio-based conversion unit accounts for about 50% of the EPC, which is due to the high expenses associated with the gasification process when it is performed at such a low scale. This portion is made up of the annuity[29] with a weight of roughly 27% as well as the fixed operating costs with circa 15% and also the variable costs representing about 8%. In contrast, the other half of the EPC is composed of the respective cost constituents involving harvesting and transport of wood resources. Whereas the cost component of harvesting represents approximately 35%, the share concerning the transport of forest residues stands for about 15% of the specific EPC. As a singularity in relation to the prior cost breakdown, it should be mentioned that the slightly lower EPC of the power plant in Neckar-Odenwald-Kreis (10.09 €cent/kWh_e) compared to that of the other units (see Figure 7.1) is mainly caused by the lower expenses incurred from the use of cheaper deciduous forest residues. These are in higher proportion in the districts of northern Baden-Württemberg in comparison to the more densely forested south, where coniferous forests are prevalent (see Figure 6.1).

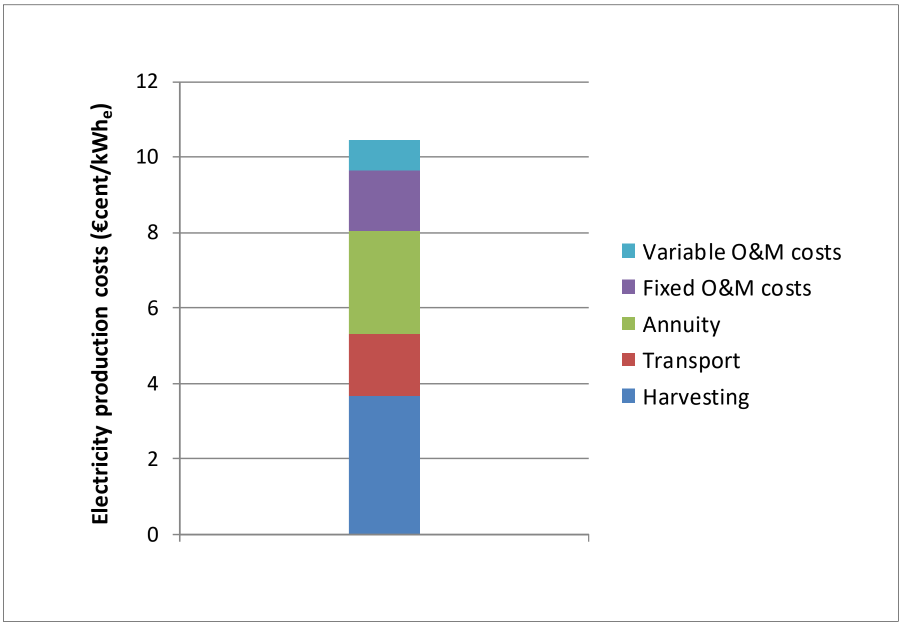

Figure 7.2: Cost breakdown of the electricity production costs of a representative FBG+E-based power plant of 20 MW_e into their cost elements

The cost component associated with the process of harvesting represents the largest portion of the specific electricity production costs registered by a FBG+E-based power plant of 20 MW_e. With the purpose of shedding light on the reasons causing such elevated expenses, a cost breakdown of the specific harvesting costs incurred in the forest areas within the zone of influence of each bio-based conversion unit is accomplished and shown for the unit of

[29] The annuity of an investment in a power plant is calculated on the basis of an interest rate of 6% over a period of 20 years from its commissioning to the end of its economic life.

Emmendingen in Figure 7.3. The resultant cost components are determined according to two different criteria, namely as a series of cost contributions derived from either each of the three harvesting stages (collection, moving and chipping) or the four types of wood chips harvested from coniferous and deciduous forest residues analysed as a by-product, namely SPFO and LFO (see Table 6.3).

As a result of forest residues being regarded as a by-product, the collection stage is not taken into account. Therefore its costs are not considered as part of the total costs of wood chips at forest road but allocated to the value chain of timber. Thereby, no collection costs appear as a cost component of the specific harvesting costs for the supply chains of the FBG+E-based power plants. Consequently, the cost elements linked to both moving and chipping stages respectively account for around 62% and 38%, and are consistent with the greatest variance experienced by the moving (59.1-62.6%) and chipping stages (37.4-40.9%).

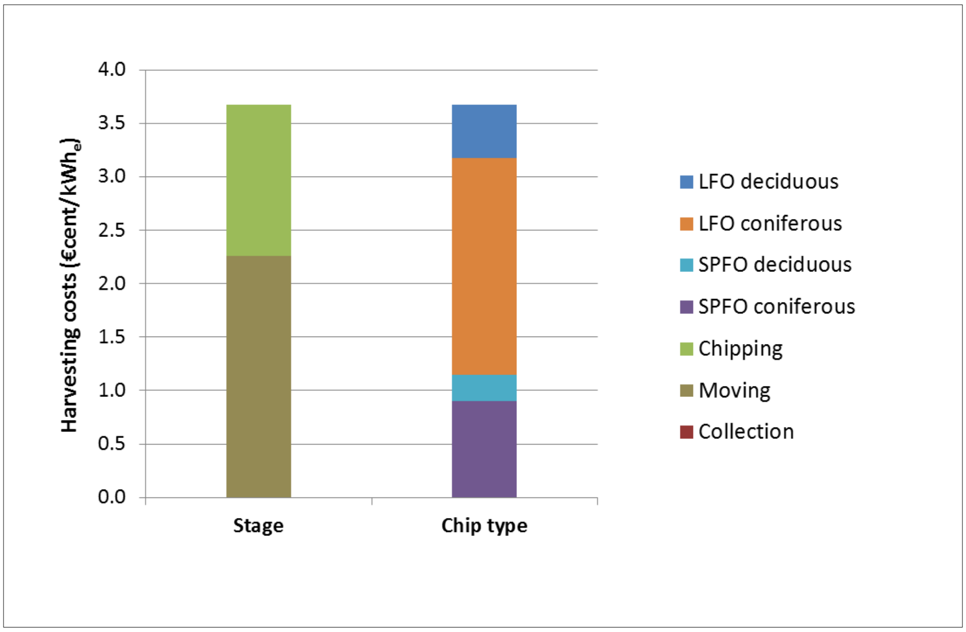

Figure 7.3: Cost component split of harvesting costs on the basis of both the harvesting stages and the types of wood chips for the supply chain of a representative FBG+E-based power plant of 20 MW_e

On another level, the specific harvesting costs can be broken down into the elements involving the four types of wood chips obtained from forest residues as a by-product. In this regard, Figure 7.3 refers to the coniferous forest areas managed by large forest owners, which produce the most significant cost component. The corresponding chip type of coniferous LFO (large forest owner) is identified as the most important input of forest residues to the representative power plant. This amount together with the coniferous SPFO chip type (small private forest owner) constitutes the most expensive contribution to the conversion units basically owing to the larger quantity harvested in the forests of Baden-Württemberg as well as the lower bulk density of coniferous compared to deciduous wood. The remaining portion relates to the deciduous part of forest residues, an amount that is categorised into the deciduous SPFO chip type and that of deciduous LFO. In general, these percentages depend mainly on the free potentials of forest residues – regarded as a by-product – that arise in each catchment area of a given power plant (see Figure 6.1 and Table 6.6). Anyhow, the cost component split of harvesting costs for the different FBG+E-based power plants yield certain changes with respect to the breakdown of the representative power plant shown in Figure 7.3.

7.2.2. Energy conversion of wood chips derived from forest residues as a by-product and landscape wood raw material

The implementation of the FBG+E technology for conversion of wood chips generated from forest residues as a by-product and landscape wood raw material (CHP/ByPro/LaW scenario) yields a solution, which is characterised by a spatial distribution of ten bioenergy plants with the maximum power output capacity of 20 MW_e throughout the whole region of Baden-Württemberg. They are installed in the following predetermined cities of Mosbach (Neckar-Odenwald-Kreis), Schwäbisch Hall, Aalen (Ostalbkreis), Pforzheim, Freudenstadt, Tübingen, Emmendingen, Tuttlingen, Biberach an der Riß and Waldshut-Tiengen (see Figure 7.4).

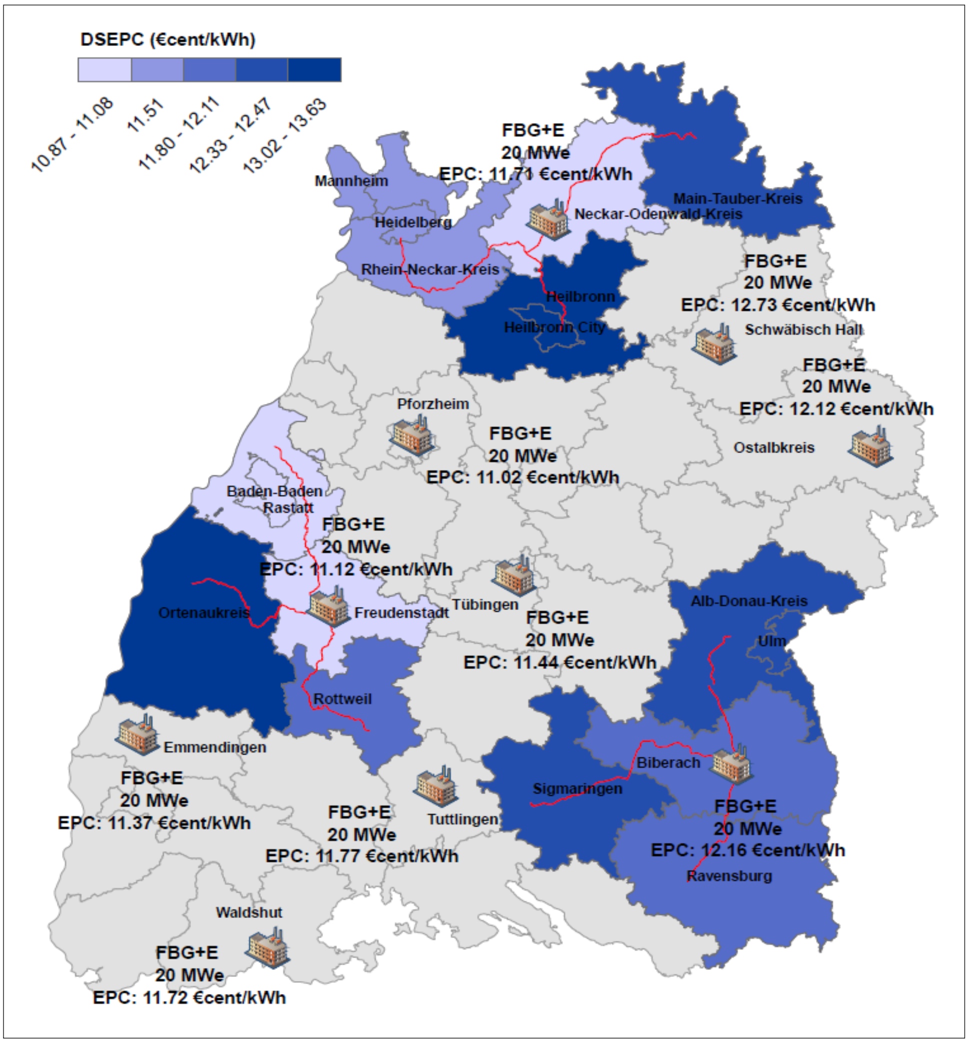

Figure 7.4: Location of the ten FBG+E-based power plants with the respective EPC along with three representative catchment areas illustrating the DSEPC in the corresponding administrative units

As a fluidised bed gasification process coupled to a gas engine shows an availability of 90% and is run at an utmost rate of 7,500 full-load hours per year, the chosen bio-based power plants render a specific electricity production cost (EPC) ranging between 11.02 €cent/kWh$_e$ in Pforzheim and a maximum value of 12.73 €cent/kWh$_e$ in the plant of Schwäbisch Hall. In this context, it is to be noted that the units located in Schwäbisch Hall, Ostalbkreis and Waldshut are respectively operated for 6,180, 6,303 and 7,066 h/a at full load. Therefore, a maximum EPC for the plant of Schwäbisch Hall might be accounted for, as this unit shows the higher reduction in its yearly operation time as compared to the other two. For reasons of clarity, only the catchment areas of three conversion units are depicted in Figure 7.4, concretely those of Neckar-Odenwald-Kreis, Freudenstadt and Biberach. They are all representative power plants of the set of all ten selected units, as they all three similarly describe the techno-economic features of this standard CHP technology. Thus, their catchment zones supply forest residues as well as landscape material to the corresponding bioenergy units for conversion into power. As a result, the DSEPC of the plant of Neckar-Odenwald-Kreis as well as those of Freudenstadt range from 10.87 €cent/kWh$_e$ in the central districts, where the plants are located, to 13.63 €cent/kWh$_e$ in the outlying administrative units. On the contrary, the DSEPC of the districts within the catchment area of the conversion unit to be installed in Biberach an der Riß present a more reduced span – from 11.98 €cent/kWh$_e$ in Biberach to 12.47 €cent/kWh$_e$ in Sigmaringen – on account of collecting slightly more economical wood resources in the outlying districts than those incurred in Biberach. As mentioned in the last section for the by-product based approach, the specific electricity production cost (EPC) of each bio-based power plant can be derived from the weighting of the DSEPC of the respective catchment area on the basis of their bioenergy contribution to the conversion unit. Regarding the transport of wood resources to the selected power plants, Baden-Württemberg's secondary road network is predominantly utilised within the corresponding areas of influence of each bio-based unit. On the contrary, the set of regional highways 5, 6, 7, 8 and 81, which are mostly used in the previous compound scenario to articulate the resource allocation to the chosen power plants, remains irrelevant and underused in this case.

Similarly to the case dealt with in the previous scenario, the specific EPC of a representative FBG+E-based power plant – the Freudenstadt conversion unit – is illustrated in Figure 7.5 broken down into their five cost components: harvesting, transport, annuity and the fixed and variable operating costs. In this regard, the investment and operation costs-related portion of the bio-based conversion unit stands for around 45% of the total amount of the EPC. This elevated proportion is accounted for by the increased expenses caused by gasification, in general, and due to the small scale of 20 MW$_e$, in particular. This percentage encompasses the annuity with a weight of roughly 24%, the fixed operating costs with circa 14% and the variable costs with a share of around 7%. All three parts are somewhat lower than the respective portions obtained in the prior compound scenario mainly due to the increased costs of wood resources, including now the more costly landscape wood raw material. By contrast, the complementary part consists of those costs incurred by harvesting and transport of wood resources with approximately 42% and 13%, respectively.

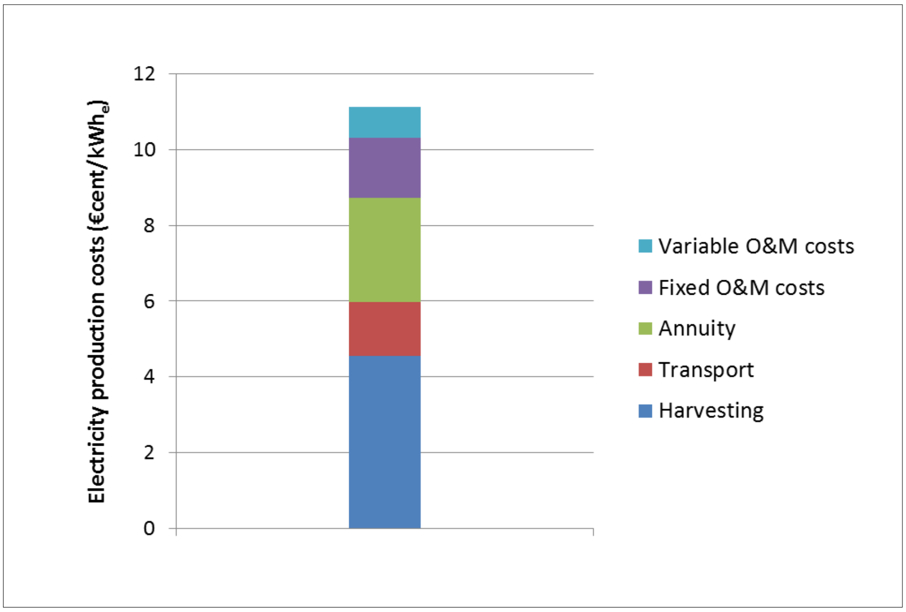

Figure 7.5: Cost breakdown of the electricity production costs of a representative FBG+E-based power plant of 20 MW$_e$ into their cost elements

As previously affirmed, the harvesting process is assigned the largest cost component within the specific electricity production costs for a FBG+E-based power plant fed with forest residues and landscape wood raw material. Aiming at gaining insight into the origin of these expenses, Figure 7.6 shows the specific harvesting costs of the representative power plant of Freudenstadt split into its fundamental cost elements. For this purpose, two different approaches are implemented, either as a breakdown into the corresponding three harvesting stages (collection, moving and chipping of wood resources) or as a division into the six types of wood chips resulting from coniferous and deciduous forest residues as a by-product, SPFO and LFO (see Table 6.3), together with S<50L and S>50L (see Table 6.2) from landscape wood raw material.

Because forest residues are considered as a by-product, no collection costs contribute to the specific harvesting costs, since these expenses are apportioned to lumber production. Nevertheless, landscape wood raw material is harvested as a whole tree and therefore involves some minor amount of collection costs (see Figure 7.6). This, on account of the reduced proportion of landscape-based resources in comparison to forest residues (ratio 1:2), gives rise to a relatively low share of collection costs (16%), which in turn vary from one power plant to another. On the other hand, the cost component concerning moving accounts for around 50%, while it reaches an intermediate value of 34% for the stage of chipping.

When the specific harvesting costs are broken down into the contributions of the six types of wood chips produced from forest residues as a by-product and landscape-based resource (see Figure 7.6), the largest cost components are attributable to the chip types involving coniferous LFO (large forest owner) and landscape wood-based S<50L (slope lower than 50%). These types of wood chips generally change as a function of the kind of resources growing in the area of influence of each conversion unit. The remaining costs are allocated to the rest of the chip types in varying percentages that rely on the amount of free potential produced in the different catchment areas of each FBG+E-based power plant according to data from Figure 6.1 and Figure 6.3 (see Table 6.6 and Table 6.8).

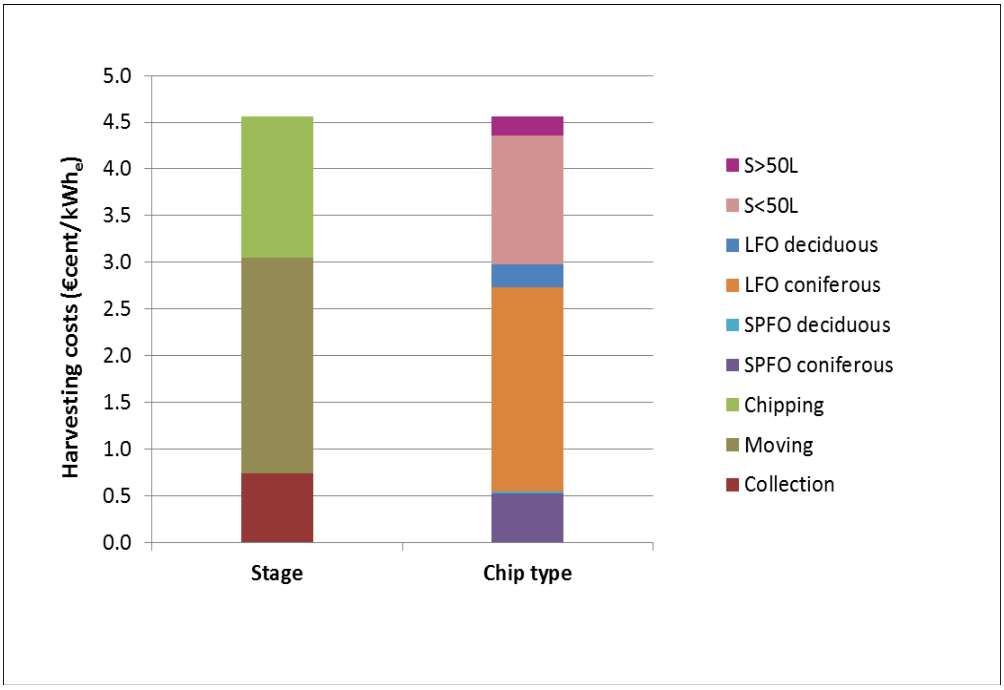

Figure 7.6: Cost component split of harvesting costs on the basis of both the harvesting stages and the types of wood chips for the supply chain of a representative FBG+E-based power plant of 20 MW_e

7.2.3. Energy conversion of wood chips derived from forest residues as a joint product

The CHP/JointPro/NonLaW compound scenario consists in the energy conversion of forest residues as a joint product by means of the technology option based on FBG+E. This scenario yields a similar solution to that obtained when this resource is contemplated as a by-product. As total unit costs of chip types involved in one scenario are different to those costs of the other (compare Table 6.3 and Table 6.4), then the outcome of both cases is also different – although this difference appears exclusively in terms of costs. Nevertheless, the allocation of wood resources to the diverse conversion units as well as their location within the region of Baden-Württemberg is for this specific spatial partition based on districts completely equal in both scenarios. In this sense, the corresponding solution comprises the same six FBG+E-based power plants equipped with a maximum capacity of 20 MW_e, as in the by-product approach. Therefore, they are equally placed in the same predetermined sites, namely the cities of Mosbach (Neckar-Odenwald-Kreis), Aalen (Ostalbkreis), Calw, Freudenstadt, Emmendingen and Sigmaringen (see Figure 7.7).

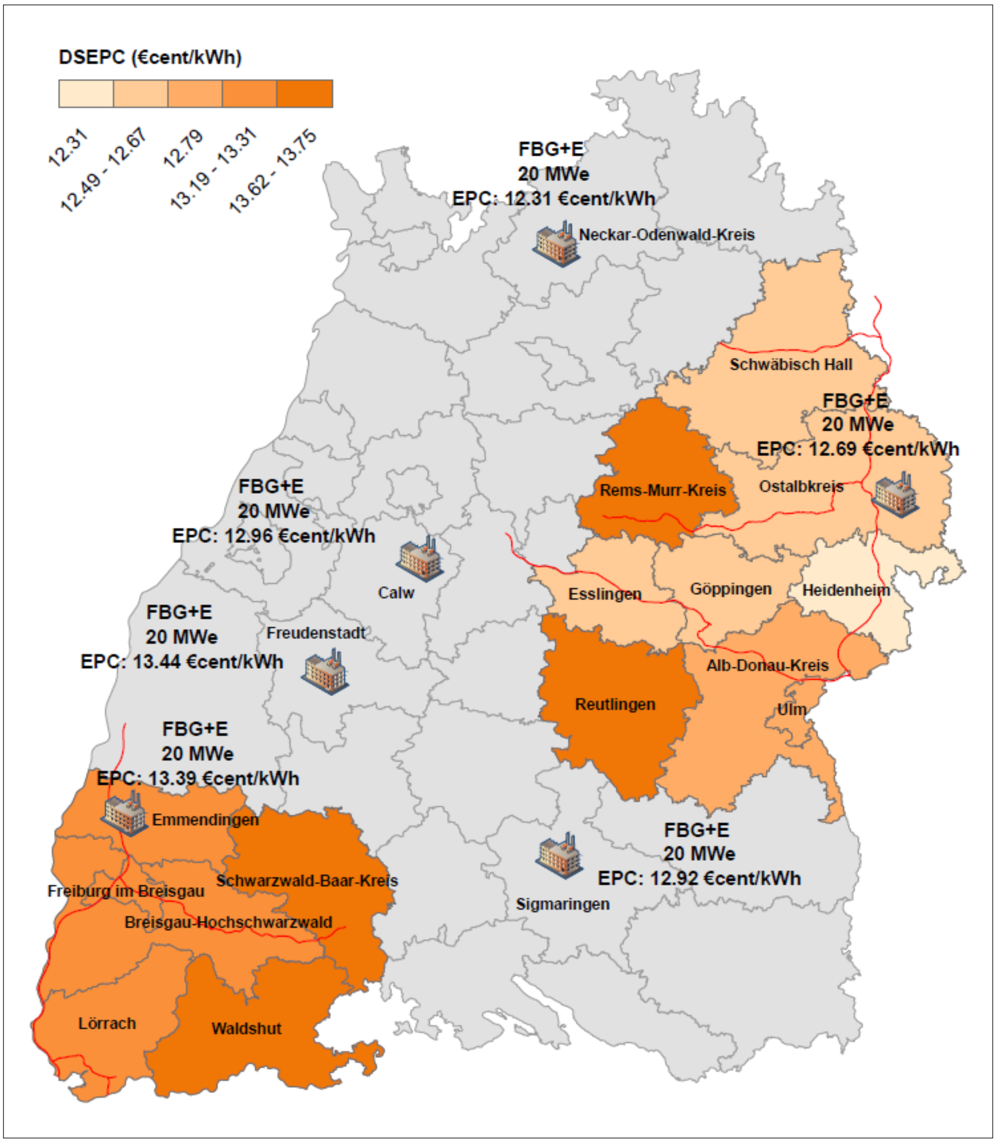

Figure 7.7: Location of the six FBG+E-based power plants with the respective EPC along with two representative catchment areas illustrating the DSEPC in the corresponding administrative units

All six chosen bio-based power plants work yearly for 7,500 hours at full load. Accordingly, they show specific electricity production costs (EPC) comprised between 12.31 €cent/kWh$_e$ in Neckar-Odenwald-Kreis and the highest value of 13.44 €cent/kWh$_e$ in the conversion unit of Freudenstadt (see Figure 7.7). Again, the catchment areas of the bio-based units of Emmendingen and Ostalbkreis are depicted in Figure 7.7 together with their corresponding district-specific electricity production costs. As in the by-product based scenario, both plants are taken as a representative unit as they perfectly reproduce the techno-economic behaviour of this kind of technology for the most cost-efficient scale of 20 MW$_e$. In such a context, the catchment area of the plant installed in Aalen (Ostalbkreis) presents a noticeable variation of the district-specific production costs (DSEPC), which range from 12.31 €cent/kWh$_e$ in Heidenheim to a maximum value of 13.75 €cent/kWh$_e$ in Reutlingen. In contrast, the administrative units supplying the plant located in Emmendingen are assigned a DSEPC ranging between 13.19 €cent/kWh$_e$ in Lörrach and 13.74 €cent/kWh$_e$ in Waldshut. As in the previous scenario, the weighting of all DSEPC for a given catchment area according to their bioenergy contribution yields the specific electricity production cost (EPC) of the corresponding bio-based power plant. Similarly to the case of forest residues regarded as a by-product, the district of Rems-Murr-Kreis in the catchment area of the power plant of Aalen shows a quite high DSEPC if the distance to the conversion place is allowed for. This is equally accounted for by the unique contribution of 4,109 t FW of the costly chip type, coniferous S<50F, that is harvested from forest areas with steepness of slope below 50%. Also the district of Heidenheim, as in the by-product approach, is assigned a relatively low DSEPC on account of the significant harvested amount of cheaper deciduous forest residues in comparison to other nearby administrative units. Within the Emmendingen’s catchment area, the DSEPC of Lörrach similarly remains at a quite low value – even lower than those registered for the district of the power plant in Emmendingen – as a result of its almost equal amount of free potentials for both deciduous and coniferous forest residues. This inevitably gives rise to cheaper costs of resource and hence lesser DSEPC than in most districts, where the ratio of coniferous to deciduous forest areas is significantly higher than one. Likewise, the district of Schwarzwald-Baar-Kreis shows a relatively high DSEPC – nearly as high as that of Waldshut – basically due to the expensive chip type involving coniferous S<50F, which is predominant in the district with an amount of 9,462 t FW.

Figure 7.8 illustrates the breakdown of the specific electricity production costs (EPC) incurred by the FBG+E-based plant of Emmendingen as a representative conversion unit into their cost components harvesting, transport, annuity and the fixed and variable O&M costs. The investment and operation-related share of this bio-based conversion unit reduces with respect to the previous scenarios and makes up roughly 39% of whole EPC. In this context, the annuity has a weight of about 21% while the fixed and variable operating costs account for circa 12% and 6%, respectively. The remaining costs are constituted by the contributions made by the stages of harvesting and transport. The cost component of harvesting amounts to roughly half the EPC (49%) owing to the increased expenses of forest residues when regarded as a joint product. In general, the high contribution of the harvesting cost component markedly determines the final amount of the EPC costs for all bio-based power plants. Whereas the cheapest EPC is registered by the conversion unit of Neckar-Odenwald-Kreis with the lowest harvesting costs valued at around 5.45 €cent/kWh$_e$, the power plant of Freudenstadt shows the most expensive EPC due to the highest harvesting cost of around 6.79 €cent/kWh$_e$. These higher costs in the Freudenstadt’s supply area are in turn related to the more costly coniferous forest residues, which are there in higher proportion than the more economical deciduous ones. On the other hand, the portion concerning the transport of forest residues decreases with respect to the last compound scenarios, thus representing about 12% of the specific EPC.

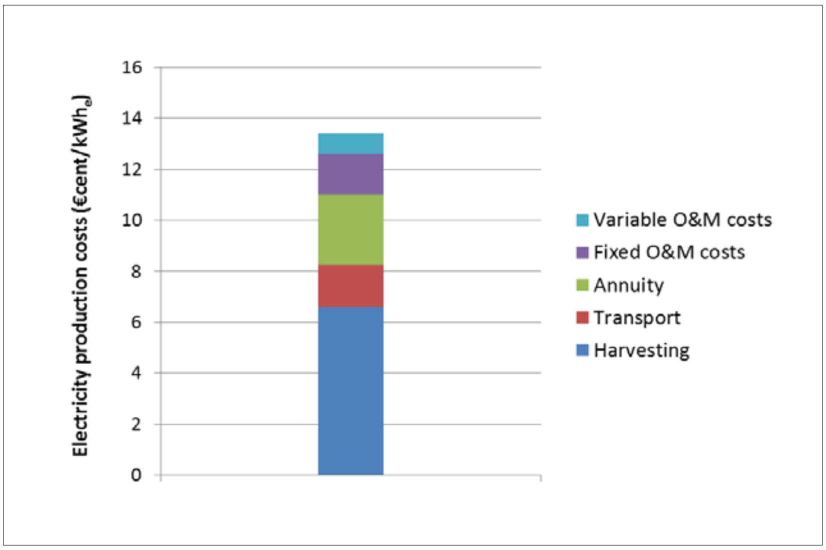

Figure 7.8: Cost breakdown of the electricity production costs of a representative FBG+E-based power plant of 20 MW$_e$ into their cost elements

The cost component associated with the process of harvesting forest residues as a joint product constitutes nearly half the specific electricity production costs of any of the FBG+E-based power plants. As a consequence of this relevance within the entire EPC costs, the specific harvesting costs of the representative power plant in Emmendingen are split into its cost components in Figure 7.9 below. As in the prior scenarios, the corresponding elements are calculated by means of a breakdown into the contributions from either the harvesting stages (collection, moving, chipping) or the four types of wood chips harvested from coniferous and deciduous forest residues contemplated as a joint product: S<50F and S>50F from areas with steepness of slope below and above 50%, respectively (see Table 6.4).

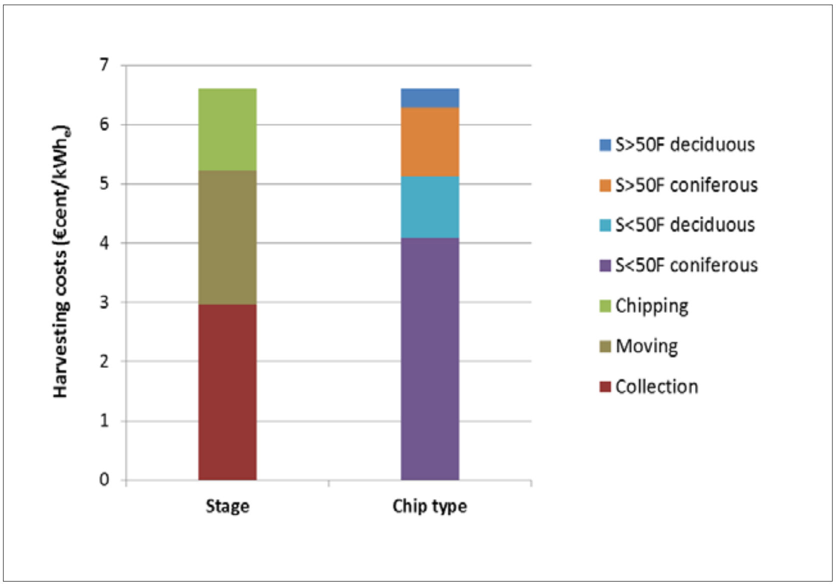

Figure 7.9: Cost component split of harvesting costs on the basis of both the harvesting stages and the types of wood chips for the supply chain of a representative FBG+E-based power plant of 20 MW$_e$

When forest residues are considered as a joint product, those costs incurred in the collection stage are then taken into account within the entire specific harvesting costs. The cost component of this stage constitutes around 45% of EPC for the representative power plant of Emmendingen. On the other hand, the cost elements concerning the moving and chipping stages make up roughly 35% and 20%, respectively (see Figure 7.9).

If the specific harvesting costs are split into the elements regarding the four kinds of chipped forest residues as a joint product, the type of wood chips involving the coniferous portion of S<50F (slope below 50%) contributes with the most important input to such costs. This cost component represents a span comprised between 60% and 70% of harvesting costs for all bio-based conversion units. This elevated percentage is mainly caused by the comparatively greater quantity of this resource as well as the lower bulk density of coniferous with respect to deciduous wood. The deciduous share mostly stands for an overall cost component of approximately 20-25% and is particularly represented by the S<50F chip type with a 15% portion in the case of the representative power plant of Emmendingen. In general, these fractions are mainly dependent on the free potentials of forest residues (joint product) originating in each specific catchment area (see Figure 6.2 and Table 6.7). As a result, they vary significantly from one power plant to another.

7.2.4. Energy conversion of wood chips derived from forest residues as a joint product and landscape wood raw material

The use of the FBG+E-based technology option for conversion of wood chips derived from forest residues as a joint product and landscape resources in the CHP/JointPro/LaW scenario generates an analogous solution to the case in which the chipped wood resources result from processing forest residues regarded as a by-product as well as landscape wood raw material. The unalike cost allocation methods employed for assessing forest residues in both scenarios definitely makes the difference in the cost structure of the targeted bioenergy subsystem. Nevertheless, the spatial distribution of wood resources among the different bio-based power plants as well as the location of such facilities throughout the region of Baden-Württemberg is the same in both situations for this sort of spatial unit (district). In this way, the solution is consists of an array of ten FBG+E-based conversion units with the most cost-efficient power output capacity of 20 MW_e. Moreover, the identified power plants are assigned to the same districts as in the compound scenario where forest residues as a by-product and landscape wood resources are valorised. Concretely, the selected locations for the selected power plants are the cities of Mosbach (Neckar-Odenwald-Kreis) and Aalen (Ostalbkreis) as well as the capital cities of the districts of Schwäbisch Hall, Pforzheim, Freudenstadt, Tübingen, Emmendingen, Tuttlingen, Biberach and Waldshut (see Figure 7.10).

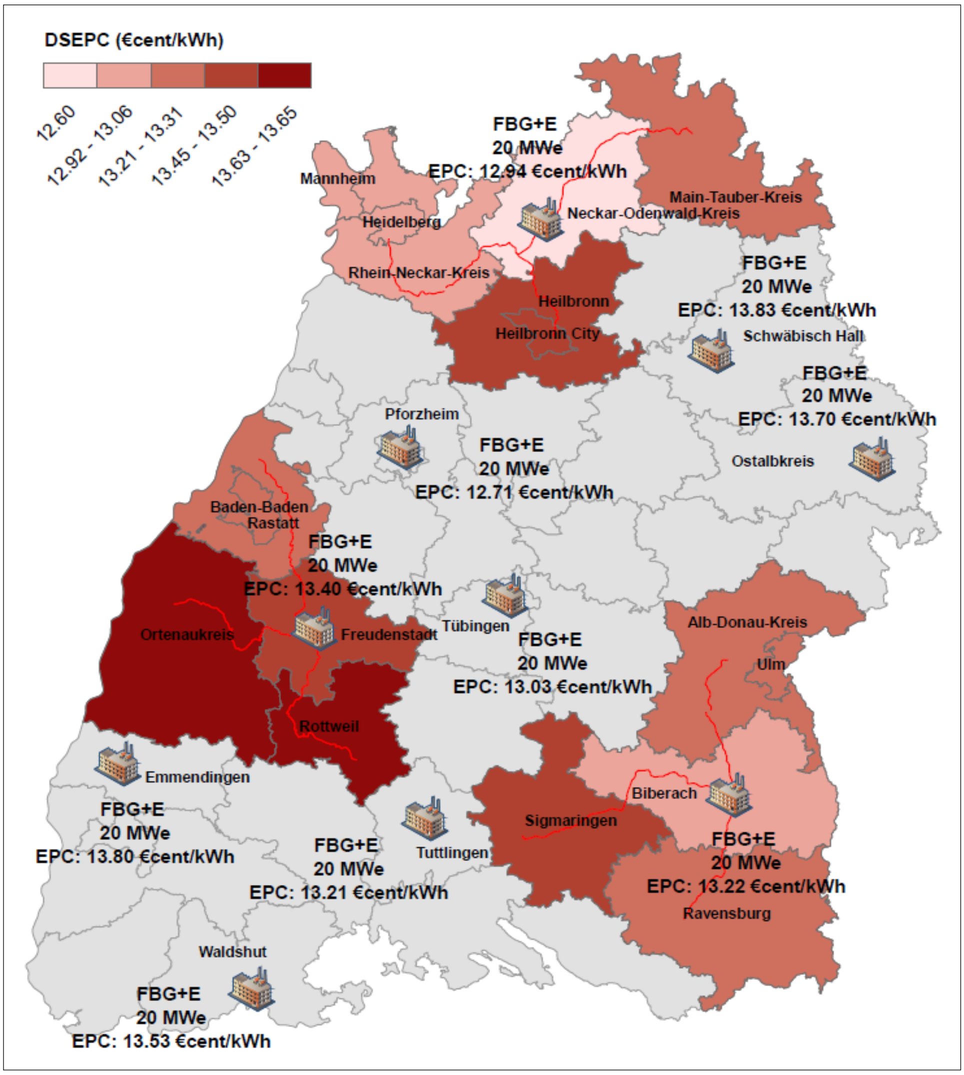

Figure 7.10: Location of the ten FBG+E-based power plants with the respective EPC along with three representative catchment areas illustrating the DSEPC in the corresponding administrative units

On the basis of a process availability of 90%, the ten FBG+E-based power plants are operated for a maximum of 7,500 h/a under full load at a specific electricity production cost (EPC) ranging from 12.71 €cent/kWh$_e$ in Pforzheim to 13.83 €cent/kWh$_e$ in the power plant of Schwäbisch Hall. Similarly, both conversion units respectively reproduce the lowest and the highest EPC as in the scenario involving wood chips derived from forest residues as a by-product and landscape resources. In this regard, the elevated EPC of the latter plant equally derives from a shorter operation time of 6,180 h/a at full load than the rest of the conversion units. As in the other compound scenario, the power plants of the Ostalbkreis and Waldshut districts work at a yearly rate of respectively 6,303 and 7,066 h under full load thus also showing substantially higher production costs than the rest. In order to represent the solution of this scenario, Figure 7.10 illustrates the location of all ten power plants along with their electricity production costs. In this sense, only three conversion units serving as representative bio-based power plants are depicted with their corresponding catchment areas for reasons of clarity. These units are the same that those showed in the scenario dealing with forest residues as a by-product and landscape resources, namely the bio-based units installed in the districts of Neckar-Odenwald-Kreis, Freudenstadt and Biberach. The electricity production costs (EPC) of all three units are associated with the weighted average of all district-specific electricity production costs (DSEPC) within each catchment area. In this connection, both plants of Freudenstadt and Biberach an der Riß show DSEPC gradually varying from 13.06 €cent/kWh$_e$ at the site of conversion to 13.65 €cent/kWh$_e$ in the peripheral districts. On the contrary, a broader range of DSEPC (12.61-13.47 €cent/kWh$_e$) results for the area of influence of the bio-based unit located in Neckar-Odenwald-Kreis owing to the comparatively lower costs of wood resources growing in the central district in relation to the outlying areas. Additionally, the districts of Baden-Baden and Rastatt within the catchment area of the Freudenstadt power plant render a little lower DSEPC (13.21 €cent/kWh$_e$) in comparison to the value of 13.45 €cent/kWh$_e$ that is registered for the administrative unit itself, where the power plant is installed. This effect is accounted for by the higher amount of the more economical deciduous portion of both S<50F and S>50F chip types (forest areas with steepness of slope below and above 50%), which total 14,371 t FW in Rastatt and Baden-Baden versus a more reduced quantity of 1,223 t FW harvested in the forests of Freudenstadt.

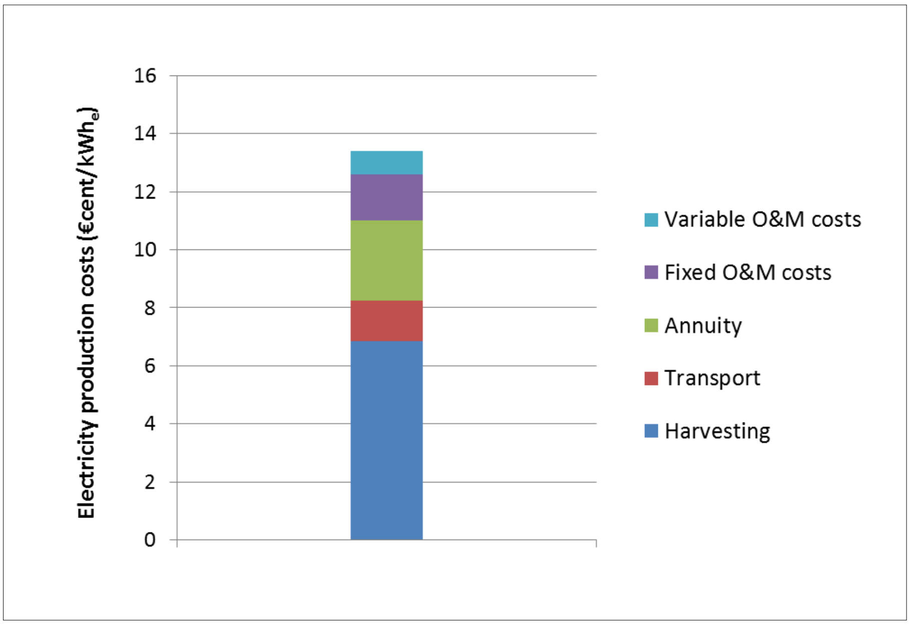

Figure 7.11: Cost breakdown of the electricity production costs of a representative FBG+E-based power plant of 20 MW$_e$ into their cost elements

Figure 7.11 shows the cost breakdown of the specific EPC registered in the FBG+E-based power plant of Freudenstadt, one of the three representative 20 MW$_e$ power plants being provided with forest residues and landscape wood raw material. The cost components relate to the corresponding portions of the harvesting and transport processes besides those concerning the annuity and the fixed and variable O&M costs. The shares involving the investment and operation expenses of the chosen bio-based power plant constitutes roughly 39% of the EPC as in the previous scenario. In the same way, each constituent is assigned a percentage of 21%, 12% and 6% for the annuity, the fixed and variable operating costs, respectively. On the other hand, the portions of harvesting and transport make up around 50% and 11%, in that order. In this regard, the increasingly higher costs of wood resources with respect to the prior compound scenarios induce a slight rise of the harvesting cost component.

Since the harvest of wood resources accounts for half the specific EPC of the conversion unit, a further analysis into the costs elements forming the specific harvesting costs is required. For this purpose, Figure 7.12 illustrates these expenses broken down into its cost components for the representative power plant of Freudenstadt.

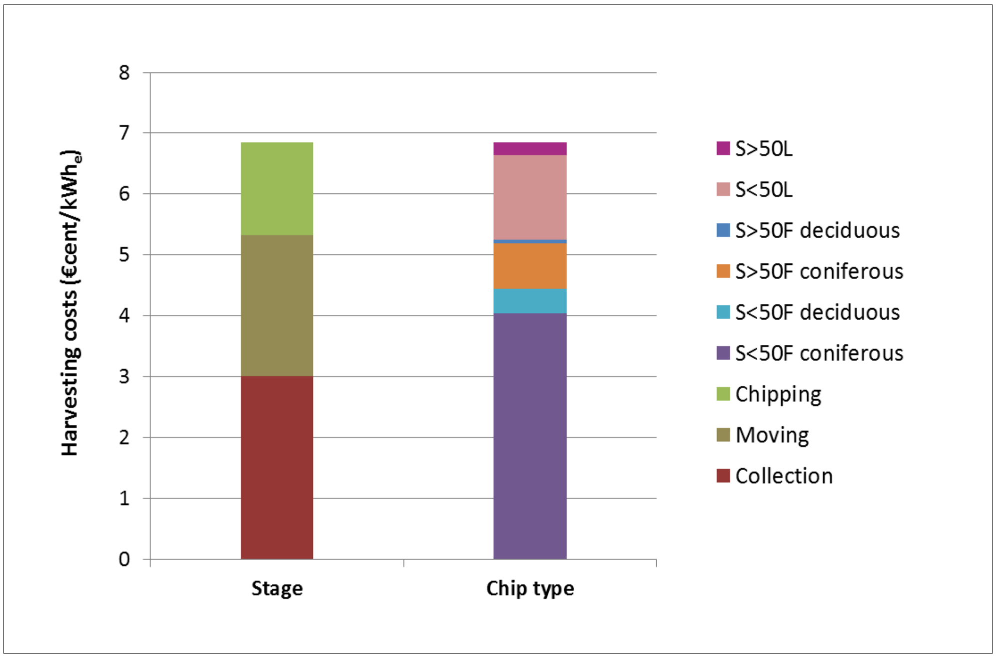

Figure 7.12: Cost component split of harvesting costs on the basis of both the harvesting stages and the types of wood chips for the supply chain of a representative FBG+E-based power plant of 20 MW_e

The cost component split of the specific harvesting costs expressed as a series of contributions associated with the three stages of harvest (collection, moving and chipping of wood resources) yields a major share of 43% for the collection labours, while the moving and chipping processes respectively represent around 34% and 23% depending on the proportion of the chip types fed to each power plant.

On the other hand, if harvesting costs are broken down into the shares concerning the six types of wood chips produced from forest residues as a joint product and landscape wood raw material (see Table 6.2 and Table 6.4), the cost components associated with the chip types involving coniferous S<50F and S<50L from forest and landscape areas with a slope lower than 50% total approximately 80% of the whole harvesting costs for most conversion units. The rest of the costs are apportioned to the remaining types of wood chips in variable proportions according to the free potentials growing in the different catchment areas of each FBG+E-based unit (see Figures 6.2-3 and Tables 6.7-8).

7.3. Scenarios based on the co-firing technology

As in the last section, the technology simple scenario is combined with two further simple scenarios relating to both cost allocation methods employed for estimating the total unit costs of chipped forest residues as a by-product or as a joint product. Similarly, the consumption or not of landscape wood raw material is considered as two further simple settings. Thus, the resulting four compound scenarios represent dissimilar conditions where the free potentials of wood resources are supplied to coal-fired power plants equipped with co-firing based retrofitted combustion systems for conversion into bio-based power. In this regard, power produced from wood resources in such facilities is remunerated on a different basis than the electricity generated from coal. The latter is sold in power wholesale markets at freely determined prices that are paid to plant operators without consideration of market premiums.

Table 7.3: Techno-economic features of the preselected coal power plants eligible for co-firing based retrofitting in existing units of Baden-Württemberg

Power plant	**Location / District**	**Bio-based capacity**	**Specific capital costs**	**Specific fixed O&M costs**	**Specific variable O&M costs**	**Electric efficiency**
		MW	*€/kW$_e$*	*€/kW$_e$*	*€cent/kWh$_e$*	*%*
ALT HKW 1	Altbach / Esslingen	43.3	256	40.62	0.52	36.1
ALT HKW 2	Altbach / Esslingen	33.6	258	42.28	0.53	35.5
HLB 7	Heilbronn	77.8	249	37.03	0.50	37.5
RDK 7	Karlsruhe	50.5	254	39.64	0.52	36.5
RDK 8	Karlsruhe	84.2	249	36.57	0.50	37.6
Block 6	Mannheim	25.5	261	44.16	0.54	34.9
Block 8	Mannheim	43.5	256	40.59	0.52	36.1
Block 9	Mannheim	84.3	248	36.56	0.50	37.6
GAI DT 14	Gaisburg / Stuttgart	2.2	289	64.77	0.63	29.3
MÜN DT 12	Münster / Stuttgart	4.5	281	58.09	0.60	30.9
MÜN DT 15	Münster / Stuttgart	4.5	281	58.09	0.60	30.9
HKW Magirusstr.	Ulm	2	290	65.67	0.63	29.1

Table 7.3 introduces the list of coal-fired power plants that can be partially adapted to co-firing of wood resources and therefore be involved in the modelling of the targeted bioenergy system for this technology. This table includes twelve existing coal conversion units – with locations in the districts of Esslingen, Heilbronn, Karlsruhe, Mannheim, Stuttgart and Ulm – that were previously preselected in subsection 6.7.1. These power stations are characterised by the fact that they can be fed with up to a 10% share of wood resources within the total primary energy input made up of coal and wood, if direct co-firing is implemented (see subsection 4.1.4). Therefore, the portion of their bio-based capacity – which consequently relates to a 10% part of the original power output capacity of each coal-fired power plant (see Table 6.5) – is estimated for each of the power generation units. In addition, the electric efficiency along with the specific incremental investment costs and the fixed and variable operating costs for each power plant are detailed in Table 7.3 on the basis of the regression curves of Figures 4.1-4 as techno-economic input data for modelling this technology.

Since the availability of coal-fired power plants typically reaches up to 94% [EPA 2007], they could operate for a maximum number of full load hours in the order of 8,000 h/a in case that the installation of co-firing might prove to be economically attractive. As total system costs are minimised, the analysed bioenergy system might evolve towards an ensemble of conversion units being run for the highest possible amount of hours at full load. Nevertheless, this is currently not the reality of existing coal power plants in Baden-Württemberg or Germany. In fact, hard coal-fired power stations in Germany operate a rather lower amount than 8,000 h/a, specifically an annual average of 3,600 full load hours according to the statistics published by [Statista 2018]. Actually, the averaged load factor of hard coal-fired power stations in the southern federal states of Germany is even somewhat lower than the above referenced level. As the ultimate goal is the reduction of greenhouse gases (including CO_2) through an adequate energy policy based on sustainable and environmentally friendly power generation, an even lower annual amount in the order of 3,000 full load hours is assumed for the modelling of the four co-firing compound scenarios in Baden-Württemberg. In this way, the use of coal is not only reduced by 10% due to the input of biomass, but there is also a small consumption owing to the lowering of load factor. As referred to in the last section, lower full load hours than those previously determined at 3,000 full load hours are only reached when the free potentials of wood resources are exhausted and no additional bio-based power is produced.

The simple scenario of co-firing is combined with four additional base scenarios built upon the type of cost allocation procedure for chipped forest residues as a by-product or as a joint product and two further simple scenarios relying on the utilisation or not of landscape wood raw material as wood resource for conversion into power. The resulting four compound scenarios together with their solutions are described and illustrated in the following subsections for the wood resources-based bioenergy system of Baden-Württemberg. This is carried out by means of eliminating the effect of the profitability constraints involving each possible bioenergy plant for all its possible locations and its whole range of capacities but complying with this restriction at a high enough level of remunerations – i.e. higher than the corresponding electricity production costs obtained at the breakeven point.

7.3.1. Co-firing of wood chips derived from forest residues as a by-product

The Cofi/ByPro/NonLaW scenario, which is based on the use of co-firing technology by co-combusting chipped forest residues regarded as a by-product, renders a solution consisting of seven units. These power plants are the most cost-efficient and are selected from the list of eligible coal-fired power stations of Baden-Württemberg in Table 7.3. They can be retrofitted with the aim of converting the free potentials of forest residues into power. The resulting facilities, which are illustrated in Figure 7.13, are ALT HKW 1 and ALT HKW 2 in Altbach (Esslingen), HLB 7 in the urban district of Heilbronn, both RDK 7 and RDK 8 in the city of Karlsruhe as well as both Block 6 and Block 9 of Mannheim respectively with a bio-based power output capacity of 43.3, 33.6, 77.8, 50.5, 84.2, 25.5 and 84.3 MW_e. As an example, the catchment area of RDK 8 is represented on the map of Figure 7.13 by means of a coloured unit along with its electricity production costs (EPC) and district-specific electricity production costs (DSEPC) for each district. The rest of the retrofitted coal-fired power plants are similarly placed in their corresponding locations by showing a black-and-white image together with their respective EPC. As previously indicated, a maximum level of 3,000 full load hours per year is assigned to the operation of each selected conversion unit. In fact, all but one are run at this maximum rate with the exception of Block 6. This unit in Mannheim is operated for 2,910 hours per year at full load owing to the exhaustion of free potentials of forest residues over the federal state. For these operating conditions, the selected upgraded power plants register EPC varying from 6.57 to 8.35 €cent/kWh_e with expenses showing no economies of scale due to the distortion effect induced by both harvesting and transport costs. In this respect, the Block 9 coal power plant with 84.3 MW_e is the largest unit within the targeted region (see Table 7.3) and hence shows the lowest capital and operating costs. Thus, it also renders the lowest EPC even though both harvesting and transport costs might have become enough large so as to set its EPC higher. On the other hand, the highest EPC registered by Block 6 are inevitably associated with the reduced rate of full load hours (2,910) as against the higher level (3,000) of the remaining units. Mention should also be made of the different highways and major roads permitting forest residues to be transported from forest areas to the corresponding conversion unit of each catchment area. The highway 5 together with other secondary roads are the main transport infrastructures within the supply area of RDK 8 in Karlsruhe, whereas the thoroughfares 8, 81 and 6 besides their tributary roads enable forest residues from the remaining catchment zones to be carried to the corresponding bioenergy plants.

Special focus is given to the RDK 8 coal power plant so as to illustrate the cost distribution over the corresponding catchment area. This power station renders a specific EPC of 7.21 €cent/kWh_e, which results from the weighting of the DSEPC incurred within the entire catchment area with values ranging from 6.12 €cent/kWh_e in Ortenaukreis to 7.91 €cent/kWh_e in Waldshut. The aim of the optimisation process is to primarily supply more costly wood resources to bioenergy units with the cheapest investment and operating expenses or even the highest efficiency in order to reduce the total costs of the system. Moreover, the district of Emmendingen derives its total free potentials of forest residues out of the catchment area of RDK 8 by allocating them to both Block 6 and Block 9 in Mannheim.

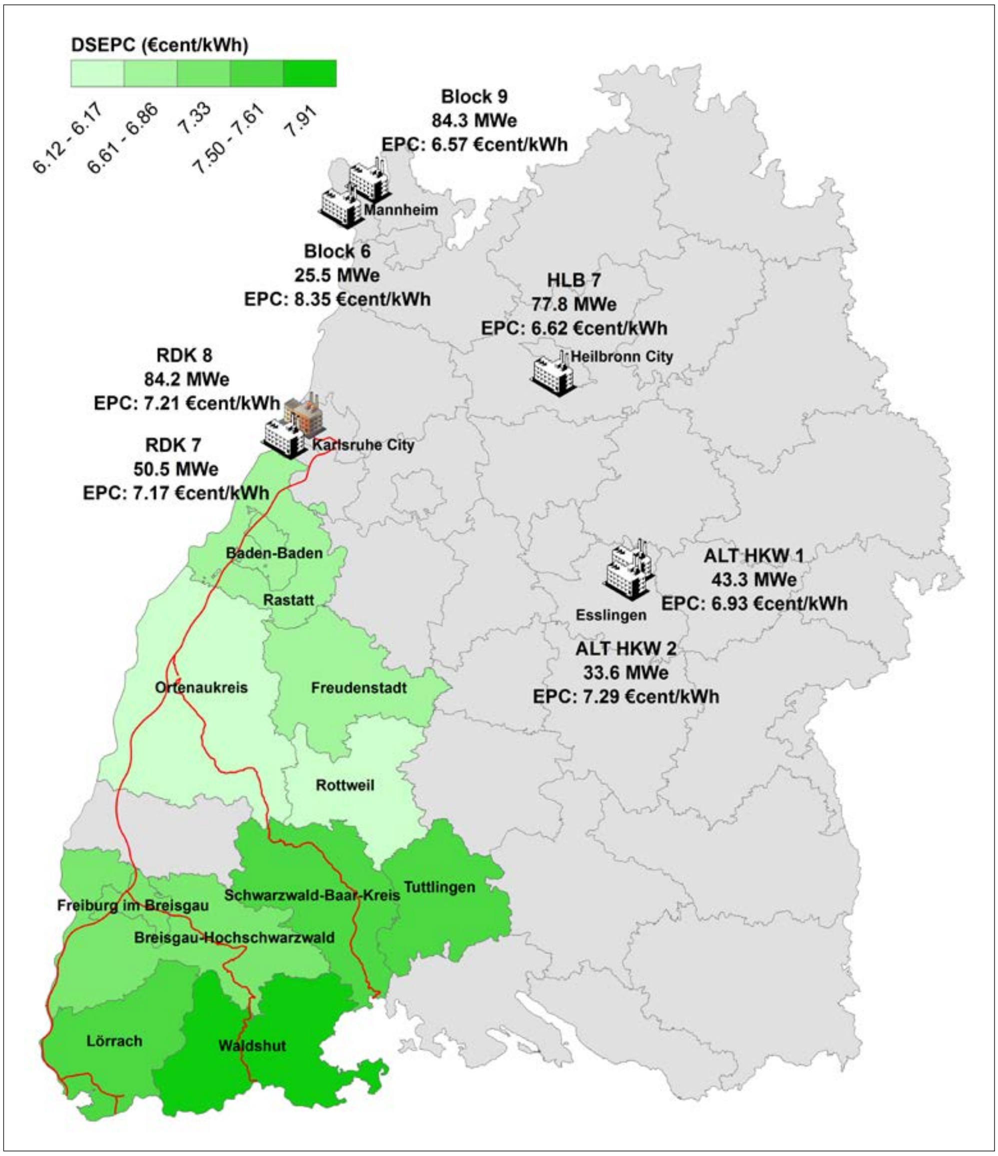

Figure 7.13: Location of the selected co-firing based coal power plants as well as illustration of the catchment area of RDK 8 respectively with their corresponding EPC and DSEPC in each specific district

On another level, the specific EPC of four representative power plants covering the whole scale range, namely RDK 8, HLB 7, ALT HKW 1 and Block 6, are displayed in Figure 7.14 broken down into the cost components concerning harvesting, transport as well as the corresponding annuity and the fixed and variable O&M costs. The incremental investment and operation costs of RDK 8 and Block 6 account for roughly 34% of the EPC, whereas those of HLB 7 and ALT HKW 1 represent a little more around 37%. These outcomes demonstrate once again the independence of production costs with scale, albeit the technology-related cost components show the typical light dependence of co-firing. The supply chains of the four conversion units have a strong influence on the formation of EPC on account of the major weight of cost constituents involving harvesting and transport of forest residues. Whereas the cost components of harvesting and transport for both HLB 7 and ALT HKW 1 units respectively represent circa 39% and 24% of their specific EPC, those of RDK

8 and Block 6 are in the order of 37% and 29%. The higher transport share of EPC for RDK 8 in relation to that calculated for HLB 7 and ALT HKW 1 is accounted for by the fact that the Karlsruhe conversion unit lies geographically out of its catchment area (see Figure 7.13), thus bringing about increased transport costs of chipped forest residues.

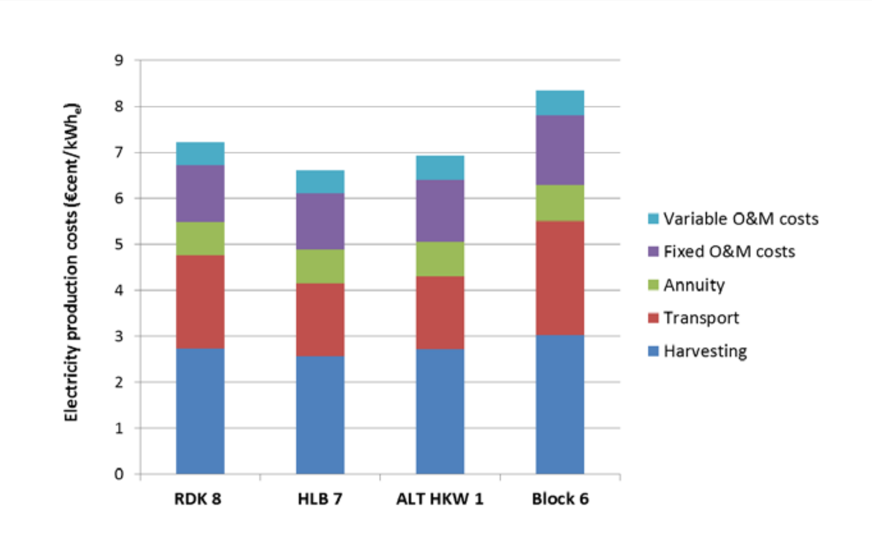

Figure 7.14: Cost breakdown of the EPC of the co-firing based RDK 8, HLB 7, ALT HKW 1 and Block 6 conversion units into their cost elements

The harvesting-related cost component of the four coal power plants represents a significant portion of circa 40%, somewhat less than half the specific electricity production costs of the plants (see Figure 7.14). Therefore, a cost breakdown of the specific harvesting costs incurred in the forest areas of the respective catchment areas (RDK 8, HLB 7, ALT HKW 1 and Block 6) is depicted in Figure 7.15 with the aim of shedding light on the factors originating such elevated expenses. For this purpose, the cost elements of the harvesting costs of each conversion unit are split according to two different criteria. That is, as a series of cost contributions either corresponding to each of the three harvesting stages (collection, moving and chipping of forest residues) or being associated with the four types of coniferous and deciduous chipped forest residues if regarded as a by-product when harvested by small private forest owners (SPFO) or large forest owner (LFO) – see Table 6.3.

As forest residues are considered as a by-product, then collection does not take place and the incurred costs are not allowed for in the total harvesting costs at forest road but apportioned to timber production. Thereby, no collection costs arise as a component of the specific harvesting costs for the supply chains of the RDK 8, HBL 7, ALT HKW 1 and Block 6 coal power plants (see Figure 7.15). The cost elements of moving and chipping respectively account for approximately 62% and 38% in all four cases. This is in line with the maximum variance of the stage of moving, namely 59.1-62.6%, as well as that of chipping with values varying between 37.4% and 40.9%.

On the other hand, when the specific harvesting costs are broken down into the contributions of the four types of chipped forest residues, different cost components arise as exposed in Figure 7.15. For the co-firing based RDK 8 coal power plant, the most important contribution of forest residues comes from forest areas administered by large forest owners, specifically from their coniferous portion. This amount constitutes roughly 69% of harvesting costs originating in the RDK 8's catchment area. Hence, it proves to be the main factor for the comparatively higher harvesting costs of this supply chain. This is to a large extent due to the lower bulk density of softwood in contrast to the higher values of deciduous wood (hardwood). Similarly, the forest areas of coniferous trees exploited by small private forest owners as part of the supply chain of RDK 8 also generates a significant cost component with a weight of around 15%. Some districts such as Freudenstadt, Rottweil and Schwarzwald-Baar-Kreis with a high share of coniferous forest areas produce a major contribution of forest residues that are finally consumed by the retrofitted coal power plant of Karlsruhe.

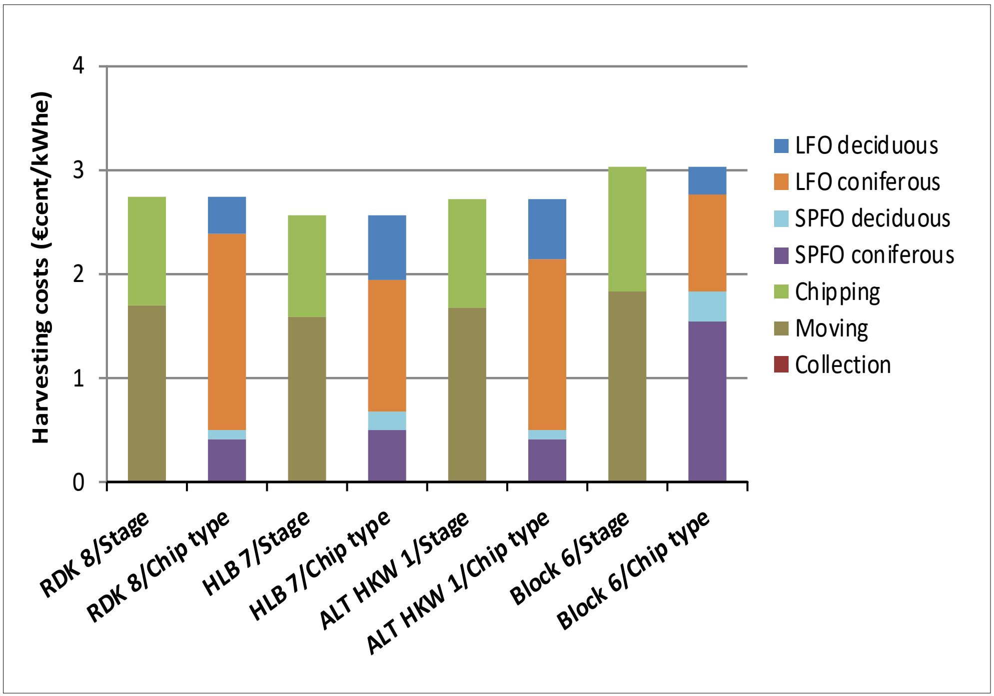

Figure 7.15: Cost component split of harvesting costs on the basis of both the harvesting stages and the types of chipped forest residues for the supply chains of the co-firing based RDK 8, HLB 7, ALT HKW 1 and Block 6 power plants

Regarding the cost component split of harvesting costs of the HLB 7's supply chain, it should be mentioned that the sum of both coniferous components (SPFO and LFO) adds up to 68.1% (19.4% + 48.7%) as opposed to a total percentage of 84.3% for RDK 8. This along with the higher proportion of the deciduous-related cost element for HBL 7 (31.9%) in opposition to that for RDK 8's supply chain (15.7%) results in noticeably lower harvesting costs of the former with respect to the latter. For ALT HKW 1, a similar cost component structure to that of RDK 8 is derived with the exception of proportion between the coniferous and deciduous share of chipped forest residues harvested by LFO. They respectively amount to roughly 59% and 22% in contrast to approximately 69% and 12% in the case of the conversion unit of Karlsruhe. By contrast, the smaller Block 6 power station presents a completely different costs component split where the coniferous portion of SPFO harvested wood residues accounts for up to 51%. This percentage is much higher than that of the remaining plants compared in Figure 7.15. In return, a lower coniferous fraction of chipped forest residues harvested by LFO (31%) are registered in comparison to the rest of the supply chains.

7.3.2. Co-firing of wood chips derived from forest residues as a by-product and landscape wood raw material

The option of co-firing wood chips produced from forest residues regarded as a by-product and landscape wood raw material in the framework of the Cofi/ByPro/LaW compound scenario generates a more complex solution for the targeted bioenergy subsystem of Baden-Württemberg. This is obtained by taking into account all the preselected coal-fired power plants of Baden-Württemberg (see Table 7.3) as suitable units for being upgraded to the cleaner co-firing technique. Thus, the retrofitted power plants convert the most economical wood resources into power while a fraction of the more costly resources remains unconsumed. The model-based solution is made up of all twelve eligible power stations with their corresponding bio-based capacity fraction: namely both ALT HKW 1 (43.3 MW_e) and ALT HKW 2 (33.6 MW_e) in the city of Altbach (Esslingen), HLB 7 (77.8 MW_e) in Heilbronn, both RDK 7 (50.5 MW_e) and RDK 8 (84.2 MW_e) in the urban district of Karlsruhe, the three Blocks (6, 8 and 9) of Mannheim – with respectively 25.5, 43.5 and 84.3 MW_e –, GAI DT 14 (2.2 MW_e) in Gaisburg (Stuttgart), both equally scaled MÜN DT 12 and MÜN DT 15 (4.5 MW_e) in the city of Münster (Stuttgart) as well as the Ulm coal-fired power plant with 2 MW_e of bio-based installed capacity. In this regard, Figure 7.16 illustrates by way of example both catchment areas of RDK 8 and HLB 7 (coloured units) with their corresponding electricity production costs (EPC) and district-specific electricity production costs (DSEPC), while solely the locations as well as their respective EPC are showed for the remaining power stations (black-and-white images). All the retrofitted power plants are yearly run at the maximum rate of 3,000 full load hours and hence still leave a significant amount of wood resources unconsumed – concretely for landscape wood raw material, whereas forest residues are fully converted into power. Under these conditions, the EPC of the twelve upgraded power stations range from 7.06 to 9.42 €cent/kWh_e. These specific magnitudes are basically independent from the respective power output capacity since the remaining cost contributions (harvesting and transport) substantially alter the expected scale effect. On a separate issue, it is to be noted that the different highways and major roads allow wood resources to be transported from forest and landscape zones to the respective bio-based coal-fired power plant within each catchment area. The highways 5, 6, 8 and 81 together with further secondary roads constitute the main transport infrastructures that permit organising the spatial distribution of wood resources and thus their allocation to the selected conversion units of Baden-Württemberg.

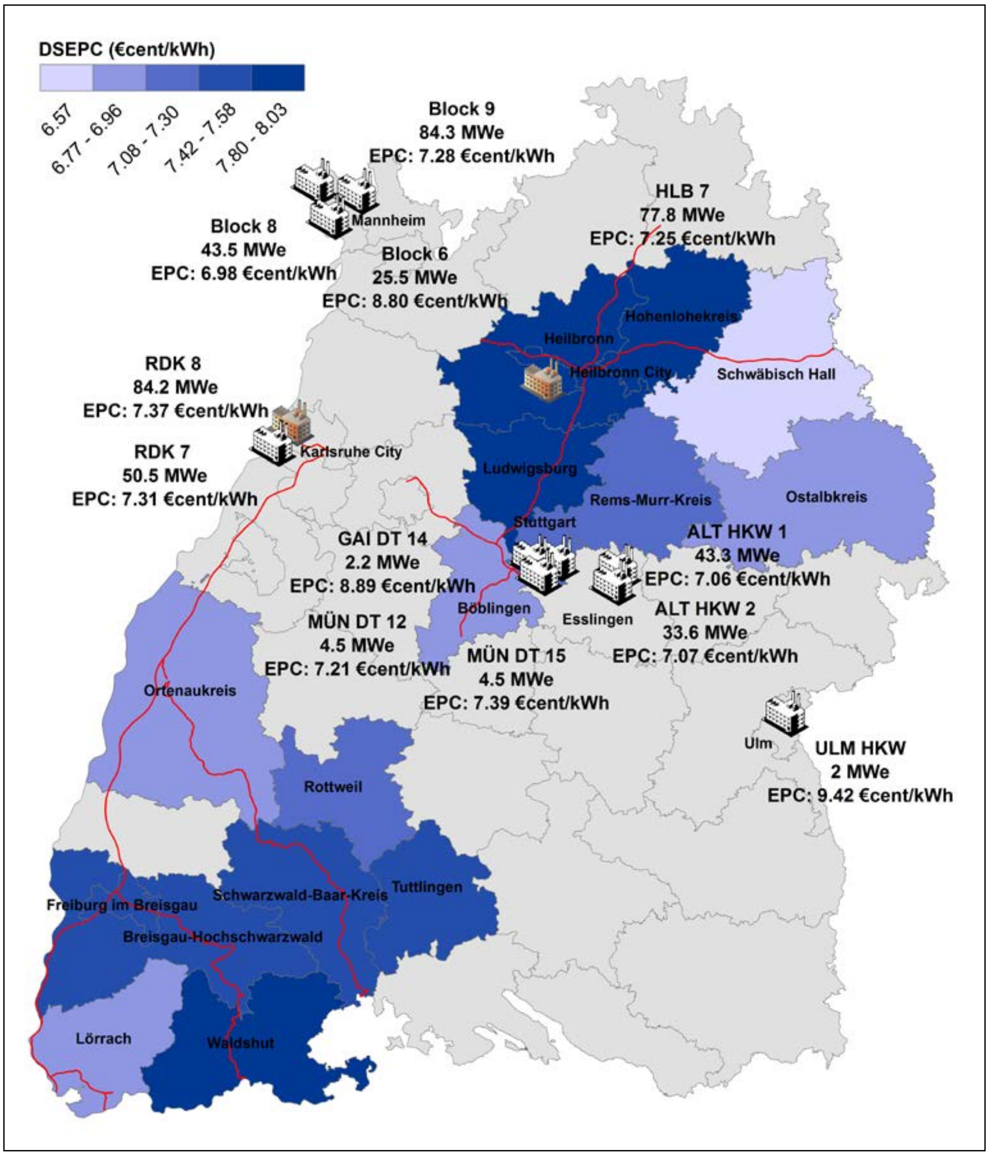

Figure 7.16: Location of the selected co-firing based coal power plants as well as illustration of the catchment areas of RDK 8 and HLB 7 respectively with their corresponding EPC and DSEPC in each specific district

The retrofitted RDK 8 coal power station registers a specific electricity production cost of 7.37 €cent/kWh$_e$. This amount results from weighting the DSEPC incurred in each district of the entire RDK 8's catchment area with expenses ranging from 6.77 €cent/kWh$_e$ in Ortenaukreis to 7.85 €cent/kWh$_e$ in Waldshut. As in the last section, the aim of the optimisation analysis is to primarily feed the most cost-effective conversion units with comparatively more expensive wood resources so that the total system costs can be limited to the lowest possible extent. In fact, RDK 8 as the largest conversion unit shows the cheapest specific investment and operating costs among the selected bio-based power plants. As a consequence, this power station is supplied with more costly forest and landscape-based resources and even is located out of its own catchment area in order to facilitate the allocation of cheaper resources to other less cost-efficient plants. In addition, the district of Lörrach exhibits relatively cheap DSEPC for its distance from the conversion unit in Karlsruhe basically due to the low cost contributions of the deciduous share of both chipped wood resources harvested by SPFO (5,493 t FW) and LFO (12,883 t FW). On the contrary, Schwarzwald-Baar-Kreis allocates a significant amount (7,238 t FW) of coniferous LFO – as well as no resource derived from landscape – to RDK 8. This leads to an increase of its DSEPC for a comparable haul from Karlsruhe to the referenced district (see Figure 7.16).

Alternatively, the HBL 7 coal power plant is located in Heilbronn in an outlying place within its catchment area according to Figure 7.16. The conversion plant shows EPC of about 7.25 €cent/kWh$_e$, which are again as in the previous scenario somewhat lower than those of RDK 8 (7.37 €cent/kWh$_e$). This trend continues in spite of the higher specific capital and operating expenses of HBL 7 as compared to those of the 84.2 MW$_e$ plant in Karlsruhe. This amount of electricity production costs is calculated as a weighted average of the DSEPC obtained in the districts of the whole catchment area of HBL 7. The district-specific electricity production costs across the entire catchment area are comprised between 6.57 €cent/kWh$_e$ in Schwäbisch Hall and 8.03 €cent/kWh$_e$ in Ludwigsburg. Whereas wood resources provided by the former district are basically characterised by the expensive S<50L landscape wood resources as well as the less costly coniferous and deciduous portion of LFO – all in a similar order of magnitude –, the latter district predominantly produces the more costly S<50L chipped wood resources from landscape areas with a steepness of slope lower than 50% (8,354 t FW). This drives up its corresponding DSEPC for a distance from Ludwigsburg to HLB 7 quite similar to that covered from Schwäbisch Hall to Heilbronn.

The specific electricity production cost of the most relevant co-firing based conversion units, namely RDK 8, HLB 7, ALT HKW 1 and Ulm HKW are represented in Figure 7.17 split into their respective cost components of harvesting and transport as well as the power plant-related expenses including annuity and both fixed and variable O&M costs. The share of the incremental investment and operating costs for each of the four coal power plants increases progressively from 33% to 39% while scaling down the capacity of the bio-based units in the order in which they are presented. The remaining expenditures incurred by the respective supply chains of these conversion plants are directly determined by adding the cost components concerning harvesting and transport of wood resources. The share of the cost element involving harvesting varies from around 38% for RDK 8 to circa 47% in the case of HLB 7 and clearly depends on the type of harvested chipped wood resources as well as the electric efficiency of each bio-based unit. As a result, the harvesting-related cost component of all four coal power plants (see Figure 7.17) accounts for somewhat less than half the specific EPC of the bio-based plants. Regarding transport, its cost component ranges from around 19% in HLB 7 to approximately 29% for RDK 8. The explanation for this rests on the fact that HLB 7 is placed on a quite centred site within its catchment area in comparison to the power plant of Karlsruhe with respect to its area of influence. In this sense, transport costs and hence the respective cost components are remarkably dependent on the dimension of the catchment areas. As regards ALT HKW 1 and Ulm HKW, their catchment areas are quite important in extension compared to those of the other units under consideration, besides the fact that Altbach and Ulm lie at one end of the corresponding catchment zones. This generates relatively important contributions of transport activities to their respective EPC.

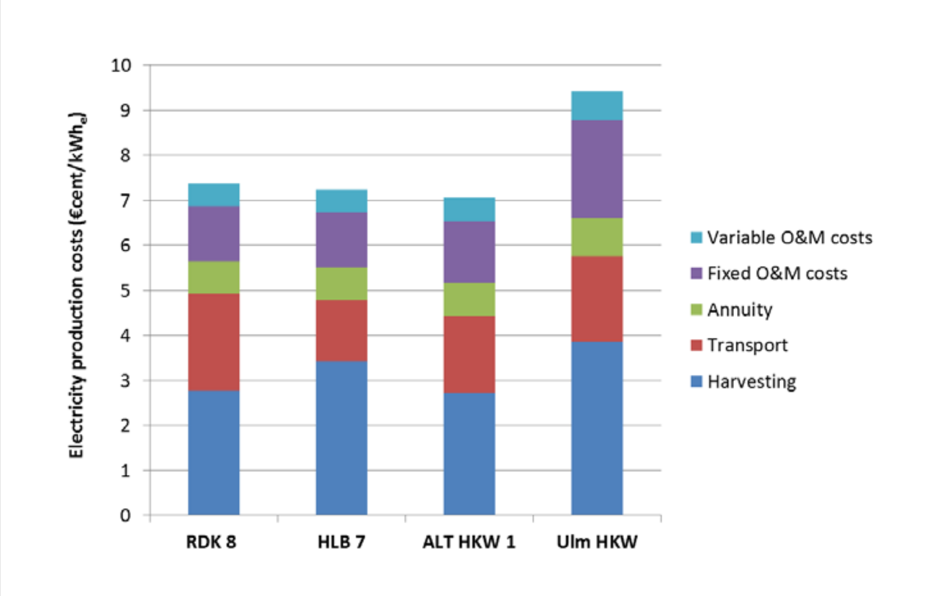

Figure 7.17: Cost breakdown of the EPC of the co-firing based RDK 8, HLB 7, ALT HKW 1 and Ulm HKW conversion units into their cost elements

On account of the significant weight of harvesting costs within the EPC, a cost component split of the specific harvesting costs originated in the forest and landscape areas of the respective four catchment areas is depicted in Figure 7.18. Thereby, the cost components of the specific harvesting costs of each conversion unit are reproduced as in the last subsection based on two different methodologies. On the one hand, as a breakdown into the corresponding three harvesting stages (collection, moving and chipping of wood resources) and, on the other, being divided into the six types of chipped wood resources resulting from the coniferous and deciduous shares of both SPFO and LFO forest residues – when analysed as a by-product (see Table 6.3) – together with landscape wood raw material from both S<50L and S>50L chip types (see Table 6.2). Figure 7.18 exhibits the cost component split of harvesting costs according to both exposed criteria so that the sum of the cost elements on the basis of the former criterion equals to that of those components calculated according to the latter.

Due to the fact that forest residues are regarded as a by-product, no collection costs arise in forest areas, since these expenditures are allocated to the lumber production. However, landscape wood raw material is harvested as a whole tree and hence its collection stage generates costs that do contribute to the total harvesting costs. In this regard, only the harvesting costs involving the supply chain of HLB 7 register such collection contribution as this power plant in contrast to the rest is fed with a portion of landscape wood raw material (see Figure 7.18). For this reason and owing to the lower quantity of landscape resources compared to forest residues (ratio 1:2), the collection-related share of the specific harvesting costs for HLB 7 reaches a relatively low percentage of around 21%. Meanwhile, the the same cost elements of the remaining units in Figure 7.18 equal to zero percent owing to the fact that such plants are supplied exclusively with forest residues. In addition, it is to be noted that the HLB 7’s catchment area is formed by some of the districts of Baden-Württemberg with higher levels of free potentials for landscape-based resources (see Figure 6.3 and Table 6.8). Thus, the contribution of landscape areas explains the incurred collection costs in the EPC of the retrofitted power station in Heilbronn. The cost component relating to the stage of moving stands for around 60% in the case of RDK 8, ALT HKW 1 and Ulm HKW; while it amounts to approximately 47% within the catchment area of HLB 7. Accordingly, the chipping-related cost element of the four selected conversion units ranges from around 32% in HLB 7 to an average value of 40% in the three remaining power plants as shown in Figure 7.18.

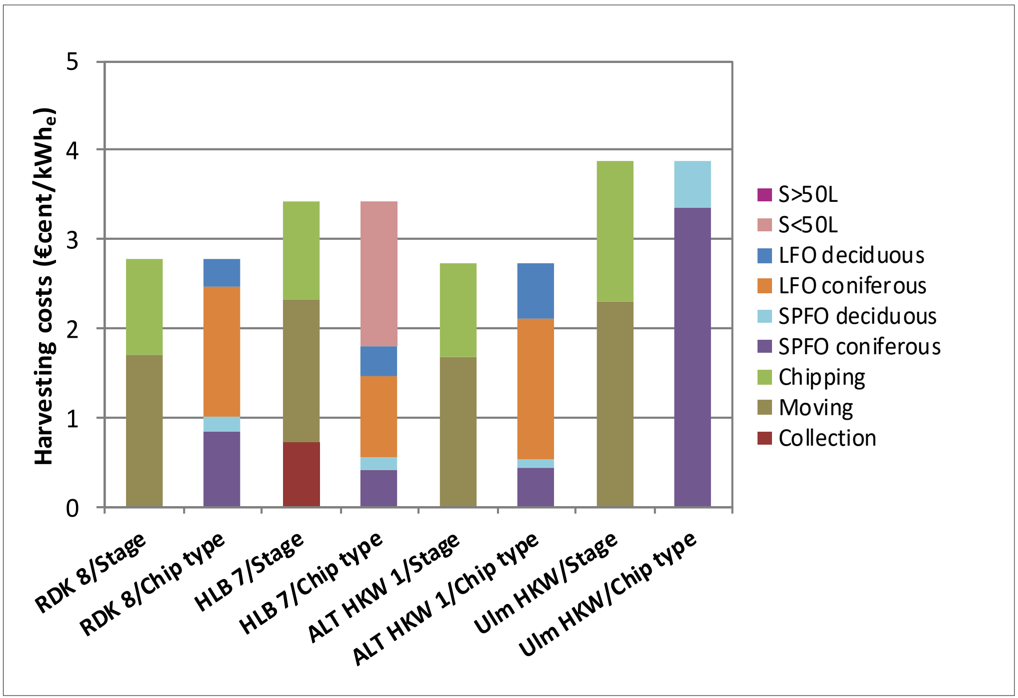

Figure 7.18: Cost component split of harvesting costs on the basis of the harvesting stages and the types of chipped wood resources for the supply chains of the co-firing based RDK 8, HLB 7, ALT HKW 1 and Ulm HKW power plants

If the breakdown of the specific harvesting costs into the contributions of the six types of chipped wood resources is taken into account, a different cost distribution is obtained for each separate bio-based conversion unit with respect to those previously accomplished for the three harvesting stages. For the co-firing based RDK 8 coal power plant, Figure 7.18 indicates that the major input of wood resources is derived from forest areas administered by large forest owners (LFO), particularly from their coniferous portion. This type of chipped wood resource makes up roughly 53% of the harvesting costs of the RDK 8's supply chain, whereas the second largest cost component relates to the coniferous share of the SPFO type with a portion a little higher than 30%. Specifically, the former type involving the coniferous share of LFO is the cause why moving costs are so high (61%) for RDK 8. In this sense, the coniferous forest areas exploited by small and large private owners within the supply chain of RDK 8 produces a substantial cost contribution of circa 83%, especially in certain districts such as Calw, Freudenstadt and Schwarzwald-Baar-Kreis. Regarding HLB 7, S<50L chipped wood resources from landscape areas with a steepness of slope higher than 50% represents the greatest contribution to the EPC of this conversion unit with a percentage of around 48%. The second largest share (27%) derives from the coniferous portion of chipped wood resources harvested by LFO. The input of S<50L primarily comes from districts such as Hohenlohekreis and Schwäbisch Hall, which possess major amounts of this resource (see Figure 6.3 and Table 6.8). In relation to the harvesting costs of ALT HKW 1, the coniferous part of LFO chipped wood resources accounts for approximately 59% as cost component of its supply chain. The deciduous share of this chipped raw material accounts for around 22% and constitutes the second largest contribution to the EPC of ALT HKW 1. On the other hand, the cost components of both coniferous and deciduous portions of chipped raw material harvested by SPFO within the supply chain of Ulm HKW are the sole elements contributing to its EPC with a share of 87% and 13%, respectively. Forest areas provide RDK 8, ALT HKW 1 and Ulm HKW with the whole amount of the respective type of chipped wood resources, while landscape areas only supply to HLB 7.

7.3.3. Co-firing of wood chips derived from forest residues as a joint product

Burning coal with wood chips generated from forest residues when assessed as a joint product in the framework of the Cofi/JointPro/NonLaW scenario gives a similar solution to the setting in which the forest resources are regarded as a by-product. The seven most cost-efficient power stations are taken from the list of eligible coal-fired power plants of Baden-Württemberg (see Table 7.3) and thus upgraded into the co-firing mode with the goal of converting free potentials of forest residues into power. The resulting bioenergy subsystem is made up of ALT HKW 1 and ALT HKW 2 in the city of Altbach (Esslingen), HLB 7 in Heilbronn, RDK 7 and RDK 8 in the urban district of Karlsruhe as well as both Block 8 and Block 9 in the city of Mannheim respectively with a bio-based power capacity of 43.3, 33.6, 77.8, 50.5, 84.2, 43.5 and 84.3 MW_e (see Figure 7.19). In order to gain insight into the distribution mechanisms of wood resources, focus is given to the catchment area of RDK 8 (coloured unit) in Figure 7.19 by illustrating its district-specific electricity production costs (DSEPC) within each district. Meanwhile, the remaining retrofitted coal-fired power stations (black-and-white images) are equally pointed out in Figure 7.19 together with their electricity production costs as part of the total solution. All the retrofitted power stations except for Block 8 operate at an annual amount of 3,000 full load hours. The unit of Mannheim is only run for 1,767 full load hours per year, actually owing to depletion of the existing free potentials of wood resources. On the basis of such operation conditions, the EPC of all retrofitted facilities amount to a range comprised between 8.27 to 11.69 €cent/kWh_e. Thus, the resulting bioenergy subsystem shows no clear scale effect due to the origination of certain cost compensation mechanisms in order to reach the intended cost minimisation objective. Similarly to the Cofi/ByPro/NonLaW scenario, Block 9 with 84.3 MW_e as the largest coal-fired power station (see Table 7.3) exhibits again the lowest EPC within the federal state. In addition, the highest EPC is equally allocated to the 43.5 MW_e Block 8 conversion unit on account of the aforementioned reduction of its yearly operation time to 1,767 full load hours. Regarding the transport of forest residues to the selected power plants, Baden-Württemberg's secondary road and highway networks are principally utilised within the corresponding catchment areas of each bio-based unit. Specifically, the highway 5 along with its tributary roads is the main transport infrastructure for hauling wood resources within the supply area of RDK 8. On the other hand, the regional thoroughfares 8, 81 and 6 besides their major roads enable articulating the allocation of forest residues to the remaining bioenergy plants.

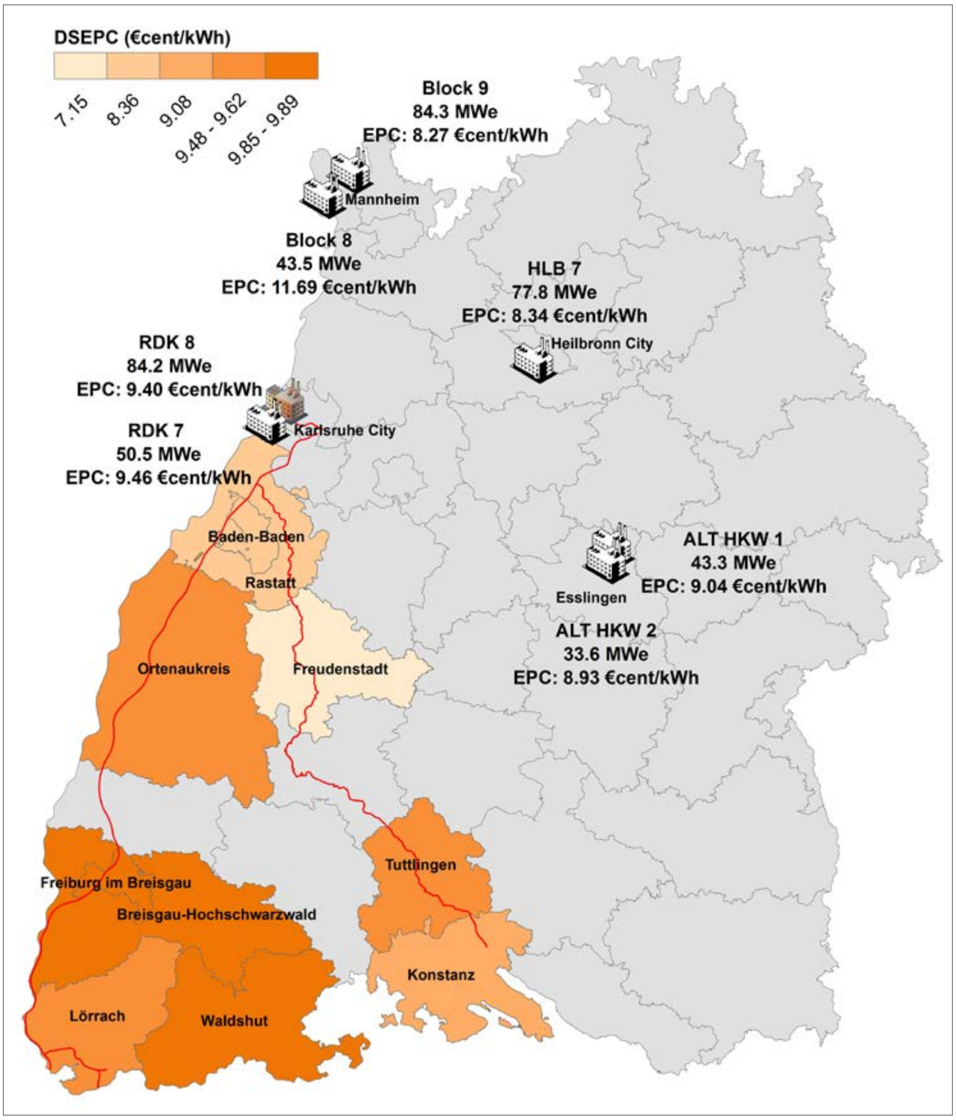

Figure 7.19: Location of the selected co-firing based coal power plants as well as illustration of the catchment area of RDK 8 respectively with their corresponding EPC and DSEPC in each specific district

The upgraded RDK 8 coal power station (8000 full-load h/a) renders a specific electricity production cost of 9.40 €cent/kWh$_e$ at 3,000 full load hours per year. This value is obtained by weighting the district-specific production costs (DSEPC) incurred in each district of the RDK 8's catchment area. DSEPC do not progressively increase with the distance between Karlsruhe and the corresponding districts but on an irregular basis owing to the dissimilar types of chipped wood resources. They vary from 7.15 €cent/kWh$_e$ in Freudenstadt to 9.89 €cent/kWh$_e$ in the districts of Breisgau-Hochschwarzwald and Freiburg im Breisgau regardless of their distance to the conversion unit. The shape of the RDK 8's catchment area is constituted by three spatially isolated clusters of districts (see Figure 7.19) that are directly linked to the most cost-efficient resource distribution pattern for the whole territory. In this sense, those districts located among the aforementioned clusters within the catchment area of RDK 8 are, however, apportioned to the area of influence of the other conversion unit in Karlsruhe, namely RDK 7. Particularly, the district of Freudenstadt presents a relatively low DSEPC with respect to its location from the bioenergy plant in Karlsruhe (see Figure7.19). This basically results from the only contribution (1,105 t FW) of the cheapest type of wood chips based on deciduous forest residues harvested in woodlands with a steepness of slope lower than 50% (S<50F).

On the other hand, Figure 7.20 shows the EPC of the bio-based RDK 8, HLB 7, ALT HKW 1 and ALT HKW 2 conversion units split into the cost elements of harvesting, transport as well as the annuity and the fixed and variable operating costs. The investment and O&M costs of these power plants make up a lower share in the total EPC than that of the same plants in the by-product approach basically on account of the increased total costs of power generated with forest residues as a joint product. This share constitutes approximately 30% of the EPC for HLB 7, ALT HKW 1 and ALT HKW 2. The corresponding value for RDK 8 descends to around 26%. To this extent, the scale and the electric efficiency of RDK 8 are higher than those of the rest (see Table 7.3) thus favouring a lower percentage for the plant of Karlsruhe. Moreover, the resulting amount of EPC for the compared conversion units markedly depends on the respective cost components of harvesting and transport of forest residues. The average cost components of both harvesting and transport stages for RDK 8, HLB 7, ALT HKW 1 and ALT HKW 2 respectively represent circa 52% and 20% of their specific EPC. Regarding both percentages, that relating to the harvesting tasks significantly increases compared to the one obtained for the by-product approach due to the higher costs of the joint products, while the transport contribution becomes less relevant as a consequence thereof.

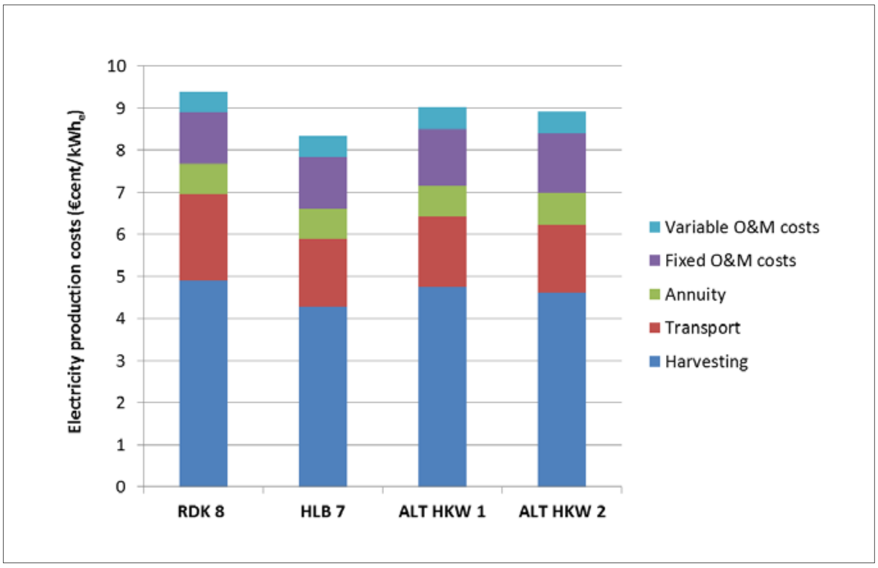

Figure 7.20: Cost breakdown of the EPC of the co-firing based RDK 8, HLB 7, ALT HKW 1 and ALT HKW 2 conversion units into their cost elements

On account of the relative importance of harvesting expenses, a cost component split of such specific costs for the supply chains of RDK 8, HLB 7, ALT HKW 1 and ALT HKW 2 is performed and exhibited in Figure 7.21. As accomplished in the previous sections, the cost elements of the specific harvesting costs for each bio-based unit may be estimated by appropriately dividing these expenditures into the three harvesting stages (collection, moving and chipping of forest residues) or alternatively into the four types of wood chips obtained from coniferous and deciduous forest residues as a joint product when harvested in woodlands with a steepness of slope below and over 50% i.e. S<50F and S>50F (see Table 6.4).

Figure 7.21 indicates that the relative share of collection tasks in the harvesting costs incurred in the supply chain of the RDK 8 power plant accounts for circa 46%, whereas those of HLB 7, ALT HKW 1 and ALT HKW 2 average 40%. In relation to this, the larger percentage in the case of the former plant relies undoubtedly on the greater contribution of the more costly S>50F wood chip type. Additionally, both moving and chipping cost elements roughly represent 37% and 23% of the EPC incurred in RDK 8. On the contrary, the corresponding percentages of HLB 7, ALT HKW 1 and ALT HKW 2 become on average somewhat greater as a result of the higher proportion of S<50F if compared with that of RDK 8.

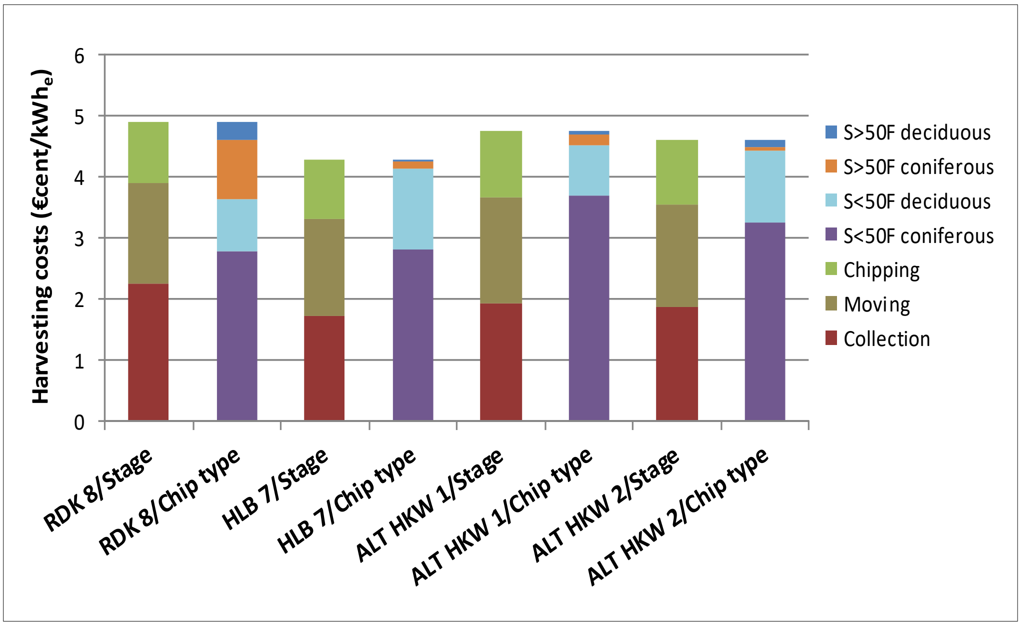

Figure 7.21: Cost component split of harvesting costs on the basis of both the harvesting stages and the types of wood chips for the supply chains of the co-firing based RDK 8, HLB 7, ALT HKW 1 and ALT HKW 2 power plants

Breaking down the specific harvesting costs into the contributions of the four types of wood chips derived from forest residues as a joint product, different cost components are calculated. They all add up to the same quantity as that obtained by using the cost distribution criterion based on the three harvesting stages (see Figure 7.21). Regarding the co-firing based RDK 8 coal power station, the most important contribution of forest residues comes from the wood chip type of coniferous S<50F with approximately 57% of total input. A further 20% derives from the coniferous S>50F type thus totalling around 77% of the entire input of forest residues, which according to Figure 6.2 originates predominantly from the Rastatt, Ortenaukreis, Freudenstadt, Breisgau-Hochschwarzwald and Waldshut districts. Both the coniferous and deciduous cost components of the expensive S>50F type reach a share of roughly 23%. This portion is much more elevated than that (3.5%) obtained for the case of HLB 7, thus explaining the higher EPC of RDK 8 as compared to that of the plant of Heilbronn. In contrast, though the HLB 7 conversion unit is to a large extent provided with coniferous resources – basically S<50F at around 68% –, a relative higher portion (31%) of deciduous resources in comparison to the case of RDK 8 (17%) is allocated to the power station in Heilbronn. This deciduous input is mainly harvested in districts such as Schwäbisch Hall, Rems-Murr-Kreis, Ostalbkreis and Heidenheim, which are reasonably near to the conversion unit (see Figure 6.2) thus helping to reduce transport costs. Similarly to HLB 7, the retrofitted ALT HKW 1 and ALT HKW 2 power stations have assigned an equivalent percentage on the order of roughly 96% for both coniferous and deciduous portions of S<50F as against a tiny contribution of S>50F.

7.3.4. Co-firing of wood chips derived from forest residues as a joint product and landscape wood raw material

Co-firing wood chips obtained from forest residues as a joint product and landscape wood raw material (Cofi/JointPro/LaW scenario) renders a similar solution to that resulting from the combustion of forest residues as a by-product in addition to landscape-based resources. The optimisation analysis foresees the installation of the twelve eligible coal-fired power stations of Baden-Württemberg (see Table 7.3). Therefore, a part of the free potentials is not consumed as they exceed the total bio-based capacity of the existing conversion units. As in the Cofi/ByPro/LaW compound scenario, the selected coal-fired power plants are assigned a capacity fraction that is to be upgraded to the co-firing mode. Figure 7.22 shows the location and capacity of all the units: concretely, both ALT HKW 1 (43.3 MW_e) and ALT HKW 2 (33.6 MW_e) power stations in Altbach (Esslingen), HLB 7 with 77.8 MW_e in the urban district of Heilbronn, RDK 7 (50.5 MW_e) and RDK 8 (84.2 MW_e) in the city of Karlsruhe, all three Blocks in Mannheim – numbers 6, 8 and 9 with respectively 25.5, 43.5 and 84.3 MW_e –, GAI DT 14 (2.2 MW_e) in Gaisburg (Stuttgart), both 4.5 MW_e MÜN DT 12 and MÜN DT 15 power stations located in the city of Münster (Stuttgart) as well as the Ulm coal-fired power plant with 2 MW_e of bio-based capacity. Moreover, Figure 7.22 also depicts the particular cases involving both catchment areas of RDK 8 and HLB 7 (coloured units) with their respective electricity production costs (EPC) and district-specific electricity production costs (DSEPC). By contrast, only the specific EPC are indicated for the remaining power stations (black-and-white images). All the upgraded conversion units are operated for 3,000 full load hours per year, with the result that a share of forest residues and landscape wood raw material is not consumed. For such operation conditions, the EPC of the twelve retrofitted power stations range between 8.62 to 11.46 €cent/kWh_e. In the same vein as in the previous co-firing compound scenarios, the specific amount of EPC does not show a marked dependence on scale because harvesting and transport costs distort it when resources are allocated to power plants. In addition, mention should be made of the highways 5, 6, 8 and 81 along with the secondary roads. They permit wood resources to be transported from woodlands and landscape areas to the coal-fired power stations thus enabling the spatial distribution of wood resources as well as their allocation to the selected units.

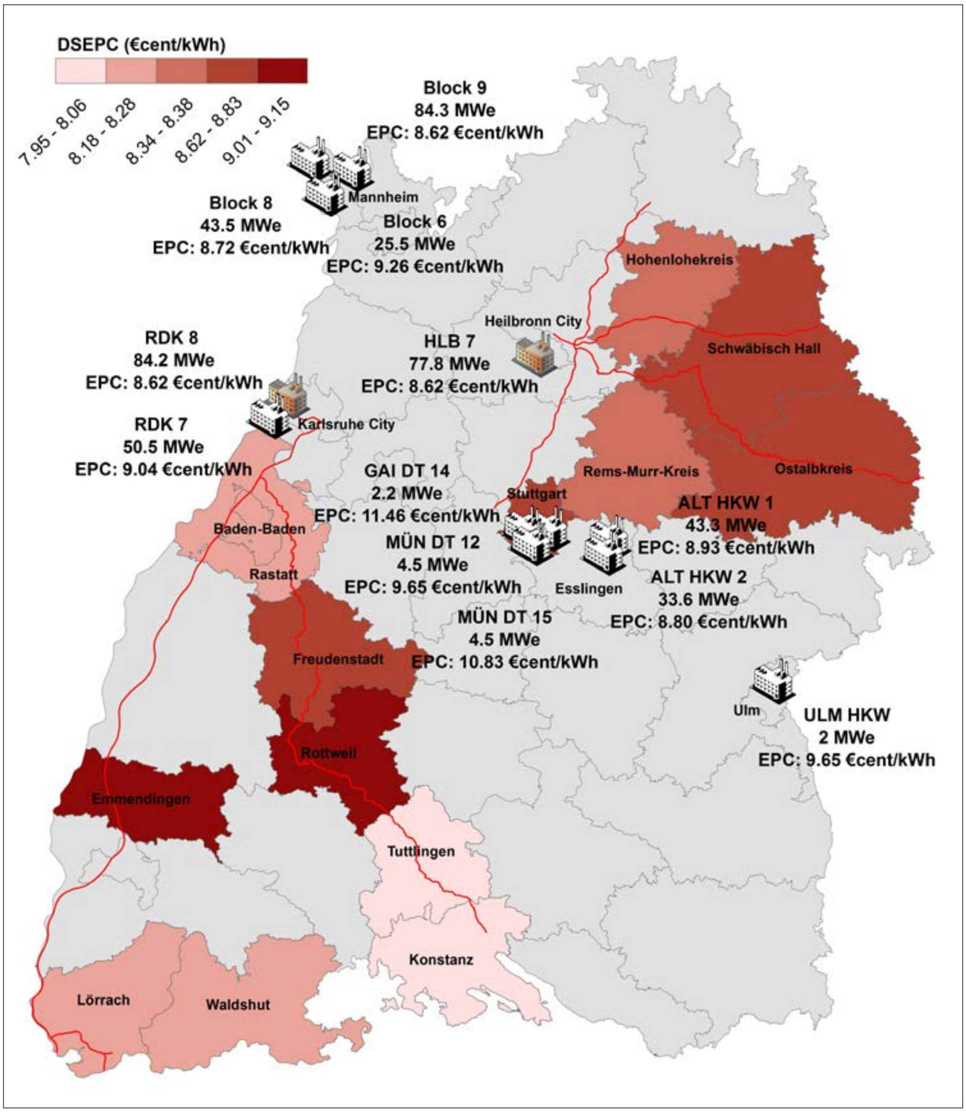

Figure 7.22: Location of the selected co-firing based coal power plants as well as illustration of the catchment areas of RDK 8 and HLB 7 respectively with their corresponding EPC and DSEPC in each specific district

The specific electricity production costs of the bio-based RDK 8 conversion unit amounts to 8.62 €cent/kWh$_e$ at the indicated rate of 3,000 full-load hours per year. These EPC are the result of weighting the district-specific production costs incurred within each district of the entire RDK 8's catchment area. They specifically vary from 7.95 €cent/kWh$_e$ in Tuttlingen to 9.15 €cent/kWh$_e$ in Rottweil (see Figure 7.22). In this regard, the district of Rottweil is assigned a relatively high DSEPC in relation to its distance from the conversion unit in Karlsruhe. This is due to the important contribution of the costly S<50L chipped landscape wood raw material (5,362 t FW) and the comparatively expensive deciduous share of S>50F (134 t FW). Nevertheless, the district of Konstanz allocates a similar amount (5,718 t FW) of S<50L to RDK 8, although the inputs of less costly coniferous and deciduous S<50F (6,608 t and 4,731 t FW) keep the DSEPC relatively low for the long stretch between the district and the conversion site.

The co-firing based HBL 7 coal power plant in Heilbronn is supplied with wood resources originating within its catchment area in north-eastern Baden-Württemberg (see Figure 7.22). For a yearly rate of 3,000 hours at full load, the retrofitted HLB 7 power plant exhibits EPC of about 8.62 €cent/kWh$_e$, exactly the same as those of RDK 8 in spite of lower incremental investment and operating costs exhibited by the Karlsruhe facility. These EPC are obtained as a weighted average of the DSEPC incurred in each district of the HBL 7's catchment area. The variation of the district specific electricity production costs throughout the whole area of influence evolves from 8.34 €cent/kWh$_e$ in Rems-Murr-Kreis to 8.83 €cent/kWh$_e$ in Ostalbkreis. In view of the distance from Schwäbisch Hall and even Ostalbkreis to the conversion unit in the urban district of Heilbronn, their respective district-specific electricity production costs prove to be not so elevated. This is caused by the major weight of the comparatively economical contribution from the deciduous portion of chipped forest residues harvested in woodlands with a steepness of slope lower than 50% (deciduous S<50F).

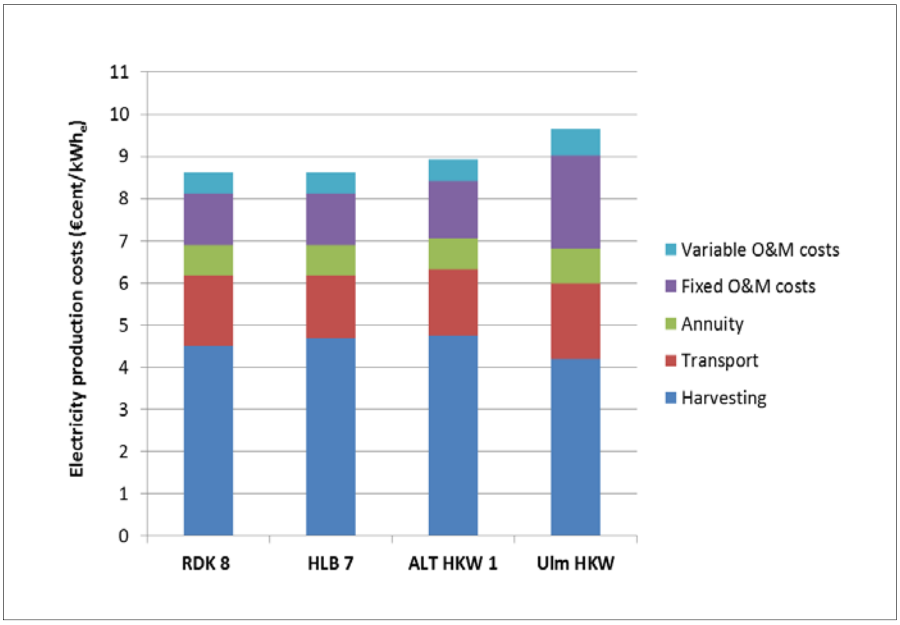

Figure 7.23: Cost breakdown of the EPC of the co-firing based RDK 8, HLB 7, ALT HKW 1 and Ulm HKW conversion units into their cost elements

On another issue, Figure 7.23 sheds light on the composition of the specific electricity production costs for the selected co-firing based RDK 8, HLB 7, ALT HKW 1 and Ulm HKW power plants. The corresponding EPC are represented broken down into the cost components of harvesting, transport, the annuity and both fixed and variable operating expenditures. It is evident from comparing all four EPC that the co-firing technology provides for a certain level of economies of scale despite the fact that the scale effect of this techique is not very pronounced. This is particularly clear when the EPC of the small-scaled Ulm HKW unit is compared with those of the remaining bio-based facilities in Figure 7.23. This way, the capital and O&M costs of both RDK 8 and HLB 7 account for approximately 28%, whereas the upgraded ALT HKW 1 power station yields a slightly higher percentage of circa 29% and that of the small-scaled Ulm HKW facility lies in the order of 38%. Besides, the cost components involving both harvesting and transport activities exhibit significant contributions in the EPC of each power plant. The harvesting-related cost element represents around 52-54% of the EPC registered by RDK 8, HLB 7 and ALT HKW 1. In contrast, a little lower share of roughly 43% is assigned to the harvesting tasks accomplished within the supply chain of Ulm HKW owing to the collection of cheaper forest residues in woodlands with a steepness of slope lower than 50%. Regarding transport costs, the corresponding components for HLB 7 and ALT HKW 1 are in the order of 17%, whereas RDK 8 and Ulm HKW show somewhat higher rates around 19% basically due to the dispersion of wood resources over spatially isolated clusters of districts. In relation to this, the particular form of the RDK 8's catchment area (see Figure 7.22) accordingly raises its respective transport cost element at a relatively high value of 19.4% owing to lack of spatial compactness.

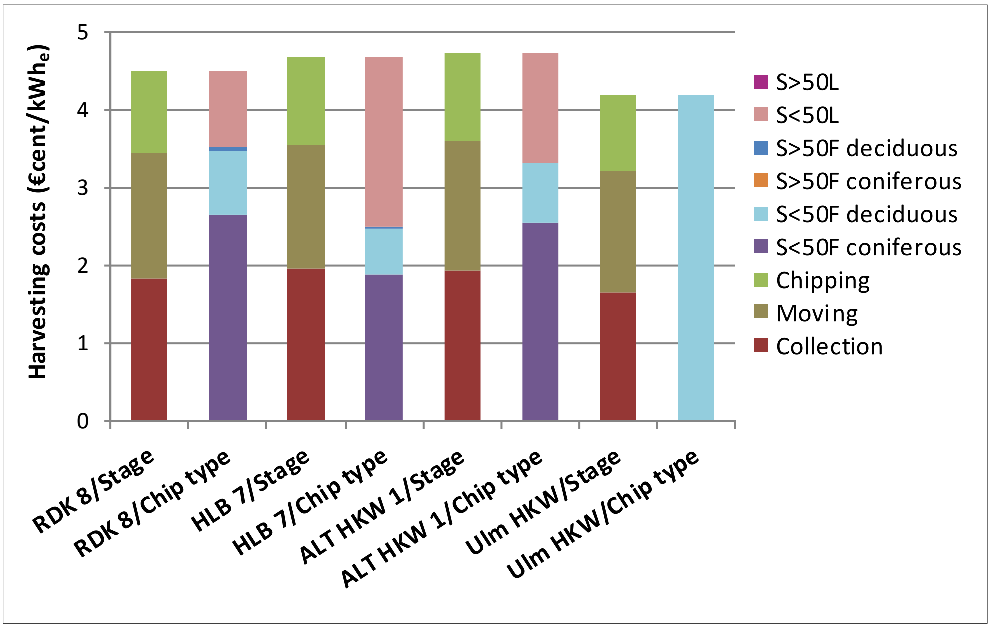

Figure 7.24: Cost component split of harvesting costs on the basis of the harvesting stages and the types of chipped wood resources for the supply chains of the co-firing based RDK 8, HLB 7, ALT HKW 1 and Ulm HKW power plants

Due to the fact that harvesting costs weighs heavily – concretely over 50% in the EPC of all conversion units – a breakdown of them into their different cost components is performed in Figure 7.24 in order to gain a deeper insight into the genesis of costs within the forest and landscape areas. The cost components of harvesting costs for each bio-based facility are derived as in other co-firing based scenarios from a breakdown either into the three harvesting stages (collection, moving and chipping) or into the six chip types originating from the coniferous and deciduous portions of forest residues regarded as a joint product, i.e. S<50F and S>50F in Table 6.4, as well as both S<50L and S>50L chipped wood resources from landscape (see Table 6.2).

Figure 7.24 points out that the collection-related cost components of the retrofitted RDK 8, HLB 7 and ALT HKW1 coal-fired power stations constitute approximately 41% of their specific EPC in contrast to those of Ulm HKW, which lie in the order of 39%. In this sense, the larger portion in the case of the three firstly indicated conversion units rests on the comparatively larger contribution of the expensive coniferous forest residues as a joint product harvested in woodlands with a steepness of slope lower than 50% (S<50F chip type) as well as the costly portion obtained for equivalent slopes in landscape areas (S<50L). In comparison, the supply chain of Ulm HKW exclusively provides the cheaper fraction of deciduous S<50F thus reducing its corresponding collection costs. The cost elements involving the moving and chipping tasks accomplished within the supply chains of RDK 8, HLB 7 and ALT HKW1 respectively make up around 35% and 24%. On the contrary, these activities respectively represent shares of around 37% and circa 23% in the EPC of Ulm HKW. These percentages are just the typical values reproduced by the stages of moving and chipping of S<50F forest residues in forest areas with slopes below 50%.

Allowing for the cost component split of the specific harvesting costs into the contributions of the six types of chipped wood resources, a different distribution of costs arises for each analysed bioenergy plant compared to those formerly carried out for the three harvesting stages. Figure 7.24 indicates that the coniferous share of S<50F chipped forest residues, which are harvested in woodlands with a steepness of slope lower than 50%, generates a major input to RDK 8's harvesting costs (around 59%) in comparison to that of HLB 7 and ALT HKW 1. This fact relies on the substantial amount of coniferous wood resources originating from the forest areas of certain districts included within the natural region of the Black Forest: Rastatt, Freudenstadt, Rottweil, Emmendingen as well as Lörrach and Waldshut (see Figure 6.2 and Table 6.7). On the contrary, HLB 7 as well as ALT HKW 1 consume large portions of the landscape-based S<50L wood raw material on the order of roughly 47% and 30%, respectively. This resource registers significant quantities of free potentials in several districts of the HLB 7's catchment area – namely Schwäbisch Hall, Rems-Murr-Kreis, Hohenlohekreis and Ostalbkreis – as well as in Alb-Donau-Kreis, Zollernalbkreis and Sigmaringen within the area of influence of ALT HKW 1 (see Figure 6.3 and Table 6.8). Meanwhile, Ulm HKW is exclusively supplied with the most economical fraction of chipped forest residues, i.e. deciduous S<50F (cf. Table 6.2 and Table 6.4), in order to compensate for its relatively high technology-related costs as a small-scaled facility.

7.3.5. Dependence on full load hours

As the availability of coal-fired power stations amounts to approximately 94% [EPA 2007], they can be run for a maximum number of 8,000 full load hours per year. Due to the fact that total system costs are minimised, the targeted bioenergy system may evolve towards an array of power plants that are operated for such highest possible amount of hours at full load. However, this solution does not correspond to the reality of any federal state in Germany. In fact, hard coal-fired power stations in Germany are operated a rather lower amount than 8,000 h/a, namely a yearly average of 3,600 full load hours as stated by the statistics published by [Statista 2018]. In this regard, the dependence relationship of specific electricity production costs and their cost components on the full load hours for the four co-firing compound scenarios is illustrated in Figure 7.25 in order to gain insight into the sensitivity of electricity production costs to the variation of this parameter.

The progressively higher EPC throughout the four compound scenarios – namely Cofi/ByPro/NonLaW, Cofi/ByPro/LaW, Cofi/JointPro/NonLaW and Cofi/JointPro/LaW – basically result from a gradual increase in the cost components involving harvesting. Only the transport-related cost components vary in magnitude as a function of the resulting size of the catchment area. In contrast, the rest of the cost elements do not vary from one scenario to another for each value of full load hours. Within each compound scenario, variable O&M costs remain constant over the entire range of full load hours. Besides, the annuity and fixed O&M costs significantly increase in value as full load hours are lessened. Under these conditions, the cost elements concerning harvesting and transport decrease respectively as a result of a change in composition via a cheaper input of wood resources and the drastic reduction in size of the catchment area – in spite of higher distance-specific transport costs (see Figure 3.10) – on account of the lower amount of required wood resources. This reduction in both components could be eliminated if a more accurate modelling of this technology would be performed by assigning lower electric efficiencies to the power plants that are operated under increasingly lesser load factors.

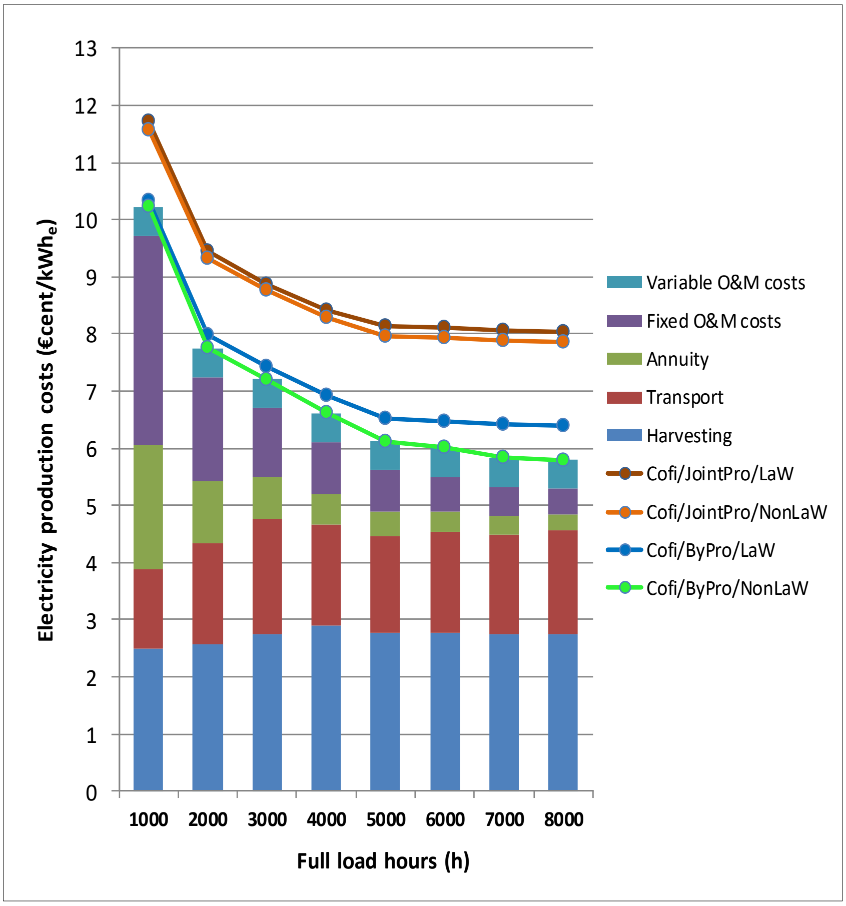

Figure 7.25: Dependence of specific electricity production costs and their cost components on the full load hours for the RDK 8 conversion unit in each of the four co-firing compound scenarios

7.4. Scenarios based on the BIGCC technology

When analysing the wood resources-based bioenergy system of Baden-Württemberg, another technological option for production of bio-based power can be implemented on the basis of a fluidised bed gasification process connected to a combined cycle. This technology can be implemented according to a centralised pattern of bioenergy generation for large scales. The type of bio-based power plant based on this conversion process is designated as biomass integrated gasification combined cycle (BIGCC) and is capable of yielding substantially more economical electricity production costs than those of combustion technologies such as stoker boilers or fluidised bed combustors coupled to a steam turbine. The prior assertion is not only sharply confirmed by data regarding specific electricity production costs of both combustion and gasification technologies (see section 4.3) but also additionally via employing high-performance computing with tests carried out on the model of the targeted bioenergy system while checking both technologies for the entire range of scales.

Accordingly, the most significant techno-economic parameters of a BIGCC power plant for some medium and large scales are listed in Table 7.4 based on data derived from regressions depicted in Figures 4.9-12. On the basis of [EPA 2007], [Tsakomakas et al. 2012] and [Do et al. 2014], the availability of BIGCC power plants averages around 90%. Therefore, a maximum amount of full load hours in the order of 7,500 h/a is considered for modelling this bioenergy technology.

Table 7.4: Techno-economic features of power plants based on a fluidised bed gasification process connected to a combine cycle as a function of their scale

Bio-based capacity	**Specific capital costs**	**Specific. fixed O&M costs**	**Specific variable O&M costs**	**Electric efficiency**	**Availability**
MW	*€/kW$_e$*	*€/kW$_e$*	*€cent/kWh$_e$*	*%*	*%*
340[30]	1,025	35.61	0.32	48.5	90
210	1,099	39.07	0.34	47.7	90
50	1,948	83.84	0.53	41.4	90

[30] The techno-economic features of a BIGCC power plant, as exposed in Figures 4.9-12, cover a maximum capacity of 160 MW$_e$. As an assumption, techno-economic data derived from the corresponding trend lines by means of diverse regression techniques are extrapolated to a maximum power output capacity of 210 MW$_e$. However, the extension to a scale of 340 MW$_e$ is not recommended on account of the fact that this best fit does not appropriately reproduce the investment and operating costs of such a large scale – e.g. if compared to the techno-economic parameters of two BIGCC facilities with 431 MW$_e$ and 442 MW$_e$ [Jin et al. 2009]. For this reason, the bio-based capacity of 340 MW$_e$ is assigned the higher and hence more appropriate techno-economic parameters of the smaller scale of 250 MW$_e$.

The four BIGCC compound scenarios involving the conversion of wood resources into bio-based power within the scheme of the German Renewable Energy Act contemplate the financial support of bioenergy production by means of revenues derived from market premiums besides those originating from wholesale markets as in the case of conventional energy sources. The GREA and its corresponding amendments [EEG 2017] provide for a legal framework for investors to receive such market premiums as an incentive in compliance with a maximum annual capacity installation of 200 MW_e for the whole of Germany. As a result, the installation of large-scaled power plants such as those of 210 and 340 MW_e (Table 7.4) could only be accomplished through an appropriate legal change in the sense of raising that ceiling.

As in the previous sections in relation to the technology options of FBG+E and co-firing, the four BIGCC compound scenarios (see Table 7.1) are built according to the chosen cost allocation techniques when applied to forest residues (by-product/joint product) as well as on the basis of the harvesting or not of landscape wood raw material. The intended modelling of the wood resources-based bioenergy system of Baden-Württemberg similarly includes eliminating the effect of the constraint of profitability by implementing high enough remunerations – i.e. higher than the corresponding electricity production costs at the breakeven point – so that the largest amount of bioenergy can be generated.

7.4.1. Energy conversion of wood chips derived from forest residues as a by-product

The BIGCC/ByPro/NonLaW scenario consists in the implementation of the BIGCC technology for conversion of chipped forest residues as a by-product. This compound scenario yields a solution based on the installation of a single unit with the largest possible and hence most cost-efficient output capacity of 210 MW_e in the central district of Böblingen (see Figure 7.26). Although a fluidised bed gasification process coupled to a combine cycle exhibits an availability of 90% and then can be run at a maximum rate of 7,500 full-load hours per year (see Table 7.4), the selected bio-based power plant operates only for 7,356 h/a under full load on account of the depletion of the free potentials of forest residues. Under these conditions, the BIGCC power plant renders a specific electricity production cost (EPC) of 5.60 €cent/kWh_e. The selected conversion unit is assigned a catchment area that is equivalent to the entire territory of Baden-Württemberg. In consequence, all districts supply their entire free potentials of forest residues to the bio-based plant so that the administrative units show a district-specific production cost (DSEPC) with a value between 4.63 €cent/kWh_e in Stuttgart and a maximum level at 6.69 €cent/kWh_e in Waldshut (Figure 7.26). These costs appear to be especially elevated in the districts of southwest Baden-Württemberg due to the high proportion of coniferous forest areas, which produce a more expensive kind of wood residue. As in the previous sections, the weighting of the DSEPC of all districts on an energy basis results in the specific electricity production cost (EPC) formerly exposed for the BIGCC power plant to be installed in Böblingen.

On the other hand, the transport of forest residues from forest roads to the bioenergy unit is carried out via the regional network of highways and major roads, namely the highways 5, 6, 8 and 81 along with other secondary roads connecting the outlying districts with the city of Böblingen.

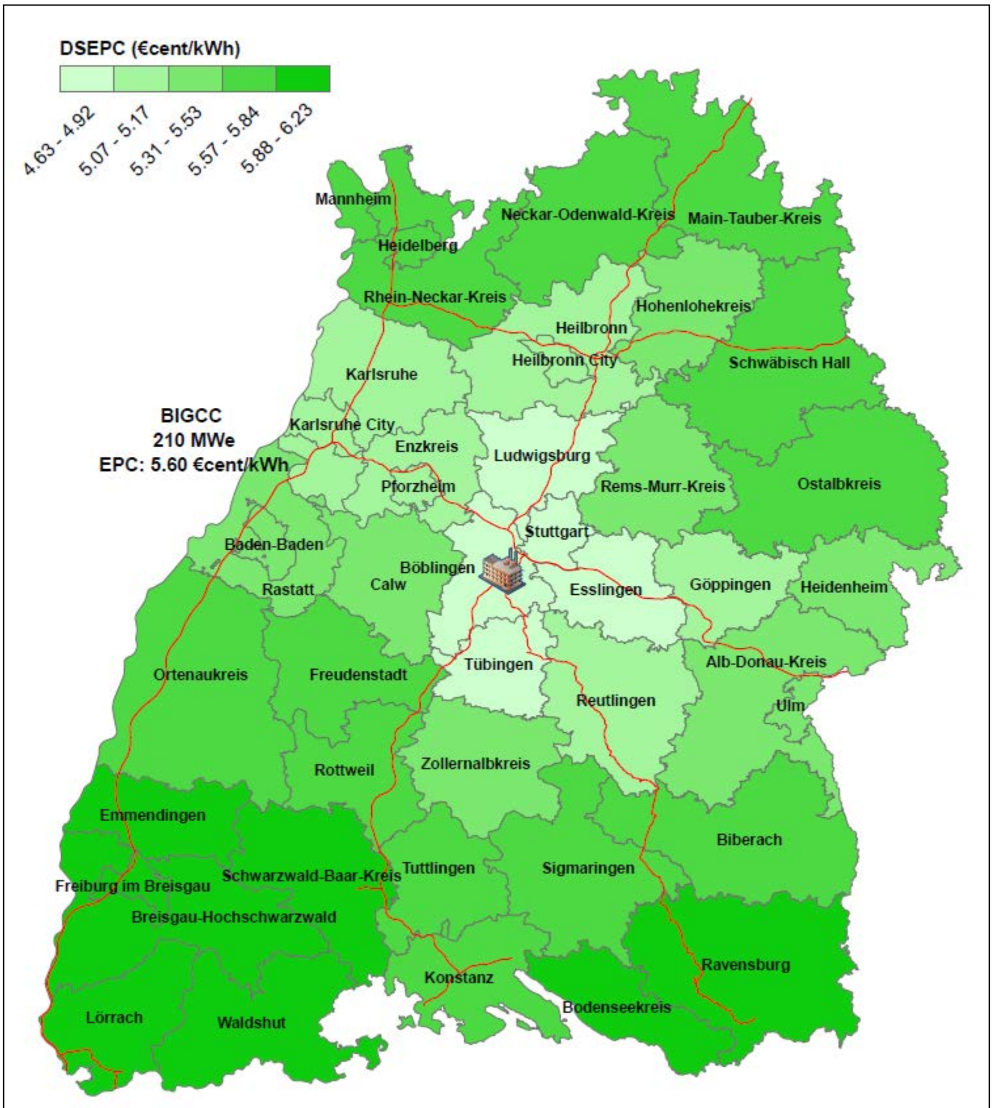

Figure 7.26: Location of the BIGCC power plant along with its corresponding electricity production cost and the district-specific electricity production costs in each administrative unit

The specific electricity production cost (EPC) of the BIGCC-based power plant of 210 MW_e is displayed in Figure 7.27 broken down into its cost components harvesting, transport as well as the corresponding annuity and the fixed and variable O&M costs. The investment and operation-related portion in the EPC of the bio-based unit accounts for a relatively important percentage, given the large scale, specifically 38.8%. This elevated share is caused by the high expenditures incurred in both the fluidised bed gasification process and the gas and steam turbines. The whole portion consists of the annuity with a weight of approximately 23% along with the fixed and variable operating costs with circa 10% and 6%, respectively. The remaining part of the EPC is composed of the cost components harvesting and transport of forest residues. Whereas harvesting costs constitute about 37% of the specific EPC, the share involving the transport of forest residues accounts for around 24% due to the large catchment area of the power plant.

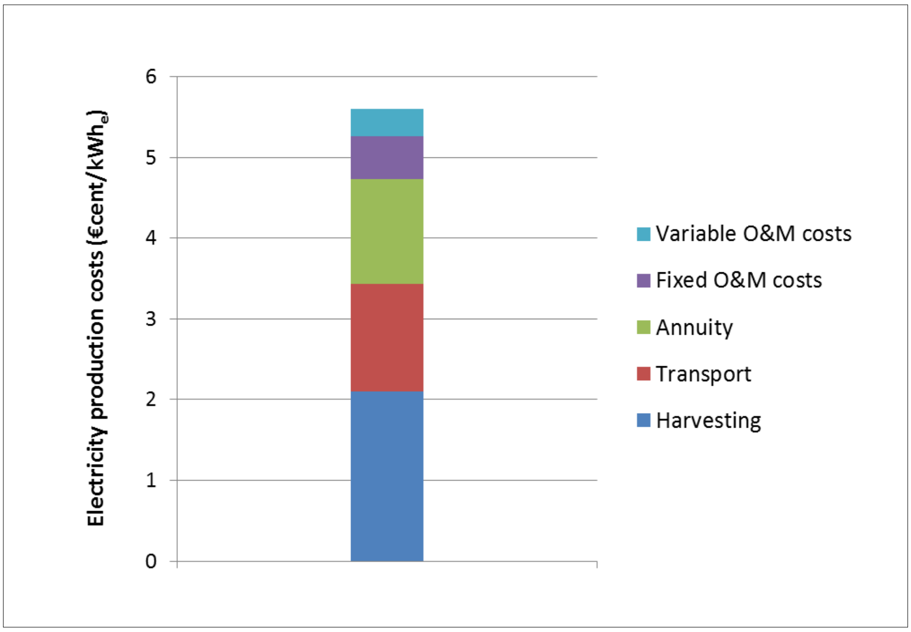

Figure 7.27: Cost breakdown of the electricity production costs incurred by the BIGCC-based power plant of 210 MW$_e$ into their cost elements

As in the previously analysed scenarios, the harvesting-related cost component represents a major portion in the specific electricity production costs of the chosen BIGCC-based power plant of 210 MW$_e$. Aiming at gaining insight into the origin of such elevated contributions, a cost breakdown of the specific harvesting costs incurred in the forest areas within the supply chain of the bio-based power plant is performed in Figure 7.28. Similarly to the approach used in all prior scenarios, the cost components are defined according to two methodologies by considering these contributions based on the three harvesting stages (collection, moving and chipping) and, on the other hand, the four types of wood chips including the coniferous and deciduous shares of chipped forest residues regarded as a by-product, SPFO and LFO (see Table 6.3).

As no collection costs arise on account of forest residues being assessed as a by-product, the specific harvesting costs are distributed among the moving and chipping labours according to a proportion of around 62% and 38%, respectively. These percentages, as in the rest of the scenarios analysing forest residues as a by-product, comply with the highest theoretical variance involving the cost elements of both moving and chipping tasks with a range of 59.1-62.6% and 37.4-40.9%, in that order.

If the specific harvesting costs are split into the elements involving all the four types of wood chips derived from forest residues as a by-product, the coniferous LFO chip type – which is collected in coniferous forest areas managed by large forest owners – yields the most important input of wood resources with a contribution of nearly 58%. Both coniferous SPFO and deciduous LFO chip types rank second with a respective share in the order of roughly

19% and 18%; while the potential resulting from deciduous forest areas exploited by small private forest owners (SPFO) accounts for barely 5% of the specific harvesting costs. These cost components are strongly linked with the amount of existing free potentials of wood chips originating from forest residues (by-product) in Baden-Württemberg (see Figure 6.1 and Table 6.6) and, on the other hand, their corresponding total unit costs (see Table 6.3).

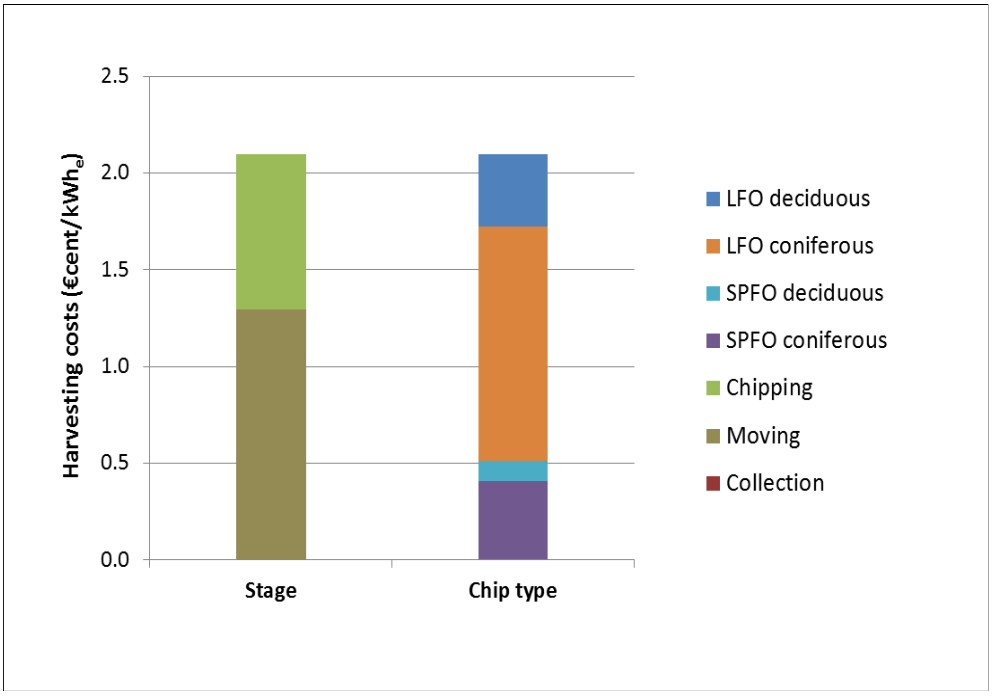

Figure 7.28: Cost component split of harvesting costs on the basis of both the harvesting stages and the types of wood chips for the supply chain of a BIGCC-based power plant of 210 MW$_e$

7.4.2. Energy conversion of wood chips derived from forest residues as a by-product and landscape wood raw material

The BIGCC/ByPro/LaW compound scenario results from the combination of the BIGCC technology with the conversion of wood chips produced from forest residues as a by-product as well as landscape wood raw material. Its solution refers to the installation of a power plant with the greatest possible and most cost-efficient output of 340 MW$_e$ in Stuttgart (see Figure 7.29). The city of Stuttgart as a site for the conversion unit owes its selection to the location of the free potentials of landscape wood raw material. The greatest amounts of this resource are predominantly produced in the northeast of the federal state (see Figure 6.2) thereby shifting the originally chosen site of Böblingen (in the by-product approach) to the capital of Baden-Württemberg. For an availability of 90%, a BIGCC-based conversion plant can work for a maximum of 7,500 full-load hours per year (see Table 7.4). Thereby, the chosen bio-based unit of Stuttgart operates for around 7,401 h/a at full load owing to total exhaustion of wood resources. As a result, the electricity production cost (EPC) of the chosen power plant amounts to roughly 6.17 €cent/kWh$_e$. The area of influence of the conversion unit equals the entire territory of the federal state thus showing a noticeable cost gradation from the site of conversion up to the outlying districts. This costs variation is clearly illustrated in Figure 7.29 by means of the district-specific electricity production costs (DSEPC), which range from 5.32 €cent/kWh$_e$ in Stuttgart to 6.85 €cent/kWh$_e$ in the administrative unit of Ravensburg. As usual, an appropriate weighting of the entire DSEPC registered in all districts perfectly reproduce the specific electricity production costs (EPC) of the bio-based plant installed in the capital of the federal state. Similarly to the last section, the transport of wood resources from forest and landscape areas to the conversion unit takes place across Baden-Württemberg's network of highways (numbers 5, 6, 8 and 81) and some major roads, which connect the whole districts with Stuttgart.

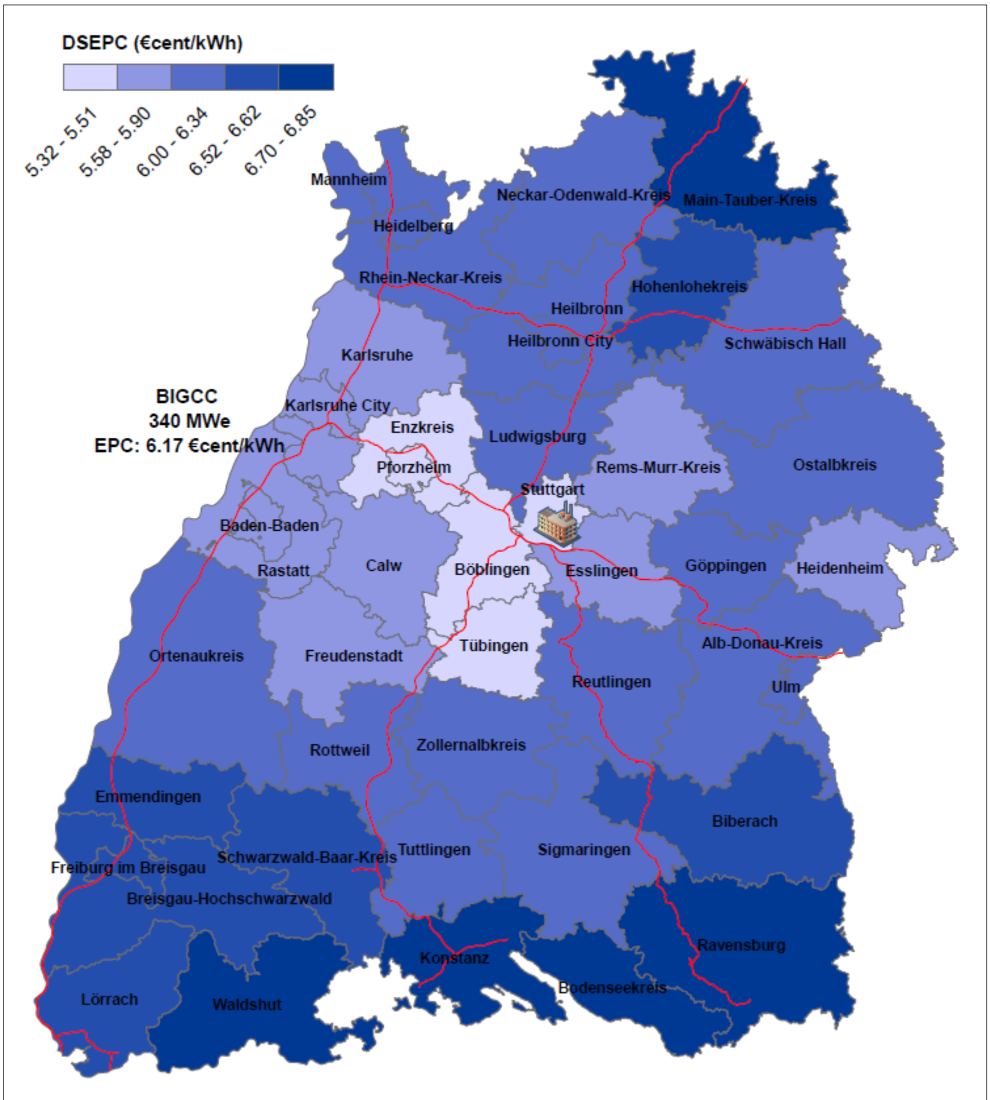

Figure 7.29: Location of the BIGCC power plant along with its corresponding EPC and the DSEPC in each administrative unit

Regarding the structure of costs, Figure 7.30 breaks down the specific electricity production cost (EPC) of the BIGCC plant (340 MW$_e$) into its cost constituents. These elements are linked to the harvesting and transport processes besides the annuity and the fixed and variable O&M costs. The portion concerning the investment and operation costs incurred by the gasification process and the prime mover makes up a surprisingly low contribution of barely 32% due to its large dimension, which benefits from economies of scale. This share is constituted of the annuity, which accounts for circa 19%, in addition to the fixed and variable operating costs with roughly 8% and 5%, respectively. In contrast, the harvesting-related cost component yields the most significant part of the EPC with approximately 45%. This is caused by the cost increase brought about by the use of landscape resources. The cost component involving the transport of forest and landscape resources to the conversion plant is attributable to the large size of the whole catchment area – namely, all of Baden-Württemberg –, and therefore it stands for a similar portion (22%) to that of last scenario.

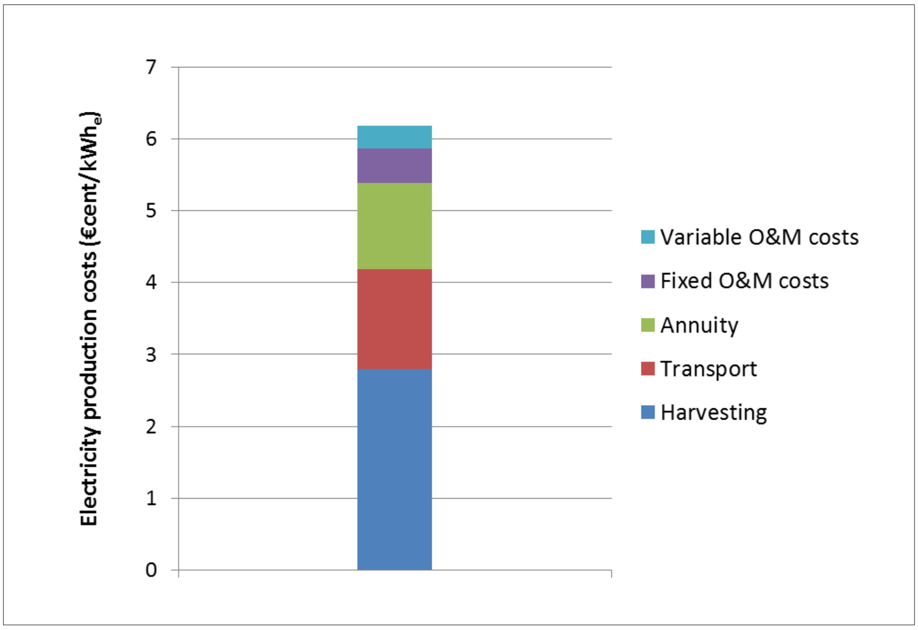

Figure 7.30: Cost breakdown of the electricity production costs incurred by the BIGCC-based power plant of 340 MW$_e$ into their cost elements

In relation to the cost component split of harvesting costs into the corresponding contributions of all three harvesting stages (collection, moving, chipping), a relatively low portion of collection costs (around 24%) together with a share of 45% for moving and 31% for chipping is showed in the graph of Figure 7.31. In this regard, the reduced contribution of collection can be accounted for by the fact that only landscape wood raw material is assigned collection costs, on the one hand, and that this resource grows in smaller amounts than forest residues all over the districts of Baden-Württemberg, on the other.

The procedure of cost allocation turns out to be different, provided that harvesting costs are broken down into the constituents involving the coniferous and deciduous portions of chipped forest residues as a by-product (see Table 6.3) as well as landscape-based resources (see Table 6.2). Under this condition, Figure 7.31 indicates that the highest cost components are ascribed to the chip type concerning coniferous LFO (large forest owner) with a share of circa 50% and also the landscape wood-based sort of S<50L (areas with slope below 50%) in the order of 27%. The rest of the expenses are apportioned to the remaining types of wood chips in quite small portions. These clearly depend on the amount of wood resources harvested in the whole area of Baden-Württemberg in keeping with the free potentials exposed in Figure 6.1

and Figure 6.3 (see Table 6.6 and Table 6.8) as well as with the corresponding unit costs of Table 6.3 and Table 6.2. In this sense, the set of chip types including coniferous SPFO and deciduous LFO are both classified second with a fraction between 8% and 9%, while the cost components related to deciduous SPFO and S>50L are of minor importance with a share less than 4%.

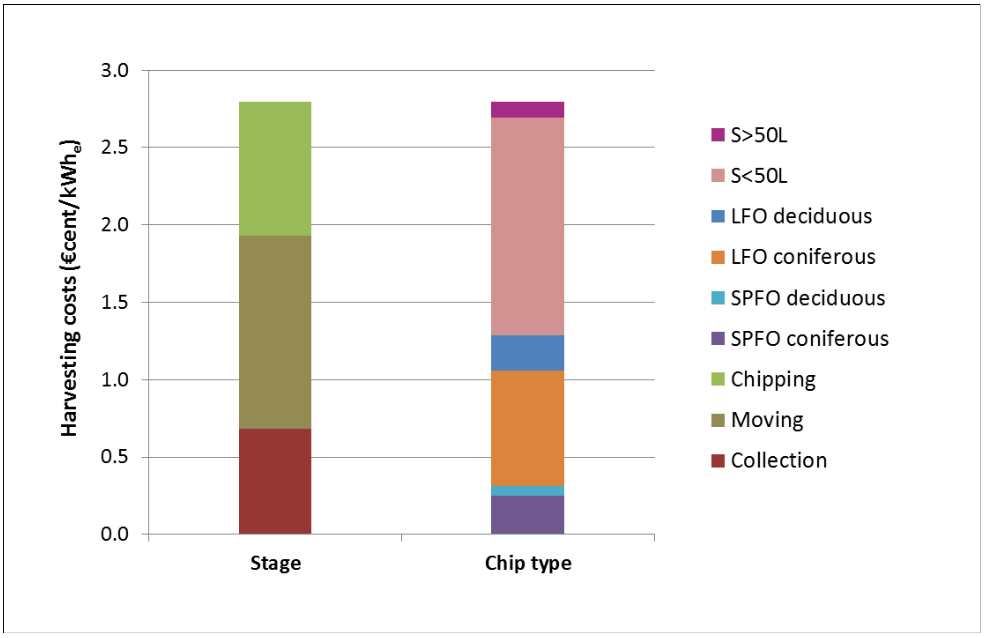

Figure 7.31: Cost component split of harvesting costs on the basis of both the harvesting stages and the types of wood chips for the supply chain of a BIGCC-based power plant of 340 MW_e

7.4.3. Energy conversion of wood chips derived from forest residues as a joint product

The BIGCC/JointPro/NonLaW scenario is based on the BIGCC technology, which is supplied with wood chips derived from forest residues considered as a joint product. Its solution involves the commissioning of a power plant with 210 MW_e in the capital city of Böblingen (see Figure 7.32) as in the case, in which forest residues are analysed according to the by-product approach. Likewise, its yearly operation time amounts to 7,356 h/a at full load because the input of forest residues is the same independently of the cost allocation performed. In such a context, a specific electricity production cost (EPC) of 7.12 €cent/kWh_e is reproduced for the selected BIGCC power plant. The catchment area of this conversion unit equally corresponds to the entire federal state. Thus, all districts provide the plant with their whole input of forest residues at a given district-specific production cost (DSEPC), which varies from 5.79 €cent/kWh_e in Stuttgart to 7.81 €cent/kWh_e in the district of Waldshut (see Figure 7.32). Similarly to the by-product based scenario for forest resources, the more abundant share of coniferous woodlands in the zone of the Black Forest translates into higher DSEPC within the southwest of Baden-Württemberg regardless of the distance to the site of conversion.

Figure 7.32: Location of the BIGCC power plant along with its corresponding EPC and the DSEPC in each administrative unit

The specific electricity production cost (EPC) of this BIGCC-based conversion unit with a power output capacity of 210 MW_e is illustrated in Figure 7.33 split into its cost components harvesting, transport, annuity and both operating costs. The share concerning investment and operation of the bio-based unit constitutes barely 30% of EPC mainly due to the elevated electric efficiency but despite the relatively high expenses of the BIGCC technology. This percentage consists of the annuity with a weight of roughly 18% and the fixed and variable operating costs with around 7% and 5%, respectively. The remaining part of EPC encompasses the cost constituents derived from harvesting and transport of wood residues. Whereas harvesting costs accounts for nearly half the specific EPC, the part associated with transport of forest residues makes up a relatively small amount of roughly 19% in spite of the extremely vast area of influence of the bio-based plant installed in Böblingen.

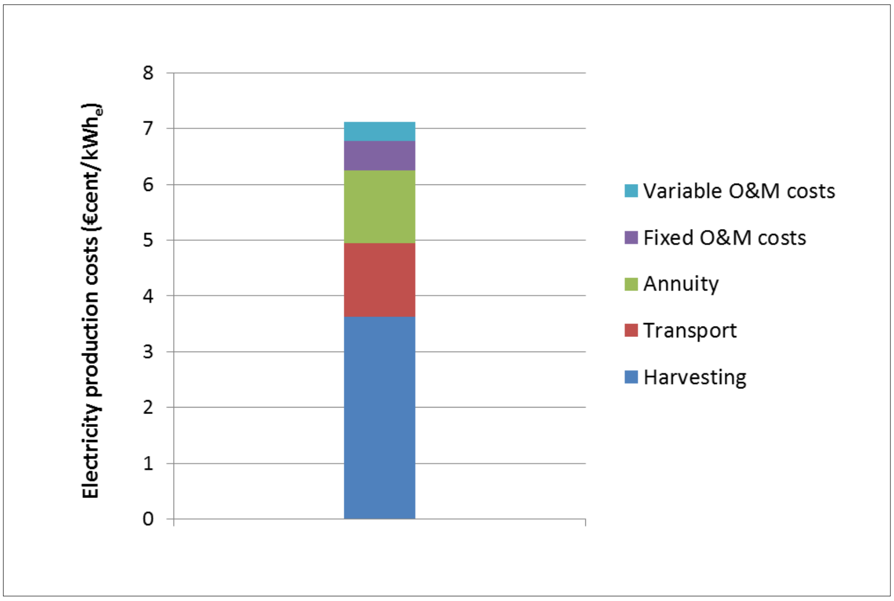

Figure 7.33: Cost breakdown of the electricity production costs incurred by the BIGCC-based power plant of 210 MW$_e$ into their cost elements

On the subject of the cost component split of harvesting costs into the elements concerning all three harvesting stages (collection, moving, chipping), a major share of 42% is assigned to collection tasks (see Figure 7.34). On the other hand, moving and chipping stand for circa 36% and 22%, in that order. These percentages are similar to those obtained in the other technology scenarios, where forest residues are analysed as a joint product. Indeed, these percentages are within the ranges of the maximum theoretical variances for the stages of collection, moving and chipping, respectively 39.5-63.8%, 23%-37.3% and 13.2-23.2%.

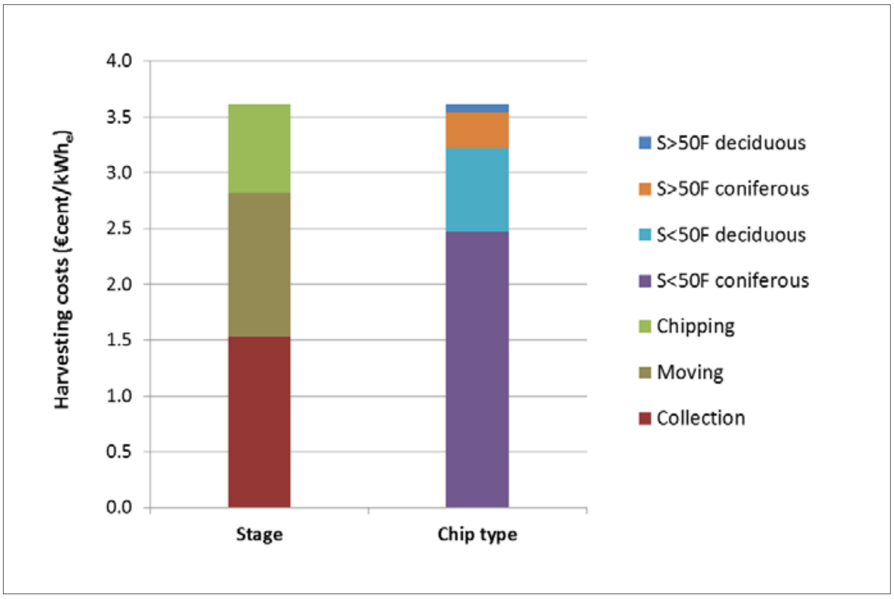

Figure 7.34: Cost component split of harvesting costs on the basis of both the harvesting stages and the types of wood chips for the supply chain of a BIGCC-based power plant of 210 MW$_e$

The cost breakdown of harvesting costs may also be carried out into the constituents associated with the four types of chipped forest residues as a joint product, namely the coniferous and deciduous portions of S<50F and S>50F (Table 6.4). In this case, the coniferous fraction of the S<50F chip type makes the greatest contribution to the harvesting costs with a share of roughly 68%. This percentage together with a 9% share of coniferous S>50F indicates the prevailing weight of coniferous woodlands in terms of quantity and costs as compared to that of deciduous ones in the forests of Baden-Württemberg. This deciduous share is made up of the S<50F chip type with a portion of 20.8% in addition to a small amount of around 2% including S>50F. In general, these cost components ultimately depend on the reported free potentials and the corresponding unit costs of wood chips produced from forest residues when contemplated under the joint product approach (see Figure 6.2 and Table 6.7 as well as Table 6.4).

7.4.4. Energy conversion of wood chips derived from forest residues as a joint product and landscape wood raw material

The BIGCC/JointPro/LaW compound scenario that involves the conversion of forest residues analysed as a joint product as well as landscape wood raw material by using the BIGCC option renders a similar solution to that obtained in the scenario in which landscape resources and forest residues as a by-product are valorised by this technique. This result equally entails installing a BIGCC plant of 340 MW_e in the district of Stuttgart (see Figure 7.35), although the costs of electricity generation are largely unalike. Likewise, the selected bio-based unit is run for circa 7,401 h under full load, thereby showing an electricity production cost (EPC) of approximately 7.11 €cent/kWh_e. As its catchment area equally corresponds to the whole territory of Baden-Württemberg, a singular cost pattern throughout the districts of the federal state is identified. This allocates a district-specific electricity production costs (DSEPC) to each administrative unit (see Figure 7.35) with values comprised between 6.01 €cent/kWh_e in Stuttgart and a maximum cost of 7.84 €cent/kWh_e in Waldshut. This latter district along with Lörrach, Freiburg im Breisgau, Breisgau-Hochschwarzwald and Emmendingen allocate the most expensive contributions to the composition of EPC, which may be calculated as a weighted average of all DSEPC.

In this way, the specific electricity production costs (EPC) of the 340 MW_e BIGCC plant located in Stuttgart are split into the corresponding cost components in the graph of Figure 7.36. The resulting cost constituents represent the portions contributed by the labours of harvesting and transport as well as the annuity and the fixed and variable operating costs. In this connection, the harvesting-related cost component makes up more than half (52.5%) of the EPC on account of the comparatively high unit costs of both sorts of wood resources used in this scenario. By the same token, the share concerning the transport of wood resources to the power plant accounts for barely 19%, the smallest contribution of all the prior BIGCC-related compound scenarios. Also the power plant-related cost element goes down to merely

28% with the annuity as well as the fixed and variable O&M costs respectively representing a share of approximately 17%, 7% and 4%.

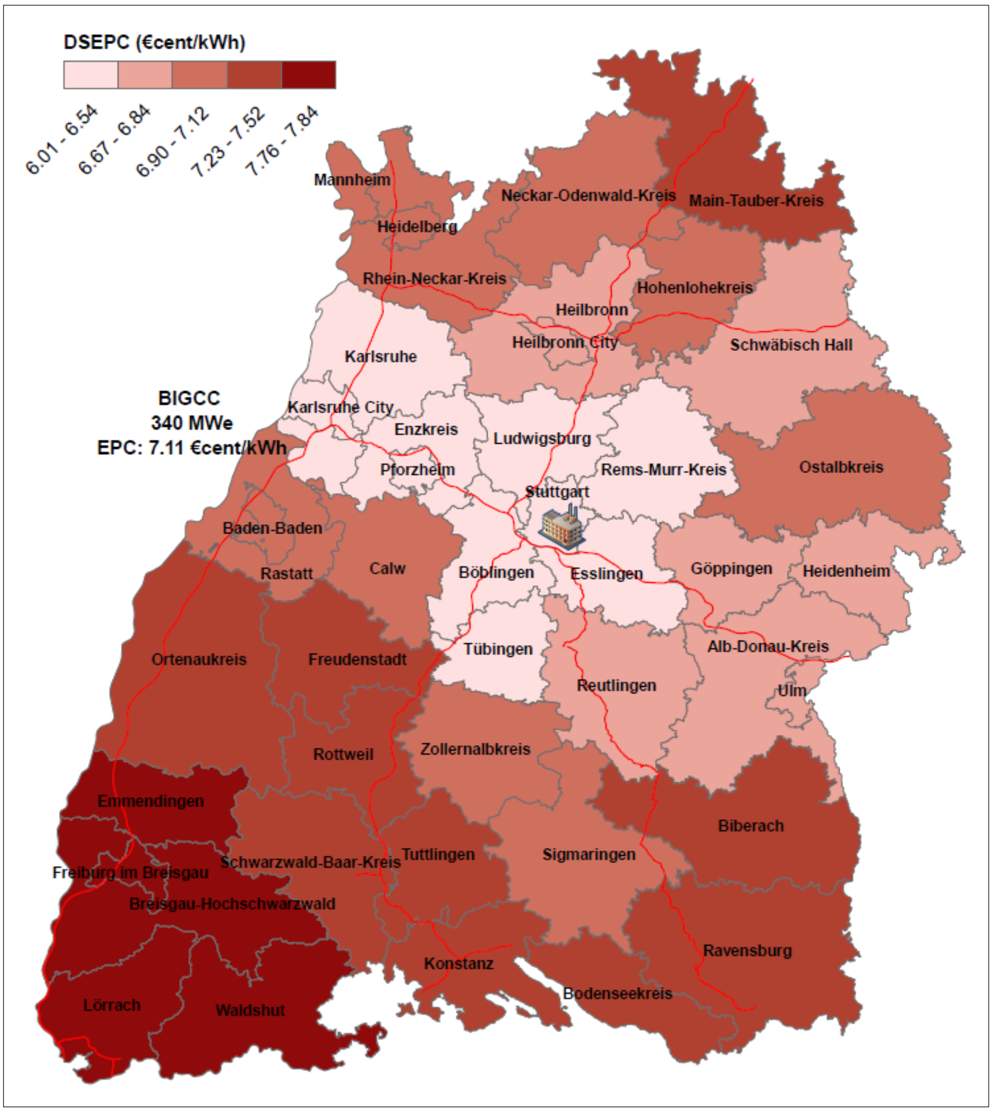

Figure 7.35: Location of the BIGCC power plant along with its corresponding EPC and the DSEPC in each administrative unit

When the specific harvesting costs are broken down into the cost elements of the three harvesting stages (collection, moving, chipping), the collection-related share takes a weight in the order of 43% (see Figure 7.37). This high percentage results from the expensive contributions of landscape wood raw material and forest residues regarded as a joint product. Both moving and chipping stages yield, in consequence, more reduced cost components of circa 33% and 23%, in that order.

If harvesting costs are split into the elements relating to the six types of wood chips resulting from forest residues as a joint product and landscape wood raw material (see Table 6.2 and Table 6.4), a different breakdown of these costs can be identified. The cost components of both coniferous S<50F and S<50L chip types, which originate in forest and landscape areas with a slope lower than 50%, add up to nearly 80% of whole harvesting costs according to the sum of both respective percentages 41% and 38% (see Figure 7.37).

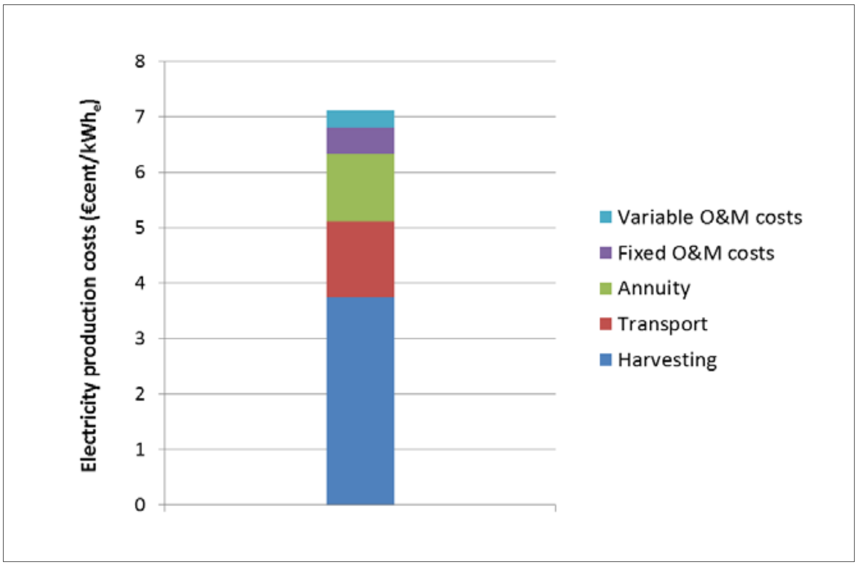

Figure 7.36: Cost breakdown of the electricity production costs incurred by the BIGCC-based power plant of 340 MW$_e$ into their cost elements

The rest of the expenses are assigned to the remaining types of wood chips in a lower proportion according to the free potentials growing in Baden-Württemberg (see Figures 6.2-3 and Tables 6.7-8) as well as the unit costs of the chip types involved (see Table 6.4 and Table 6.2). In such a context, the deciduous S<50F wood chip type is assigned a fraction of around 12%, whereas both coniferous and deciduous S>50F and the landscape resource-based S>50L type only yield cost components below a percentage of 5%.

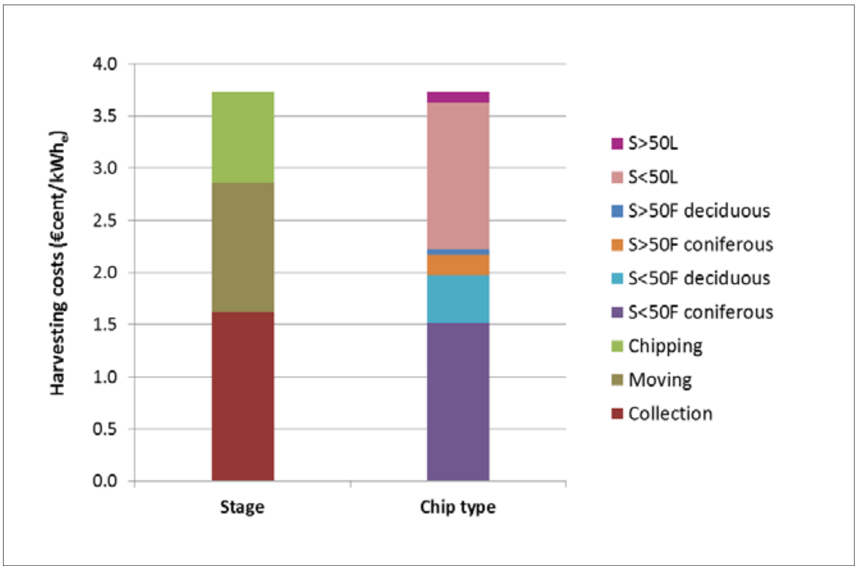

Figure 7.37: Cost component split of harvesting costs on the basis of both the harvesting stages and the types of wood chips for the supply chain of a BIGCC-based power plant of 340 MW$_e$

7.5. The decrease in remunerations below the breakeven point

The remunerations obtained via generation of power from wood resources in the context of the German energy system can be collected from subventions for capacities below 150 kW_e as well as in the framework of competitive auctions within the bidding scheme of the GREA [EEG 2017] as a sum of wholesale prices and market premiums. A further option points to the possibility of financing the generation of bioenergy by means of those revenues incurred in heat retail markets through the sales of the heat cogenerated by CHP facilities. Consequently, the remunerations granted to the power plants in each of the twelve compound scenarios within the last three sections have been modelled via setting a high enough value above the breakeven point – i.e. higher than their electricity production costs. As a result, the restrictive effect of profitability constraints within each utilisation pathway is eliminated. On the contrary, the progressive reduction of remunerations as a kind of sensitivity analysis permits gaining insight into a wide range of techno-economic configurations with different spatial arrangements and lower electricity production costs. For this purpose, remunerations in the framework of this section are systematically reduced to the level of a series of successive breakeven points in order to identify potential cost reductions. This way, remunerations are conceived as the minimum amount of incomes received by plant operators for the production of bioenergy so that the incurred production costs can at least be covered without any profit margin. In this manner, the focus of this type of modelling will be on the formation of EPC of each utilisation pathway and not on the benefit achieved by investors for each power facility.

In order to appropriately prove and visualise the referenced effect of profitability constraints on the wood resources-based bioenergy subsystem of Baden-Württemberg, the remunerations of the three conversion technology settings or simple scenarios (CHP, Cofi or BIGCC) can be modelled separately for each utilisation pathway. This methodology was previously applied to the corresponding analyses of the twelve compound scenarios (see sections 7.2-4) in which remunerations are assigned a sufficiently elevated value so as to neutralise the restrictive behaviour of mathematical constraints and ensure the profitability of each utilisation pathway. This manner, the continuous lessening of the remunerations granted to all installable power plants can generate a broad spectrum of techno-economic options with different spatial location, capacity and costs for each of the CHP, Cofi and BIGCC-related compound scenarios. Nevertheless, each of these conversion technology simple scenarios exhibits a different suitability for such a particular analysis. Indeed, the CHP-based settings are not the best scenarios for this purpose on account of the high spatial aggregation chosen for the bioenergy system, which is constructed on the basis of the district as a spatial unit. For small CHP scales and their correspondingly reduced catchment areas with a low number of districts, significant inaccuracies might appear as a result of steep increases of transport costs when wood resources from a further district close to the original[31] catchment area are supplied to the targeted power plant. This in addition to the high capital and operating costs of small-

[31] The adjective "original" refers to the bioenergy configuration achieved when the breakeven point is reached and subsequently a further lowering of the remunerations can be performed in order to generate a new bioenergy configuration with lower electricity production costs.

scaled CHP technologies might reduce the visibility of the intended effect – especially if profitability constraints with lowered remunerations are not easily fulfilled because of the great rise in electricity production costs. On the contrary, the remaining Cofi and BIGCC compound scenarios do not register the previously explained issue as most of their bio-based capacities – all in the case of BIGCC facilities – are in the domain of medium and large scales with catchment areas of correspondingly medium and large dimension, respectively. But in spite of this, the four BIGCC compound scenarios also exhibit a certain limitation with regard to the reproduction of the bioenergy subsystem of the federal state for a set of progressively reduced remunerations. This restriction is linked to the impossibility of assigning to power plants further wood resources from outside the catchment areas. This is because such areas of influence in all four BIGCC compound scenarios actually equate to the entire federal state of Baden-Württemberg as part of the boundary conditions considered in the framework of this study. With the goal of lessening the impact of this aspect while equally excluding a large part of the imprecision derived from the high level of spatial aggregation in relation to small scales, only the four Cofi compound scenarios (see Table 7.1) are identified as adequate to accomplish the proposed analysis. This is based on a methodology that consists in gradually diminishing remunerations below a certain level of profitability and repeatedly beyond the resulting electricity production costs at each breakeven point for all possible utilisation pathways.

For the sake of simplicity, this assessment is conducted exclusively for one of the four Cofi compound scenarios, concretely Cofi/ByPro/NonLaW, according to which forest residues are regarded as a by-product while no landscape wood raw material is harvested for electricity production purposes. Anyhow, the remaining Cofi compound scenarios, namely Cofi/ByPro/LaW, Cofi/JointPro/NonLaW or Cofi/JointPro/LaW, are also suitable to accomplish such a progressive reduction of remunerations for any feasible bio-based utilisation pathway – albeit the outcomes will be quite similar to those of the chosen scenario. In virtue of the above, the intended analysis aiming at assessing the consequences of decreasing the value of remunerations is implemented for the set of the preselected coal-fired power stations of Baden-Württemberg (see Table 7.3) as eligible units for retrofitting them into the co-firing mode.

According to the statistics published by [Statista 2018], hard coal-fired power stations in Germany are operated for a yearly average of 3,600 full load hours whereas dedicated biomass power plants produce bioenergy for around 5,810 load hours per year at full load. As the selected coal-fired power plants should burn a 10% portion of wood resources in case of being retrofitted, a slightly increased amount of 4,000 full load hours per year is assumed as an appropriate magnitude to model the referenced co-firing related compound scenario for the intended decrease in remunerations. Although the co-firing based coal-fired power plants are modelled in section 7.3 for a yearly rate of 3,000 full load hours, the assumption of 4,000 hours per year at full load for this analysis permits a significant reduction of the extent of the resulting solution in order to easily gain a better insight into the dynamics of the generation of new bioenergy configurations.

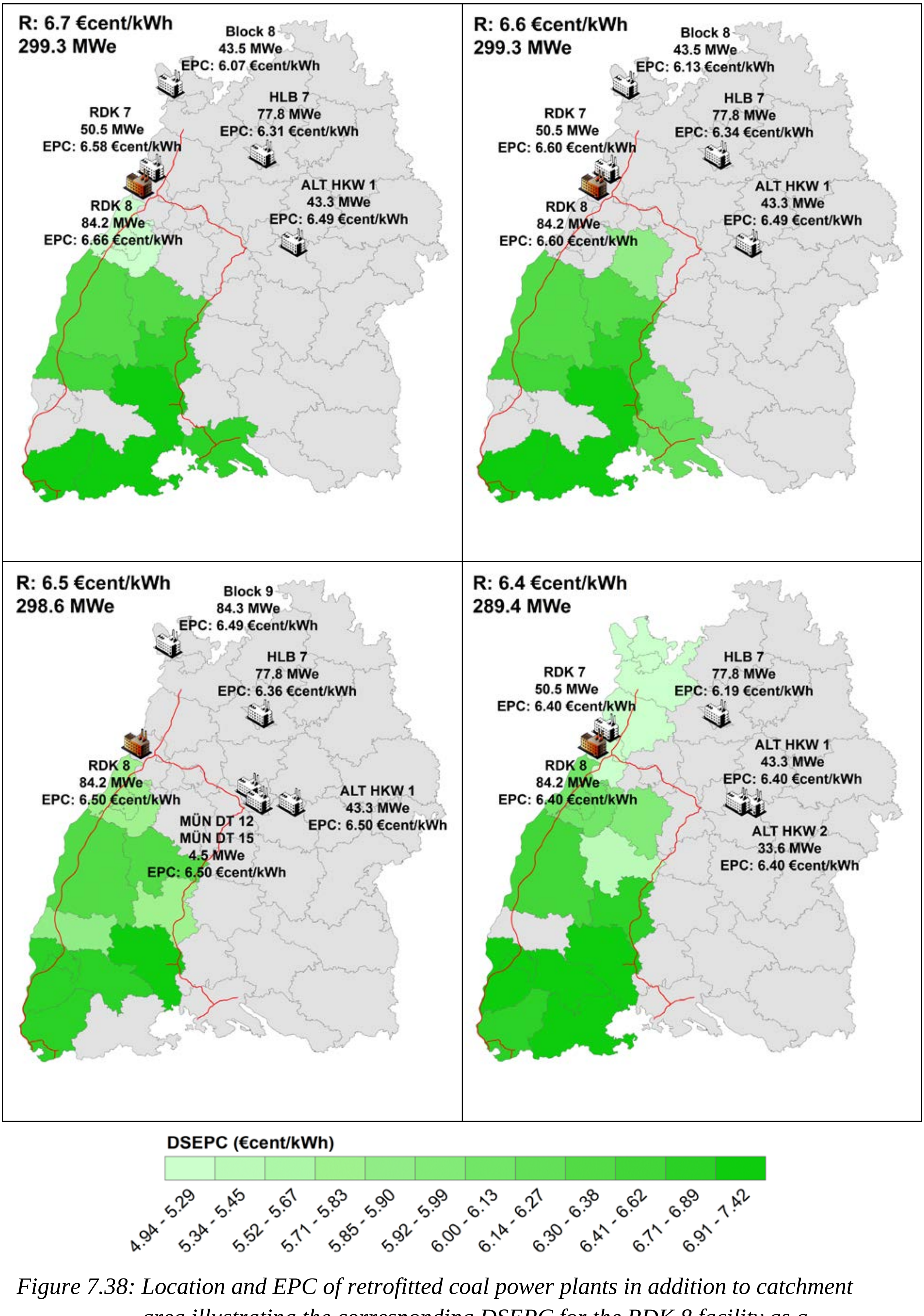

Figure 7.38: Location and EPC of retrofitted coal power plants in addition to catchment area illustrating the corresponding DSEPC for the RDK 8 facility as a function of the remuneration R (6.4, 6.5, 6.6 and 6.7 €cent/kWh$_e$)

Thereby, the model of the Cofi/ByPro/NonLaW compound scenario is run for a series of consecutive values of remunerations ranging from a certain level of profitability to the extent in which no bio-based utilisation pathway is implemented and hence no bioenergy generated. As a result, an identical solution is provided for this compound scenario when remunerations are valued above or just at 6.7 €cent/kWh$_e$. In this connection, Figure 7.38 illustrates for this remuneration *R* an array of five coal-fired power plants to be retrofitted with a total capacity of 299.3 MW$_e$, namely the RDK 7 and RDK 8 power stations in Karlsruhe, the Block 8 coal power plant of Mannheim – specifically operated for 3,980 hours per year at full load –, HLB 7 in Heilbronn and ALT HKW 1 in Altbach (Esslingen) with 50.5 MW$_e$, 84.2 MW$_e$, 43.5 MW$_e$, 77.8 MW$_e$ and 43.3 MW$_e$ of bio-based installed capacity, respectively. The corresponding electricity production costs vary between 6.07 €cent/kWh$_e$ and 6.66 €cent/kWh$_e$ – slightly below the predefined remuneration – on the basis of an appropriate mechanism of wood resources distribution. According to this, the more expensive types of wood chips, concretely both coniferous contributions of LFO (large forest owner) and SPFO (small private forest owner) originating largely from the woodlands of the Black Forest (see Figure 6.1 and Table 6.6), are allocated to the most cost-efficient RDK 8 power plant. The focus of Figures 7.38-40 is equally set on the catchment area of this retrofitted power station (coloured unit in the three Figures) together with its DSEPC so as to respectively illustrate its spatial evolution and cost development as a function of the progressive variation of remunerations *R*. Besides, it should be pointed out that the whole free potential of forest residues in Baden-Württemberg, which is estimated at roughly 950,000 tonnes FW (35% MC) in section 2.2, is completely converted into bio-based power without leaving any unconsumed fraction. In this regard, the entire value chain of forest residues for the generation of 299.3 MW$_e$ in the federal state under the referenced conditions add up to an annual quantity of total production costs of around €77.133 million.

A quite similar techno-economic configuration for the targeted bioenergy subsystem at exactly the same spatial locations is generated as against the former case, when the remuneration is set at 6.6 €cent/kWh$_e$. As depicted in Figure 7.38, the same co-firing based coal power plants – equally with Block 8 in Mannheim running yearly for 3,980 full load hours – reproduce for an identical total capacity of 299.3 MW$_e$ specific electricity production costs (EPC) ranging from 6.13 €cent/kWh$_e$ to 6.60 €cent/kWh$_e$. The rationale for the change of the respective EPC can be accounted for by the cost limitation imposed by the lower value of remunerations within the profitability constraints thereby giving rise to an appropriate reduction of 0.06 €cent/kWh$_e$ in the production costs of RDK 8. This effect simultaneously brings about a certain cost redistribution among the EPC of RDK 7, Block 8 and HLB 7, which now exhibit increased electricity production costs while those of ALT HKW 1 remain constant (see 7.38). By comparing both maps for 6.7 and 6.6 €cent/kWh$_e$, the latter remuneration yields a RDK 8's catchment area including three specific districts (Calw, Tuttlingen and Konstanz) that show lower DSEPC in the order of 5.85-6.27 €cent/kWh$_e$. In contrast, only the districts of Rastatt and Baden-Baden contribute in the former case with considerably cheaper EPC at 5.29 €cent/kWh$_e$. Anyhow, RDK 8's decrease in EPC – when performing the switch from the 6.7 to the 6.6 €cent/kWh$_e$ bioenergy configuration – is mainly due to the transfer of roughly 5,858 t FW of the more expensive chip type (coniferous SPFO) from the district of Waldshut in the relevant area of influence to those of RDK 7, Block 8 and HLB 7. As in the previous case, the entire free potential of forest residues (950,000 tonnes FW at 35% MC) is also wholly transformed into power by installing the mentioned total power capacity of 299.3 MW_e. The yearly amount of total production costs increases slightly to €77.140 million in comparison to the prior arrangement on account of the increased costs incurred by the necessary redistribution of wood resources' potentials so as to comply with lowered remunerations within the profitability constraints.

Setting remunerations at just 6.5 €cent/kWh_e induces a new techno-economic configuration that is made up of six retrofitted coal-fired power plants delivering a somewhat lower total power capacity of 298.6 MW_e (see Figure 7.38). The selected bio-based units are the RDK 8 power station in Karlsruhe, the Block 9 coal power plant of Mannheim, HLB 7 in Heilbronn, both small-sized MÜN DT 12 and MÜN DT 15 conversion units located in Münster (Stuttgart) and ALT HKW 1 in Altbach (Esslingen) with 84.2 MW_e, 84.3 MW_e, 77.8 MW_e, 4.5 MW_e, 4.5 MW_e and 43.3 MW_e of bio-based power output capacity, respectively. The specific EPC of HLB 7 are the most economical with 6.36 €cent/$kWh_{e,}$ whereas those of Block 9 amount to 6.49 €cent/kWh_e with the remainder being valued at the highest possible costs of 6.50 €cent/kWh_e. Regarding the RDK 8 conversion unit, mention should also be made of the reduction in area experienced by the catchment zone of this retrofitted facility as compared to the previous configurations obtained for higher remunerations. This is exclusively ascribed to the installation of a unique bio-based conversion plant in the district of Karlsruhe, since the formerly selected RDK 7 power station is no longer retrofitted under the referenced conditions. In this sense, the lack of competition for the existing free potentials of wood resources within the southwest of Baden-Württemberg leads to the referenced reduction effect. Furthermore, the modest decrease in the bio-based total power capacity to 298.6 MW_e proves to be linked with the lack of consumption of certain amounts of relatively expensive coniferous SPFO forest residues-derived wood chips. These contributions originate from Waldshut and Ravensburg – 5,437 and 395 t FW, respectively – and account for approximately 0.61% of total free potential for forest residues within the federal state. In relation to the yearly incurred total production costs, they reach a marginally higher value of €77.189 million for the resulting entire value chain of forest residues with respect to both prior remuneration-based cases. The outcome derived from this bioenergy subsystem configuration is that somewhat less power capacity is generated for a slightly higher level of expenditures than in both previous cases. This fact results in homogeneously high specific EPC for all installed units since the respective production costs cannot exceed the corresponding remuneration of 6.5 €cent/kWh_e.

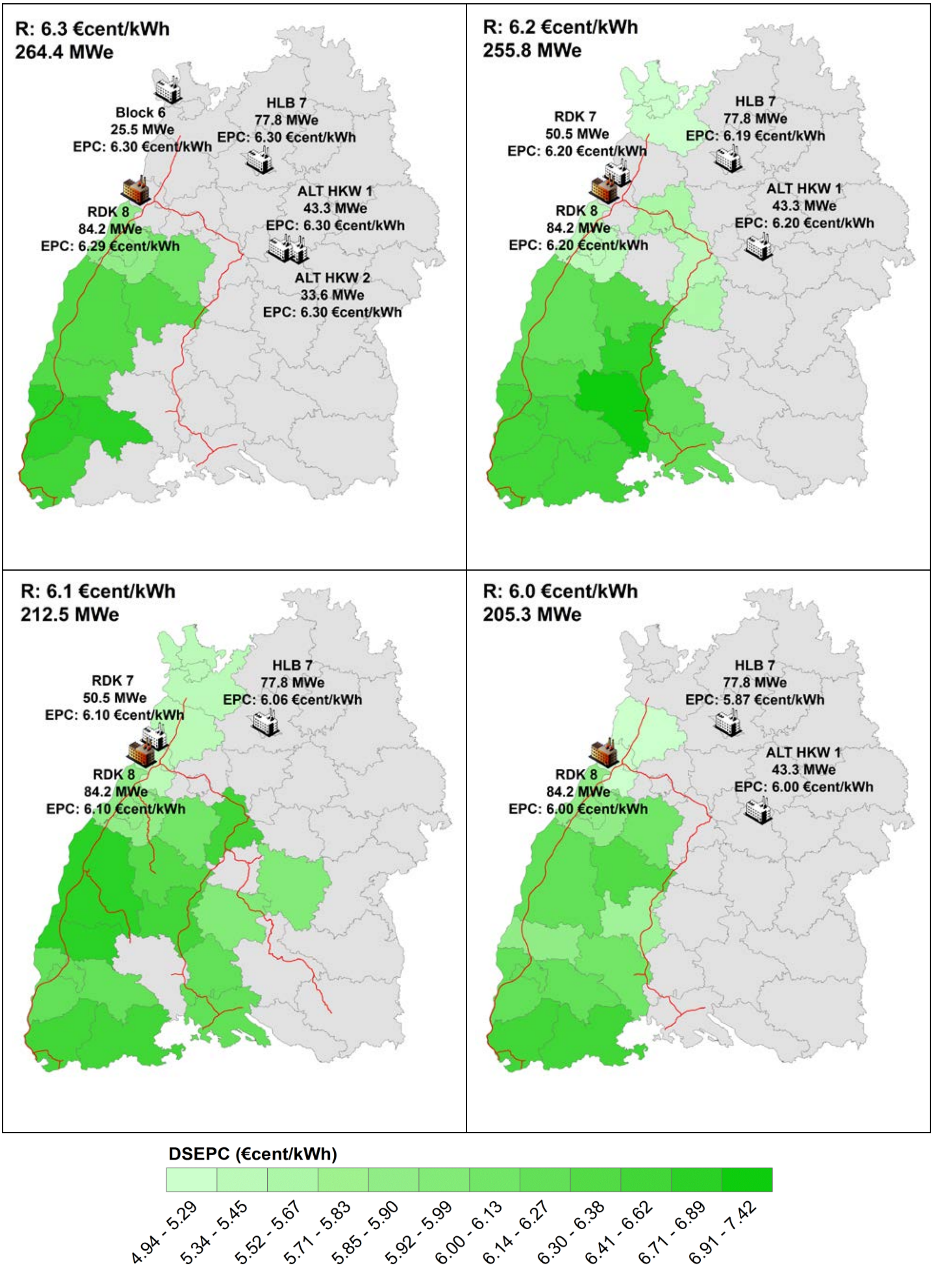

Figure 7.39: Location and EPC of retrofitted coal power plants in addition to catchment area illustrating the corresponding DSEPC for the RDK 8 facility as a function of the remuneration R (6, 6.1, 6.2 and 6.3 €cent/kWh$_e$)

A further different solution is produced when remunerations are reduced to 6.4 €cent/kWh$_e$. The resulting techno-economic configuration shows a lesser total bio-based power capacity (289.4 MW$_e$) as compared to the previous bioenergy distribution pattern in Figure 7.38. The district of Karlsruhe is again assigned both RDK 7 and RDK 8 power stations, whereas no coal power plant is upgraded into the co-firing mode in the urban district of Mannheim. Instead, a medium-scaled unit, ALT HKW 2 with 33.6 MW$_e$, is installed in Altbach (Esslingen) along with the other facility ALT HKW 1. Also, HLB 7 in Heilbronn ranks among the five selected coal-fired power plants to be retrofitted. The lowest specific EPC are registered by HLB 7 with 6.19 €cent/kWh$_e$ whereas those of the remaining plants are forcibly adjusted to the greatest value of 6.40 €cent/kWh$_e$ in order to transform the largest possible share of the existing free potentials of forest residues. The spatial expansion of the RDK 8's catchment area equally responds to the need to leverage certain inexpensive wood resources growing in nearby districts such as Karlsruhe, Rhein-Neckar-Kreis, Heidelberg and Mannheim – with the last three only supplying cheaper deciduous LFO forest residues to RDK 8. All these districts present comparatively lower DSEPC (4.94-5.26 €cent/kWh$_e$) as against the rest of the spatial units within the referenced catchment area and are besides no longer allocated to any of Mannheim's power stations on account of the applied remuneration decrease. On the other hand, the more restrictive profitability constraints yield a lower total capacity of 289.4 MW$_e$ as a result of excluding substantial amounts of relatively costly coniferous forest residues from SPFO contributions while cheaper deciduous fractions are indeed valorised. In this regard, 5,798, 11,126 and 3732 t FW (35% MC) of coniferous SPFO chipped forest residues respectively originating from Lörrach, Waldshut and Ravensburg are no longer either harvested, densified, transported or converted into bioenergy. This unconsumed amount of wood resources represents 2.16% of Baden-Württemberg's free potential of forest residues, which points to a corresponding consumed share of circa 98%. As a result, the expenditures associated with the whole value chain of forest residues for the generation of bio-based power from forest residues in Baden-Württemberg for a remuneration of 6.4 €cent/kWh$_e$ decrease with respect to the last case to an annual quantity of total production costs of around €73.428 million. This result arises as part of a new downward trend of production costs that will continue until the end of the implemented progressive reduction of remunerations by 5.5 €cent/kWh$_e$.

For a remuneration fixed at 6.3 €cent/kWh$_e$, a new bioenergy system configuration is created as depicted in Figure 7.39. The resulting ensemble comprises five retrofitted coal-fired power plants that deliver a total power capacity of 264.4 MW$_e$ The selected bio-based facilities encompass the RDK 8 power station in Karlsruhe, the Block 6 coal power plant of Mannheim, HLB 7 in Heilbronn as well as ALT HKW 1 and ALT HKW 2 in Altbach (Esslingen) with 84.2 MW$_e$, 25.5 MW$_e$, 77.8 MW$_e$, 43.3 MW$_e$ and 33.6 MW$_e$ of bio-based power capacity, respectively. All bioenergy generation units are assigned almost the same specific EPC with RDK 8 supplying power at 6.29 €cent/kWh$_e$, whereas the rest of the identified facilities exhibit the highest possible production costs of 6.30 €cent/kWh$_e$. As registered for a remuneration of 6.5 €cent/kWh$_e$, the RDK 8's catchment area extends along the corridor of the highway 5 throughout the southwest of Baden-Württemberg. In this case, the corresponding sphere of influence is slightly reduced in scope and also displays somewhat lower DSEPC that result from the apportionment of cheaper deciduous wood resources. Moreover, a major amount of more expensive coniferous SPFO and LFO chipped forest residues originating in the districts of Breisgau-Hochschwarzwald, Emmendingen, Schwarzwald-Baar-Kreis, Tuttlingen, Konstanz, Lörrach, Waldshut, Bodenseekreis and Ravensburg are no longer harvested and hence discarded for their conversion into bio-based power. In virtue of this fact, the consumed share of total forest residues in the federal state remains on the order of approximately 83%, which in turn translates into the aforementioned total capacity of 264.4 MW_e. As for the annually incurred total production costs, they amount to around €66.590 million for all identified utilisation pathways within the whole value chain of forest residues.

When remunerations lessen to 6.2 €cent/kWh_e, the analysed model provides a further singular solution for the wood resources-based bioenergy system of Baden-Württemberg. Indeed, a bioenergy configuration that is relatively similar to the result of letting the targeted subsystem evolve a decimal point below this remuneration to a value of 6.1 €cent/kWh_e (see both maps in Figure 7.39). But both patterns of course differ in the magnitude of their total bio-based power output capacities with 255.8 MW_e for the former and 212.5 MW_e in the case of the latter. Both RDK 7 and RDK 8 power stations in Karlsruhe – yet again no unit in Mannheim is selected – as well as HLB 7 in Heilbronn and ALT HKW 1 in Altbach (Esslingen) are amongst the four coal power plants to be adapted to co-firing if they are awarded remuneration at 6.2 €cent/kWh_e. Nevertheless, the smaller-sized conversion unit of Altbach is conversely not included in the selected set when the remuneration is cut down to 6.1 €cent/kWh_e. The corresponding specific EPC are however nearly the same for each of both remunerations in question. In this regard, HLB 7 exhibits slightly lower EPC of 6.19 €cent/kWh_e just below the imposed remuneration of 6.2 €cent/kWh_e. By following the same trend, this unit is assigned specific EPC of 6.06 €cent/kWh_e in the case of decreasing remuneration to 6.1 €cent/kWh_e. By contrast, the EPC of the remaining plants in both cases equal both respective levels of remuneration at 6.20 and 6.10 €cent/kWh_e. Concerning the catchment area of RDK 8, it continues to expand its surface area when remunerations decrease from 6.2 to 6.1 €cent/kWh_e especially if compared to the preceding and therefore analogous case – two installed plants in Karlsruhe and none in Mannheim – emerged for 6.4 €cent/kWh_e. In both analysed cases, the DSEPC of the districts within the RDK 8's catchment area become progressively lower to the extent that ever cheaper portions of deciduous SPFO and LFO chipped forest residues are allocated to this unit. Particularly, the corridors of the highways 5, 8 and 81 along with certain other major roads comprehend those districts supplying such more economical contributions. In this regard, some districts such as Karlsruhe, Rhein-Neckar-Kreis, Heidelberg and Mannheim but also Enzkreis, Pforzheim, Böblingen and Tübingen together with the outlying – from the viewpoint of the RDK 8's catchment area – administrative units of Zollernalbkreis and Reutlingen become involved for the latter remuneration in such kind of mechanisms aiming at reducing EPC via valorisation of deciduous wood material. As a result of this, substantial amounts of free potentials comprising the relatively expensive share of coniferous SPFO and LFO chipped forest residues are not apportioned to any bio-based plant within the resulting value chain. Therefore, a marked decline in the consumed portion of total forest residues takes place as against that of prior cases with percentages gradually decreasing to roughly 80% and 66% for the respective remunerations of 6.2 and 6.1 €cent/kWh$_e$. In a similar proportion, the yearly amount of total production costs incurred in the entire value chain of forest residues within the federal state totals up to around €63.419 million for the former and €51.726 million for the latter rate of remuneration.

A succession of four different techno-economic arrangements for the targeted bioenergy subsystem arises when remunerations are varied from a value of 6.0 €cent/kWh$_e$ downwards to 5.7 €cent/kWh$_e$ in line with the corresponding four maps depicted in Figures 7.39-40. An initial set of three retrofitted coal-fired power plants including RDK 8, HLB 7 and ALT HKW 1 and delivering a total capacity of 205.3 MW$_e$ at a remuneration of 6.0 €cent/kWh$_e$ evolves to the point that only the RDK 8 conversion unit is installed when bio-based power is remunerated at 5.7 €cent/kWh$_e$. The upgraded units within each of the consecutive stages (bioenergy configurations) present specific EPC with values either just at or slightly below the level marked by the corresponding predefined remuneration. The HLB 7 conversion unit is assigned a somewhat lower EPC than the rest of the plants for both remunerations of 6.0 and 5.9 €cent/kWh$_e$, while the remaining conversion units produce bio-based power at the highest possible production costs. On the contrary, all the bio-based plants installed in both stages under remunerations of 5.8 and 5.7 €cent/kWh$_e$ exhibit specific EPC respectively below each of these values. In relation to the bio-based RDK 8 conversion unit, its catchment area extends from a well-defined area in the southwest of Baden-Württemberg to a vast geographical zone covering most of the federal state when remunerations are decreasingly varied from 6.0 to 5.7 €cent/kWh$_e$. The corresponding DSEPC showed by the RDK 8's catchment area for each of the arrangements induced by this series of remunerations turn to be gradually cheaper. Besides, they present magnitudes mostly ranging between 4.94 and 5.83 €cent/kWh$_e$ mainly due to the increasing valorisation of deciduous forest residues. Similarly to both prior cases, the highways 5, 6, 8 and 81 equally permit to a greater or lesser extent the channelling of wood resources from the districts in peripheral areas to the RDK 8 conversion unit for the different amounts of remunerations. As a consequence of this gradual decrease in payments, less and less bio-based facilities with ever smaller total power output capacity are progressively installed due to the increasing non-consumption of comparatively more expensive wood resources. Coniferous forest residues from both SPFO and LFO chip types are the first resource not to be consumed according to such behaviour. But when the restriction imposed by profitability constraints intensifies, the most costly fraction of deciduous forest residues – namely that harvested by SPFO – also starts not to be allocated to the targeted power plants thus remaining progressively unconsumed. And the same goes for the cheapest portion based on LFO chipped deciduous forest material, which is the last resource that is steadily less and less harvested, densified, transported and converted into bio-based power. This way, an increasing number of districts no longer provide any free potential of forest residues to the bio-based units as remunerations are gradually cut down. In this respect, it should also be mentioned that expensive wood resources tendentially remain consumed in the central parts of the resulting catchment areas for each remuneration, while they become unconsumed in the outlying districts of these same zones of influence.

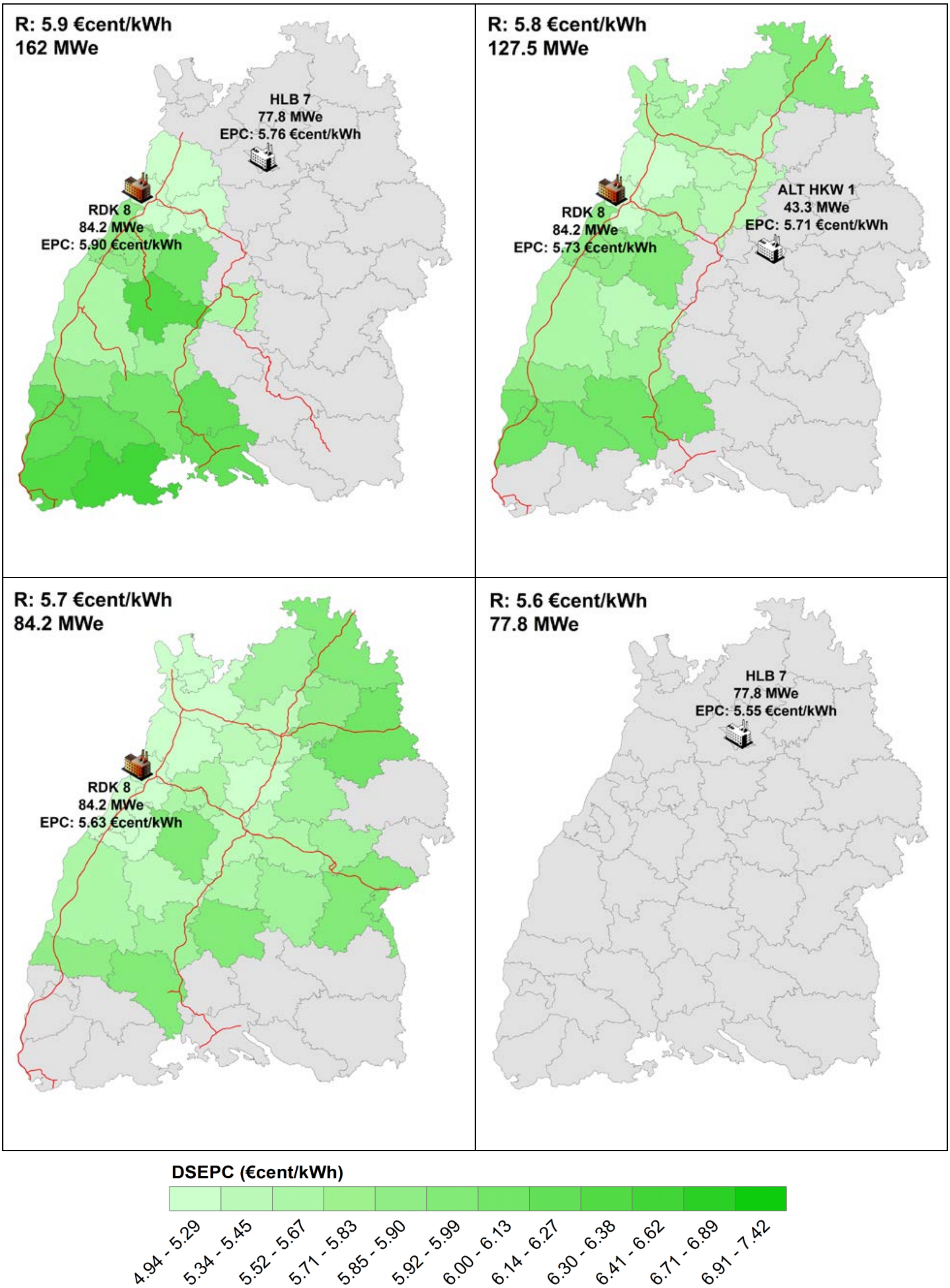

Figure 7.40: Location and EPC of retrofitted coal power plants in addition to catchment area illustrating the corresponding DSEPC for the RDK 8 facility as a function of the remuneration R (5.6, 5.7, 5.8 and 5.9 €cent/kWh$_e$)

This is basically attributable to the fact that the harvesting of expensive wood materials in woodlands far away from the conversion unit is unavoidably linked to increased transport costs that in turn raise the resulting EPC. Consequently, such free potentials are excluded from consumption for failing to comply with the corresponding profitability constraint. In view of the foregoing, the resulting consumed portion of the total free potentials of forest residues growing in Baden-Württemberg accounts for roughly 62%, 51%, 39% and 27% as bio-power is respectively remunerated at 6.0, 5.9, 5.8 and 5.7 €cent/kWh$_e$. These percentages are ultimately correlated to the annual amounts of total production costs caused by the corresponding bioenergy configurations for the respective levels of remuneration. Accordingly, these total annual expenses reach the values of €48.882 million, €37.792 million, €29.197 million and €18.949 million when specific remunerations are correspondingly reduced to 6.0, 5.9, 5.8 and 5.7 €cent/kWh$_e$.

The implemented BIOSPHERE model for the Cofi/ByPro/NonLaW scenario provides a bioenergy pattern with the smallest size when remunerations are set at 5.6 €cent/kWh$_e$. A single power plant is selected under such conditions, specifically the 77.8 MW$_e$ HLB 7 conversion unit in Heilbronn with a specific EPC of 5.55 €cent/kWh$_e$ (see Figure 7.40). In this context, only a small portion of the free potentials of forest residues, namely 24%, is converted into bio-based power. The implementation of such a utilisation pathway, constituted by a mere combination of HLB 7 and its supply chain, generates a yearly amount of total production costs in the order of €17.284 million. Finally, reducing the granted remuneration to 5.5 €cent/kWh$_e$ brings the wood resources-based bioenergy subsystem of Baden-Württemberg to a state in which forest residues are neither harvested nor densified nor transported nor converted into bio-based power. As a consequence of this, non-biogenic fuels as supplementary energy inputs for the subsystem (see section 5.4) are automatically implemented so as to ensure the convergence of the analysed mathematical model. As a final conclusion, it can be stated that lower levels of electricity production costs for different bioenergy configurations can be reached by means of decreasing remunerations. Thereby, interesting cost reductions can be identified for several utilisation pathways within the federal state of Baden-Württemberg. Indeed, such cost reductions should be equally analysed for the rest of the bio-based technologies and compound scenarios.

7.6. Sensitivity analysis

The empirical and experimental nature of data together with the effect of some statistical techniques such as interpolation or in this study the regression adjustment of certain input data (e.g. the techno-economic parameters of the preselected conversion technologies in subsection 4.4) may generate significant levels of parameter uncertainty. Due to the high level of this type of uncertainty when dealing with input data concerning the stages of harvesting, densification, transport and conversion, the economic solutions obtained for each of the twelve compound scenarios should undergo a sensitivity analysis with the aim of assessing the impact of parameter uncertainty on the dimension of some major magnitudes. In this connection, the two-dimensional sensitivity analysis of Figure 7.41 provides insight into the effect of varying the cost components and the full load hours on the electricity production costs as a measure of parameter uncertainty. For this purpose, an array of variations within a range of ±50% in these parameters for a particular bio-based power plant is performed in the case of the CHP/ByPro/NonLaW scenario as a practical example. For the sake of completeness, this kind of sensitivity analysis should equally be applied to the remaining compound scenarios in the framework of an overall assessment of the effect of such input parameters on electricity production costs.

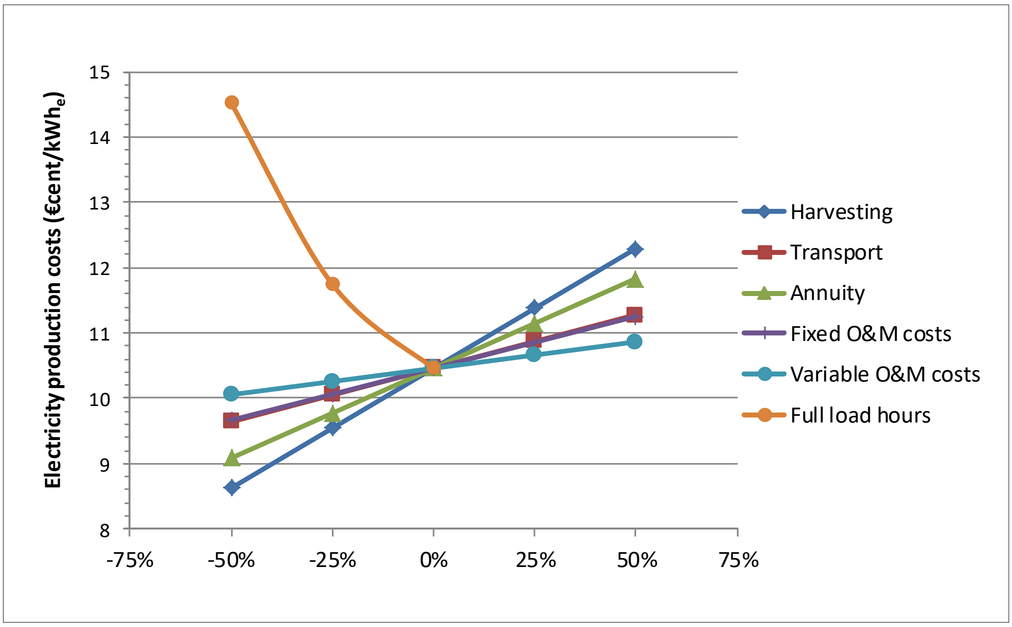

Figure 7.41: Two-dimensional sensitivity analysis of specific electricity production costs when varying the respective cost components and the full load hours for the CHP/ByPro/NonLaW compound scenario

For a FBG+E-based power plant being supplied with forest residues as a by-product, the electricity production costs exhibit its highest sensitivity for changes in the full load hours and the cost element involving harvesting tasks. The variation of the annuity also yields significant changes in the electricity production costs on account of the elevated investment costs of such bioenergy technology. The change in cost elements concerning transport and fixed O&M costs produce a similar effect on the electricity production costs, whereas the resulting EPC prove to be less sensitive to variable O&M costs. The three remaining CHP compound scenarios would yield the same behaviour with the exception of the different contribution derived for each harvesting cost component. Those scenarios including the more expensive harvesting of landscape wood raw material and/or forest residues considered as a joint product will increase the sensitivity of electricity production costs in proportion to the incurred amount of harvesting costs. The four compound scenarios, namely CHP/ByPro/NonLaW, CHP/ByPro/LaW, CHP/JointPro/NonLaW and CHP/JointPro/LaW present progressively higher harvesting costs that correspondingly induce a gradually higher sensitivity of corresponding electricity production costs to changes in the respective harvesting expenses.

Analogously, a further approach for addressing the parameter uncertainty of EPC within the same compound scenario on the basis of a three-dimensional (3-D) sensitivity analysis is carried out in Figure 7.42 by varying both the harvesting costs and the sum of the annuity and the operating costs and neglecting possible changes in transport costs. The result illustrates the corresponding sensitivity to both constituents by highlighting electricity production costs in the range from 6 to roughly 15 €cent/kWh$_e$ if harvesting costs and technology investment gradually change their value between -50% and +50%. As the cost component involving the technology expenditures are slightly higher than that of harvesting costs, the resulting electricity production costs show a higher sensitivity to the variation of the former as against the latter. This trend is systematically perceived in each of the sensitivity analyses accomplished in this section independently of their dimensional character. Therefore, the higher the contribution of e.g. the cost components of a particular bio-based power plant the more sensitive to the existing parameter uncertainty the respective EPC will be.

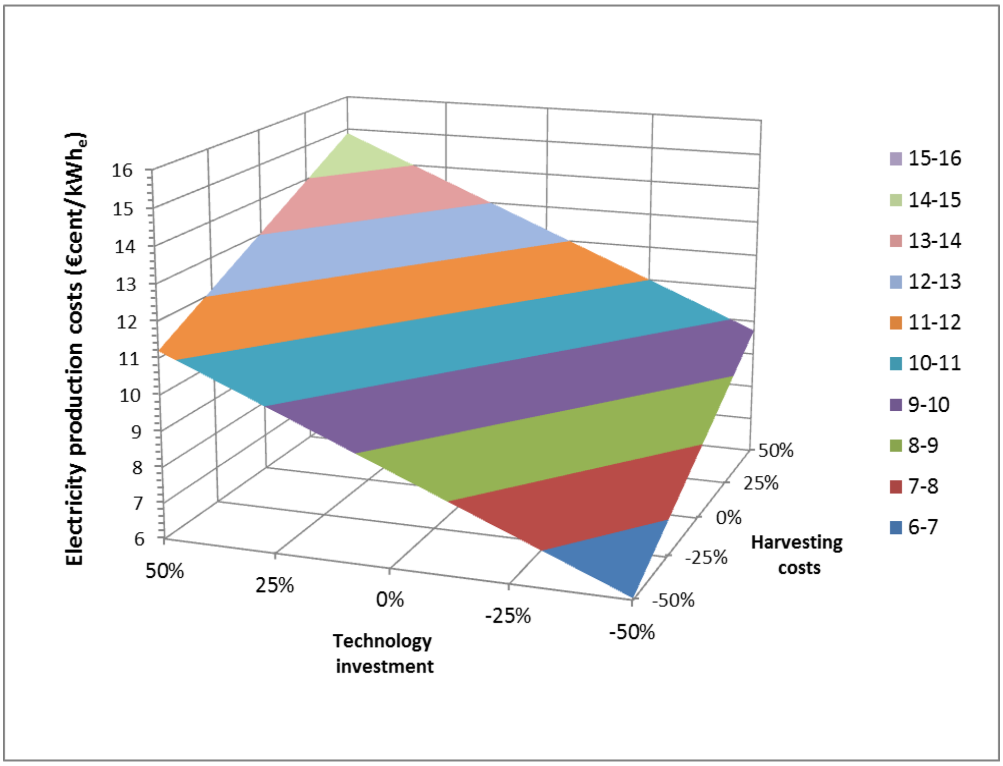

Figure 7.42: Three-dimensional sensitivity analysis of specific electricity production costs when varying the harvesting costs and the technology-related expenditures for the CHP/ByPro/NonLaW compound scenario

8. Conclusions and critical reflection

This chapter focuses on the practical conclusions drawn from the results obtained throughout this study. Concretely, it gives insight into an array of preliminary conclusions concerning the most important goals achieved. Subsequently, some spatial and economic aspects in relation to the implementation of utilisation pathways for power generation from wood resources are discussed. As the solutions presented for each scenario in chapter 7 are exposed in a sequential order, it is not easy to relate each outcome to the others in order to ascertain differences among all. For this reason, a series of comparisons are performed for the resulting electricity production costs and their cost components within each technology simple scenario and equally for each of the four resources-related compound scenarios. A further section sheds light upon the dependence of electricity production costs and their cost elements on scale for the four CHP-based scenarios so as to illustrate how they evolve for different magnitudes of power output capacity. As some cost reductions within new bioenergy configurations can be identified if remunerations are progressively decreased below each resulting breakeven point, the corresponding mechanisms are appropriately explained in an additional section. On the other hand, the feasibility of installing the three preselected bioenergy technologies in the framework of the German Renewable Energy Act is analysed via three issues. These aspects involve an eventual capacity expansion plan of these technologies over time, the profitability of bio-based conversion units based on the preselected CHP technology as well as the suitability of certain centralised technologies such as the co-firing and BIGCC technologies for their installation during the upcoming nuclear and coal phase-outs. Finally, the chapter concludes with a critical appraisal of this study as well as an analysis on the future possible developments of the topic treated in this study.

8.1. Preliminary conclusions

The existing free potentials of wood resources

A major goal in the framework of this dissertation is the determination of the free potentials of forest residues and landscape wood raw material at district level for the federal state of Baden-Württemberg. On the contrary, the remaining types of wood resources, namely woody green wastes, wood wastes and industrial wood residues are not allowed for because their free potentials are either negligible or just entirely consumed. In relation to the information published by other prior research sources, only the total technical potential of the different types of wood resources was reported instead of their free or consumed fraction. However, forest residues were successfully analysed at different spatial aggregation levels such as those of district or community although without any reference to landscape-based resources – these are presented in this study for the first time at district level. Previously, the potentials of landscape wood raw material were exclusively ascertained at the level of the federal state without analysing them at lower levels of aggregation. As a result of this research work, the spatial distribution of the free portions of the technical potentials of forest residues and landscape wood raw material is calculated for the entire territory of Baden-Württemberg at the spatial aggregation level of the district on account of the existing data availability.

The logistic chains for harvesting wood resources

A new methodological approach is put forward with the aim of techno-economically characterising the harvesting of wood resources. According to this methodology, an array of logistic chains for production of chipped forest residues is presented. It includes the motor-manual harvesting system carried out by small private forest owners as well as the partly, highly and fully mechanised harvesting procedures that are implemented by large forest owners. Chipped forest residues are considered either as a by-product or as a joint product on the basis of the by-product and joint product cost allocation procedures. Each of the four logistic chains is composed of a number of stages showing different costs that are associated with thinning activities carried out in forest areas for an average diameter at breast height of 15 cm.

In the same vein, both the partly and highly mechanised harvesting techniques, which are managed by large forestry corporations rank among the most suitable logistic chains for harvesting landscape wood raw material from copses and groves and subsequently densifying this material into wood chips. In contrast to the logistic chains of forest residues, those of landscape wood raw material only produce a unique output, specifically chipped wood resources, without generating any other by-product. This results in a direct allocation of whole production costs to such a unique product. Landscape-based wood resources from copses and groves are principally constituted of trees and bushes with an average diameter at breast height of 10 cm. This reduced diameter gives rise to the exploitation of entire trees as a whole and exclusively for energy purposes after their complete comminution into chips.

For both types of wood resources, a specific feasible range for different steepness of slope below and above 50% is assigned to each of the four logistic chains according to the harvest machinery's access to woodlands as well as copses and groves. Moreover, the resulting unit costs assessed at either the forest roadside or the chipping site are strongly correlated to the corresponding degree of mechanisation since the specific mechanisation level of each stage directly determines the magnitude of both hourly rates and productivity that ultimately fix the overall costs of each logistic chain.

The most cost-efficient technologies for conversion of wood resources into power

A preselection has been carried out for a broad spectrum of bio-based technology options aiming at conversion of wood resources into bio-based power for all capacity ranges varying from small via medium through to large scales on the basis of cost-efficiency criteria. Except for the cheaper technology of co-firing, a direct comparison of the specific electricity production costs incurred by gasification and combustion techniques permits declaring that power produced by gasification proves to be less expensive than that generated through combustion when the compared processes are run under the same operation conditions. As a consequence, direct co-firing as well as a fluidised bed gasifier coupled to a gas engine or alternatively to a combined cycle are for the first time identified as the most cost-efficient bioenergy conversion pathways within the value chain of wood resources.

The co-firing technology can be categorised into three different setups, namely direct, indirect or parallel co-firing. As both indirect and parallel option equate to the further installation of more expensive conversion structures respectively based on gasification and combustion, the most cost-efficient co-combustion scheme consisting in direct co-firing is preselected over the remaining two methods. On the contrary, the co-fire rate of both indirect and parallel arrangements can be raised as much as desired in contrast to the limitation of the direct technique (around 10%). In general, the utilisation of already existing coal-fired power plants for implementing this technology renders the investment more economical than the remaining combustion and gasification techniques and thus ensures a higher level of cost-effectiveness. Reduced electricity production costs mainly result from the incremental nature of co-firing capital costs that only account for a small portion of the investment costs of a new coal-fired power plant or even of a dedicated bio-based facility of the same size.

For the range of small and medium scale applications, a bubbling or circulating fluidised bed gasifier coupled to a gas-fired internal combustion engine has been preselected as a more cost-efficient technology than the equivalent combustion-based conversion unit (steam cycle) or even certain fixed bed gasification schemes for generating power from wood resources. In relation to the comparative analysis between gasification and combustion, the former conversion technology presents a higher cost-efficiency than that of the latter for this range of scales. In this regard, the fluidised bed gasifier coupled to gas engine – unlike the stoker boiler connected to a condensing steam turbine – maximises power generation as a result of its higher efficiency and additionally produces waste heat that can also be remunerated. In addition, both emissions-related and social aspects involving gasification-based power plants for small and medium scales are in general better valued than those concerning combustion.

With respect to the domain of large scales, cost comparison between gasification and combustion gives an equivalent economic pattern to that reproduced by small and medium scales. A clear future trend involving higher electricity production costs for stoker boiler or fluidised bed combustor-based steam cycles as against those of biomass gasification combined cycles has been identified when these processes are run under the same operation conditions. As a result, these gasification-based power plants prove to be the most cost-efficient power generation method for large scales. This is in turn correlated to the higher efficiencies exhibited by large biomass integrated gasification combined cycles compared against those of equally scaled Rankine cycles when performed under the same operating conditions.

A novel tool for modelling remunerations

The methodology that permits the integration of the intended exogenous approach on the basis of a constraint on profitability for appropriately modelling remunerations is applied to an existing bottom-up tool that has been successfully employed for conducting energy system analyses. Leveraging the structures of the existing energy and material flow model, a novel and more advanced algorithm has been constructed in order to techno-economically reproduce any energy system that may include certain subsystems for bioenergy production where profitability must unavoidably be assured for each utilisation pathway. The outcome is the BIOSPHERE model (Bioenergy Optimisation Software for Production Pathways at High Energy and Resource Efficiency), which is based on a multi-period mixed integer linear programming (MILP) approach. This model minimises an objective function that includes the discounted total costs of the targeted system in keeping with the satisfaction of an array of auxiliary conditions. These restrictions involve the issue of energy and material flow balance as well as a number of restrictions on capacity and process utilisation. Finally, a further auxiliary condition relating to the principle of profitability of separate utilisation pathways plus four sets of auxiliary equations underpinning the prior constraint on profitability have been developed as a significant methodological advance. The resulting BIOSPHERE model carries out an optimisation of the entire energy system by minimising the total expenditures incurred over a determined space of time. In this regard, the value chains of a number of specific biomass resources for bioenergy generation are equally part of the analysed energy system and hence are also analysed by considering their spatial dimension within its geographic area. Thus, BIOSPHERE can be used for investigating the effect of remunerations on the total energy system or even on a specific bioenergy subsystem in consistency with the fulfilment of the principle of profitability for separate utilisation pathways – i.e. analysing the system from the standpoint of the respective plant operators acting as differentiated observers.

8.2. Spatial and economic aspects

The performed model-based analysis of the wood resources-based bioenergy system of Baden-Württemberg yields a series of conclusions with respect to the selected utilisation pathways that convert forest residues and landscape wood raw material into power. These utilisation pathways are made up of a bio-based power plant and a supply chain implemented throughout a multiform catchment area. The number of installed power plants directly depends on the amount of the existing free potentials of wood resources as well as the scale of the finally selected conversion units. The catchment areas extend from one district to another throughout the regional network of highways and major roads within the federal state and may vary in size on account of the consideration or not of landscape-based resources. If only forest residues are valorised, the respective areas of influence become clearly larger than in the case of harvesting both forest and landscape resources. This is basically due to the increased amount of growing wood material in each spatial unit thus giving rise to a certain reduction of the distance to be driven and hence the size of the respective catchment area. For the four compound scenarios belonging to each of the three technology settings, the form of a catchment area as well as the number of districts involved for each selected bio-based power plant being supplied with forest residues as a by-product and with or without landscape wood raw material are as a general rule dissimilar to those originating from harvesting of forest residues as a joint product respectively with or without landscape resources. However, this asymmetry is in general not fully reflected in the twelve compound scenarios previously analysed in chapter 7 due to the high level of the spatial aggregation of the district. As a result of this, only the solutions provided for two co-firing compound scenarios involving the harvesting of landscape wood raw material present retrofitted coal power plants with completely different zones of influence. In contrast, the exclusive use of the free potentials of forest residues as a by-product or a joint-product generates identical catchment areas for the selected conversion units on account of the low spatial resolution. In this connection, mention should also be made that catchment areas are only a pictorial representation of a more complex reality involving a more accurate spatial input of wood resources and their allocation to a particular conversion unit.

On another issue, the specific electricity production costs of a power plant result from the weighting of the district-specific electricity production costs registered for all districts contained in the catchment area. Consequently, a spatial unit with a lower aggregation level than that of the district would generate a more accurate district-specific electricity production costs gradation from the conversion plant to the boundaries of the catchment area. Besides, the breakdown of the electricity production costs into the different cost components allows not only assessing the conversion technology-related expenses or even those of transport but also identifying the relevance of harvesting costs, which are characterised by a weight of up to around 55%. A further cost component split of harvesting expenses into its different contributions when estimated on the basis of each harvesting stage (collection, moving and chipping) or the type of wood chips – both landscape-based resources harvested in areas with a steepness of slope above and below 50% as well as coniferous/deciduous forest residues collected by small private and large forest owners or in slopes lower and higher than 50% – can be accomplished. Such cost elements provide significant insights into those factors having influence on the composition of electricity production costs: quantity in tonnes as well as costs of each contribution, ownership type, slope of terrains and variety of trees. These factors definitely relate to the different conditions that normally arise in the forest and landscape zones within the catchment area of any bio-based power plant.

Moreover, the scenario-based analysis provides assistance in identifying the different investment options resulting from conversion of wood resources into bioenergy. In this regard, the CHP simple scenario reproduces a number of six or ten bio-based power plants with different district-specific electricity production costs – higher for forest residues as a joint product and landscape material and lower for forest residues as a by-product – depending on the resources-related compound scenario in question. The spatial arrangement of these bio-based plants follows a decentralised pattern of power production in line with the paradigm of distributed generation. As the specific electricity production costs within this scenario are on the order of roughly 10.1-13.8 €cent/kWh$_e$, the profitability of such power plants is only possible if investments are supported by electricity wholesale prices and market premiums in combination with the revenues obtained from the sale of heat. This aspect is analysed in next subsection 8.7.2 in order to gain further insight into this issue.

On the contrary, both the co-firing and BIGCC simple scenarios introduce a markedly centralised spatial configuration for each of both types of power plants. The conversion units are spatially predefined in the case of the existing coal-fired power plants that are to be retrofitted for co-firing purposes. In this regard, a different number of seven or twelve power plants with different district-specific electricity production costs – greater in the case of forest residues regarded as a joint product and landscape wood raw material – are installed as a function of the four resources-related compound scenarios. The unique spatial change refers to the size variation of the respective catchment areas. Nevertheless, this behaviour is not observed in the case of the single BIGCC power plants in each of the four compound scenarios as the corresponding catchment area equates to the entire territory of the federal state. Besides, a slight variation of the district-specific electricity productions costs is registered among both pairs of resources-related scenarios based on the harvesting or not of landscape wood raw material. On an economic level, the specific electricity production costs of both types of bio-based technologies are comprised between 5.6 and 11.7 €cent/kWh$_e$ for the four different resources-related scenarios. This cost range is unlikely to be covered via the current amount and future projections of electricity wholesale prices. As a consequence, some support instruments should be introduced into Baden-Württemberg's energy system so that co-firing based coal-fired power plants and centralised BIGCC facilities might provide cost-effective and carbon neutral baseload power supply (see subsection 8.7.3). The rationale for this decision would lie in the fact that both types of centralised bio-based power plants generate more economical electricity and in larger quantities than in the case of the decentralised concept of bioenergy production, thus facilitating an eventual fostering of both centralised options.

8.3. Comparison of electricity production costs within each technology setting

The specific electricity production costs obtained for the resulting twelve (compound) scenarios in the framework of the optimisation of the wood resources-based bioenergy system of Baden-Württemberg are grouped for each of the three technologies involved: namely CHP, co-firing and BIGCC. This way, the breakdown of the specific electricity production costs into their cost elements is shown in Figures 8.1-3 within each technology simple scenario for the four resources-related compound scenarios – forest residues as a by-product or a joint product with or without landscape wood raw material (see Table 7.1).

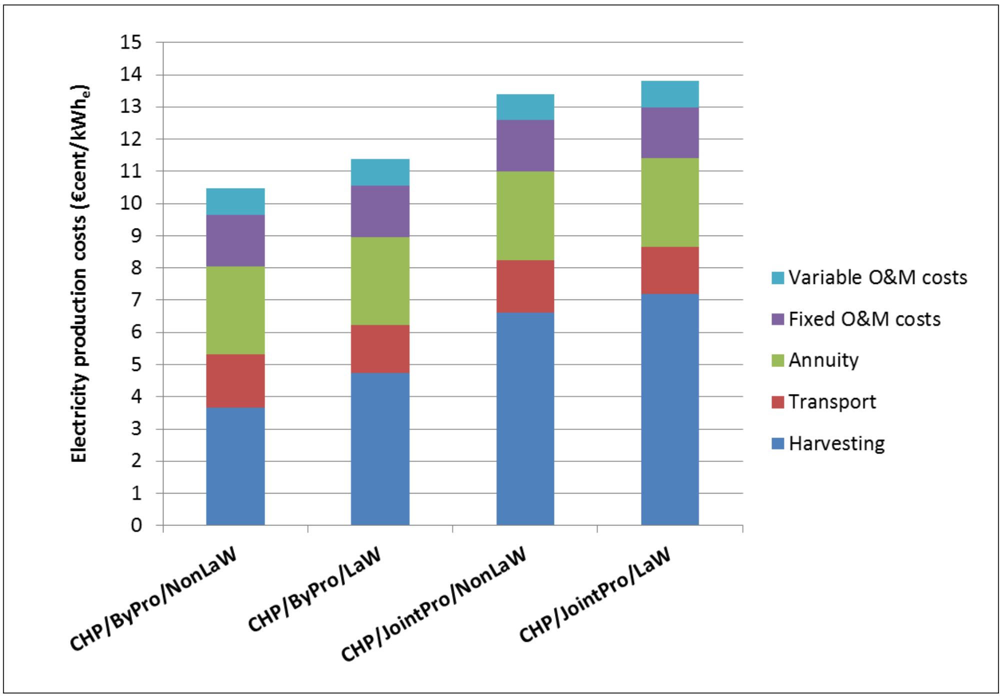

Figure 8.1: Cost breakdown of the electricity production costs incurred by the CHP-based power plant (20 MW$_e$) for the four resources-related compound scenarios

The four abovementioned resources-related compound scenarios progressively increase in costs from the most economical raw material involving forest residues as a by-product to the most expensive harvesting of forest residues as a joint product and landscape resources. These increasing costs suggets that the respective electricity production costs for each technology should evolve in a similar manner to the harvesting costs, namely increasing from the former to the latter resources-related compound scenario. And this is how the four CHP compound scenarios behave in term of production costs according to Figure 8.1. But this trend is however not followed in both scenarios where forest residues as a joint product with and without landscape wood raw material are supplied to both BIGCC power plants of 210 MW$_e$ and 340 MW$_e$, respectively. In these cases (see Figure 8.3), the corresponding electricity production costs are essentially the same due to the larger scale effect of the latter as well as the almost equal amount of harvesting costs. In the same vein, the electricity production costs of the co-firing compound scenario dealing with the harvesting of forest residues as a joint product and landscape wood raw material also reflects a lower level than those of the case in which only the former resource is consumed (see Figure 8.2). The reason for this is the particular allocation of cheaper wood resources to the Karlsruhe power plant as well as the relatively lower transport costs in the scenario including landscape wood raw material. But in theory, all three technology simple scenarios should undergo a progressive rise in harvesting costs throughout the corresponding four resources-related compound scenarios although with a different magnitude varying as a function of the electric efficiency of each technology. For this reason, the CHP technology for the lowest electric efficiency (27.7%) – compared to co-firing (37.6%) and the BIGCC-based technology (47.7-48.5%) – displays the highest harvesting costs and the most expensive electricity production costs for each of the four resources-related compound scenarios (see Figures 8.1-3).

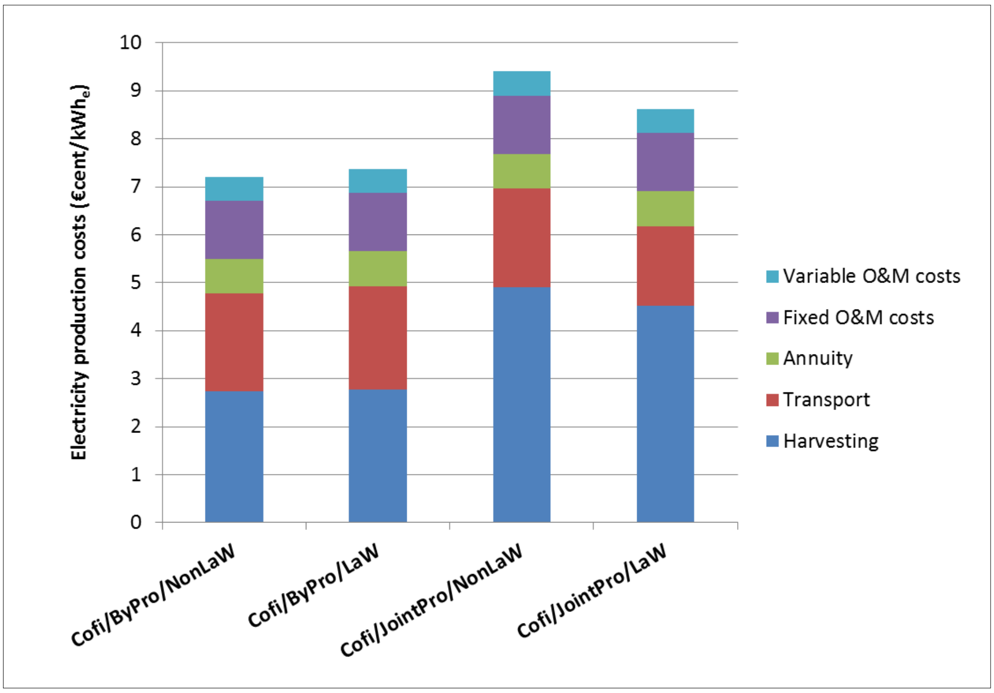

Figure 8.2: Cost breakdown of the electricity production costs incurred by the co-firing based power plant (RDK 8, 84.2 MW_e) for the four resources-related compound scenarios

Regarding transport costs, the consideration of landscape wood raw material brings some consequences such as a larger free potential of wood resources in every district of the federal state and hence a higher surface density for this material. As a result, a greater portion of wood resources are available for harvesting in the surroundings of the power plant, thus tendentially reducing the catchment area and therefore transport costs also. This is the case of the CHP simple scenario and both co-firing compound scenarios where forest residues as a joint product are provided (see Figures 8.1-2). There, the transport costs assigned to the power plants burning landscape-based resources experience a nearly unnoticeable decrease in the order of 10% for the former set of scenarios as well as a clear decline of circa 18% in the case of the latter. By contrast, the transport costs incurred in the supply chain of the co-firing based power station increase in the compound scenario dealing with both forest residues as a by-product and landscape wood raw material with respect to that only considering forest residues as a by-product (see Figure 8.2). The same trend together with a slight growth of transport costs appears in the case of the BIGCC simple scenario when landscape wood resources are burned (see Figure 8.3). The transport cost increase for co-firing in the resources-related compound scenario of forest residues as a by-product and landscape wood raw material is attributed to a new resource allocation pattern with a higher dispersion rate than that of the scenario where only forest residues as a by-product are consumed. The BIGCC technology does not reproduce any transport costs reduction as the resulting catchment area always equals to the total area of Baden-Württemberg and thus all existing wood resources have to be transported. In consequence, the presence of a further wood resource (landscape wood raw material) shifts the location of the conversion plant from Böblingen (only forest residues) to Stuttgart with a consequent increase in the transport costs for those compound scenarios considering the harvesting of landscape wood raw material. Thus, the cost components involving the transport of landscape wood raw material to the BIGCC power plant appear to be a little greater than those associated with the sole transport of forest residues, concretely a likewise imperceptible increase of 4%. On top of that, this rise in transport costs occur in spite of the higher scale – 340 MW_e instead of 210 MW_e – and efficiency registered in the case of the biggest BIGCC-based unit when supplied with forest residues as a by-product or a joint product and landscape wood resources. A priori, both compound scenarios should theoretically have led to more reduced costs components for transport, but in this case the new resource distribution pattern clearly raises the corresponding transport costs.

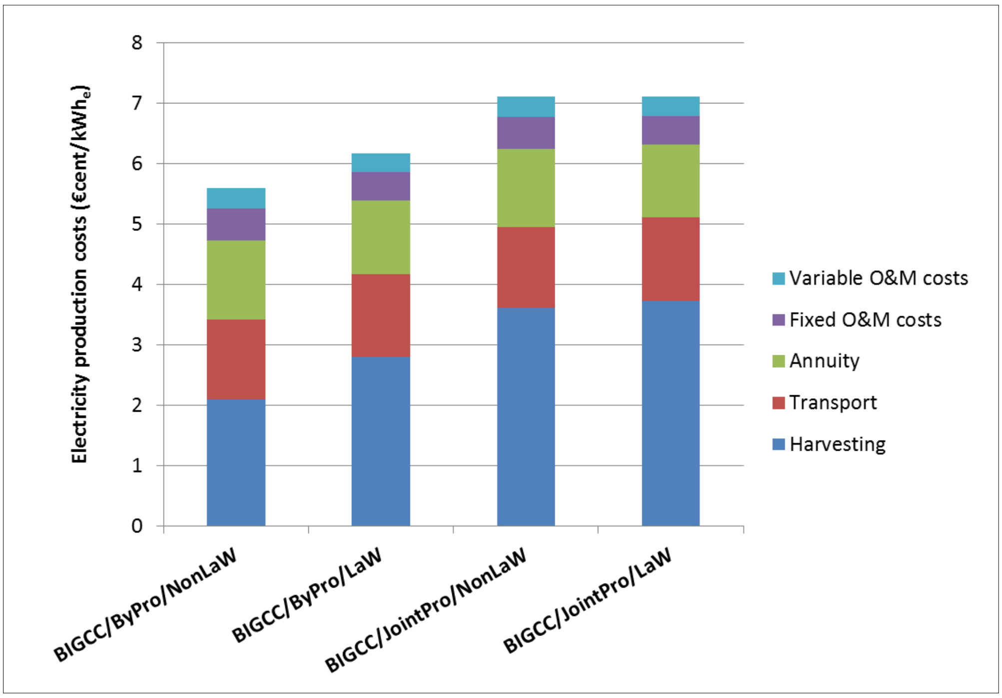

Figure 8.3: Cost breakdown of the electricity production costs incurred by the BIGCC-based power plants (210/340 MW_e) for the four resources-related compound scenarios

With regard to the investment and operating costs of the representative bio-based power plants in each technology simple scenario, the cost components of the respective electricity production costs remain, as expected, constant over the four resources-related compound scenarios for both the CHP and co-firing technologies. Nevertheless, the two different power output capacities of 210 MW_e and 340 MW_e in the framework of the BIGCC simple scenario are clearly responsible for the reduction in technology expenses from the former plant to the latter.

8.4. Comparison of electricity production costs for each resources-related scenario

The specific electricity production costs of the bio-based power plants selected for the twelve compound scenarios were grouped in the last section into the three technology simple scenarios: CHP, co-firing and BIGCC. Nevertheless, these three technologies can now be compared within each of the four resources-related compound scenarios that depend on the cost allocation technique applied to forest residues and whether landscape wood raw material is considered or not for conversion into bioenergy. In connection with this, Figures 8.4-7 compare the specific electricity production costs and the respective cost components of a set of representative bio-based power plants from each technology setting within each of the four resources-related compound scenarios.

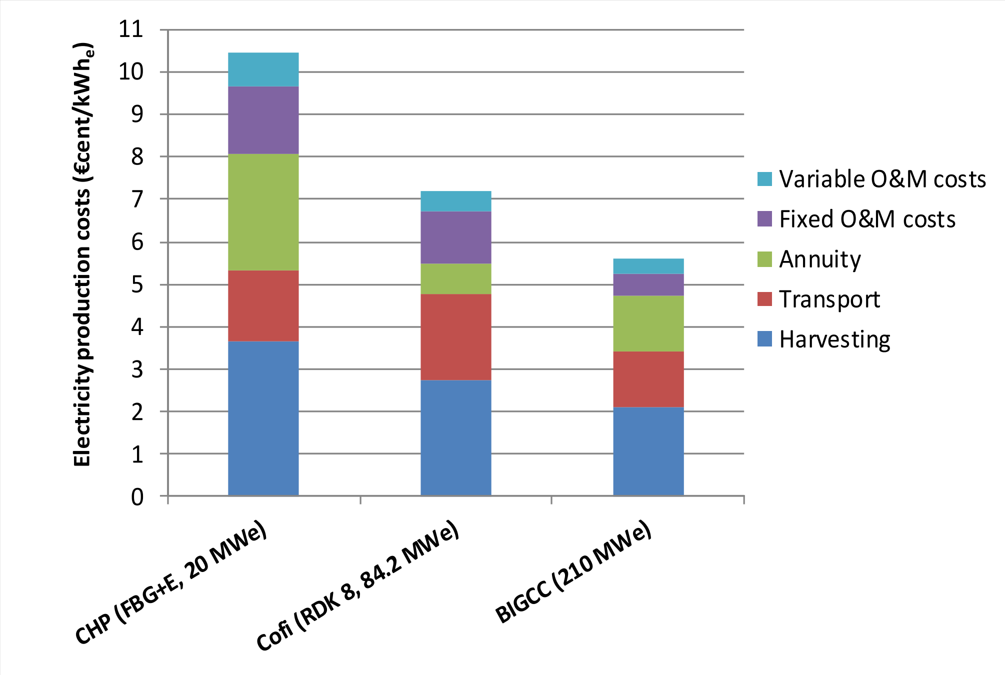

Figure 8.4: Cost breakdown of the electricity production costs incurred by the bio-based power plants of the three technology settings within the resources-related compound scenario of forest residues as a by-product

On the basis of the comparisons carried out in each of the four figures, a significant contrast between the electricity production costs of the CHP facility and those of the conversion processes involved in the co-firing and BIGCC simple scenarios is observed. Both co-firing and BIGCC-based technologies present electricity production costs with values increasing from 5.60 to 9.40 €cent/kWh$_e$ throughout the four resources-related compound scenarios arranged in the order expressed in Table 7.1. In addition, these electricity production costs are systematically lower than those of the power plant based on fluidised bed gasification attached to a gas engine within each of the respective four compound scenarios concerning wood resources (see Figures 8.4-7). This way, the electricity production costs of both plants account for slightly more than half the production costs of a bio-based unit based on fluidised bed gasification coupled to a gas engine.

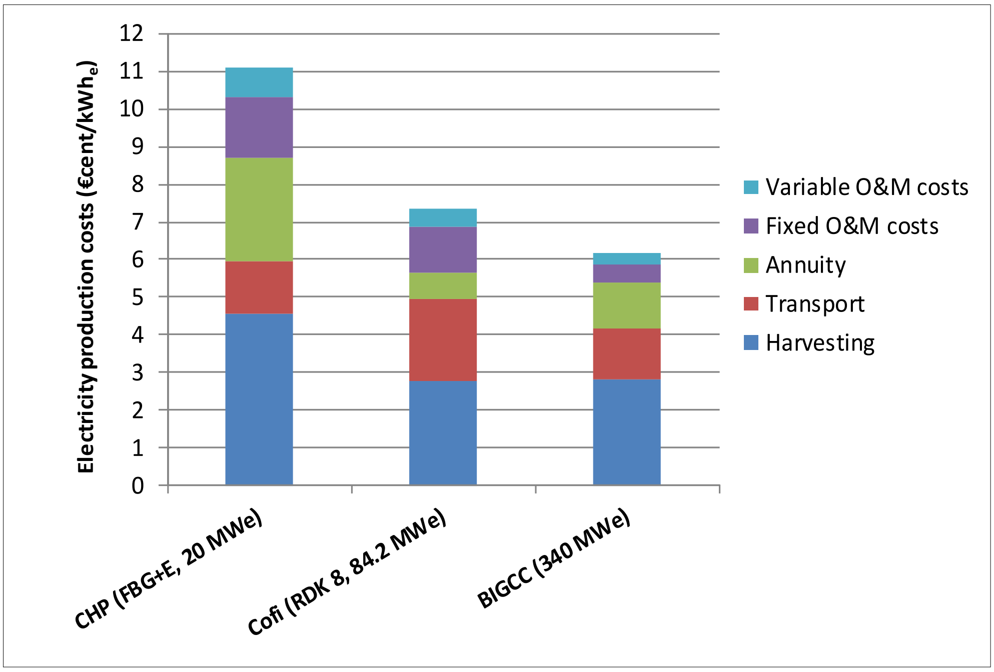

Figure 8.5: Cost breakdown of the electricity production costs incurred by the bio-based power plants of the three technology settings within the resources-related compound scenario of forest residues as a by-product and landscape wood raw material

The resultant electricity production costs in the co-firing simple scenario are actually somewhat higher (between 1 and 2.3 €cent/kWh$_e$) than those of BIGCC within each resources-related compound scenario. The difference between the electricity production costs of both co-firing and BIGCC technologies grows and decreases irregularly throughout the four resources-related compound scenarios according to the established order. The lower increase in the difference of both electricity production costs for these power plants in the resource-related compound scenarios including the by-product approach for forest residues (Figures 8.4-5) is again due to the lower costs incurred by the harvesting of the corresponding wood resources. In contrast, the highest difference in production costs is reached for the co-firing and BIGCC technologies when the bio-based power plants are provided with forest residues as a joint product with and without landscape wood raw material. This is mainly on account of the more expensive wood resources considered in the framework of these scenarios. Moreover, mention should be made of the markedly larger scale (340 MW$_e$) of the BIGCC-based power plant in both resources-related compound scenarios including forest residues and landscape wood resources (Figures 8.5 and 8.7) in comparison to the capacity of 210 MW$_e$ for the same technology when no landscape wood raw material is harvested (Figures 8.4 and 8.6).

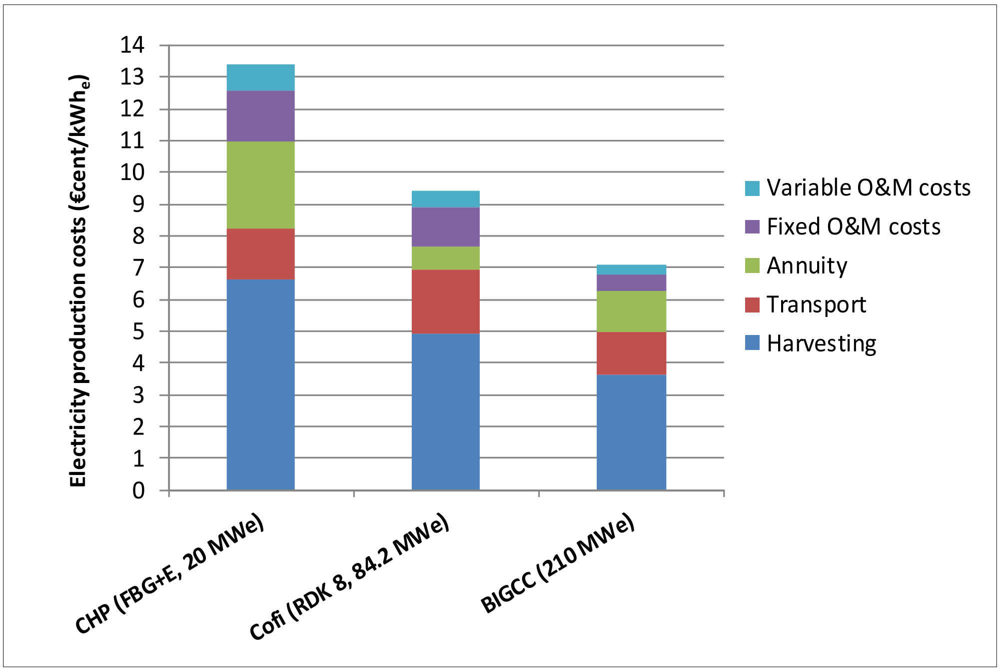

Figure 8.6: Cost breakdown of the electricity production costs incurred by the bio-based power plants of the three technology settings within the resources-related compound scenario of forest residues as a joint product

On another level, the cost elements concerning the harvesting expenses incurred for the three technologies considered (CHP, co-firing, BIGCC) within each of the four resources-related compound scenarios of Figures 8.4-7 show a reasonable decreasing effect on costs with increasing scale. This is in turn associated with a growing electric efficiency ranging from 27.7% (20 MW_e) via 37.6% (84.2 MW_e) through to 48.5% (340 MW_e). Nevertheless, this behaviour is in general not perceived for transport costs when they are compared throughout the three technology simple scenarios in the order laid down from the smaller to the larger scale. The transport costs in the case of the CHP power plant are not quantitatively relevant owing to the reduced catchment area of such a small-scaled bio-based unit. However, transport costs turn out to be comparatively higher for co-firing due to the larger dimension of the area of influence although in spite of its higher electric efficiency. In this case, the effect brought about by the larger size of co-firing related catchment areas proves to have a greater weight than the cost decreasing trend derived from the higher electric efficiency. In contrast to co-firing, the reduced share of transport costs in the specific electricity production costs of the BIGCC-based power plants for the four resources-related compound scenarios clearly translates to a greater impact of efficiency on the shaping of costs than that deriving from the extent of catchment areas. On the other hand, the fraction involving the investment costs as well as the operation and maintenance expenses of the three technologies within each resources-related compound scenario behaves on the basis of their real cost burdens but modulated by the respective electric efficiencies. As expected, the technology-related costs in the four CHP compound scenarios are higher than those of the co-firing unit in the four respective settings, with the BIGCC option reproducing the cheapest outgoings despite representing the most expensive investment. As already referenced, the different scales of 210

MW_e and 340 MW_e showed by the BIGCC technology for the different resources-related compound scenarios cause a small decrease in the investment and operating costs of the 340 MW_e power plant with respect to those of the 210 MW_e BIGCC facility.

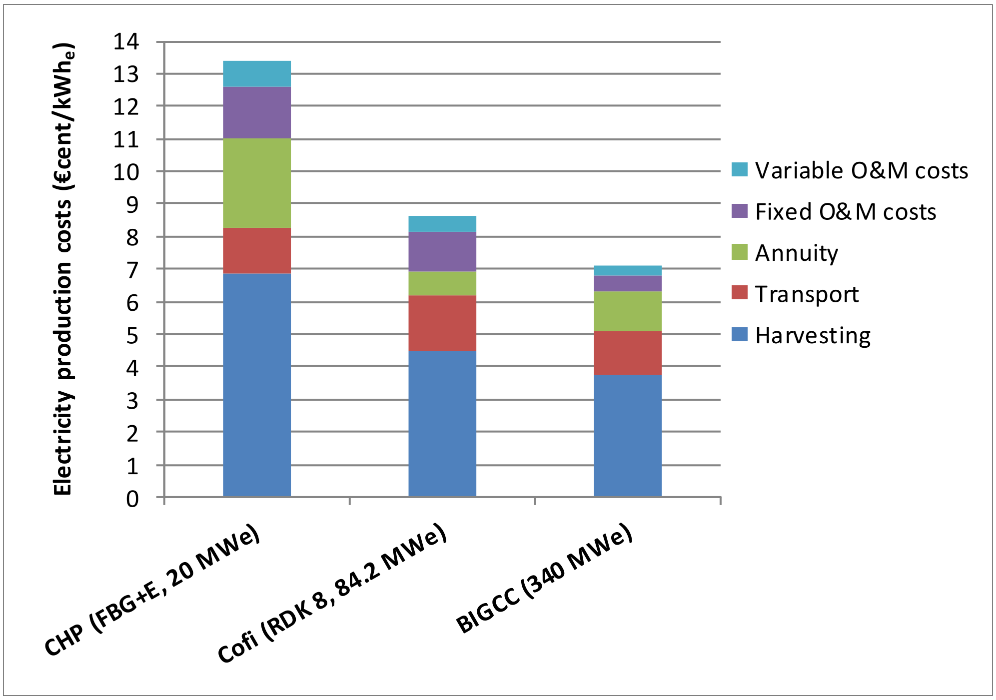

Figure 8.7: Cost breakdown of the electricity production costs incurred by the bio-based power plants of the three technology settings within the resources-related compound scenario of forest residues as a joint product and landscape wood raw material

8.5. Cost reduction mechanisms by decreasing remunerations

If remunerations are modelled and progressively reduced below each resulting breakeven point, new configurations of bio-based conversion units with lower electricity production costs can be identified on the basis of different biomass redistribution patterns. These lower ranges of electricity production costs are associated with the possibility of pointing out interesting cost reductions in the utilisation pathways of certain plant operators. As a result, three basic mechanisms based on the change in size of a given facility are observed for this sort of sensitivity analysis. They enable a better understanding of the formation of new arrangements of conversion units in the form of more economical bioenergy configurations.

On the one hand, the scale of certain bio-based power plants may decrease in size via selection of smaller conversion units when remunerations are cut down below each resulting breakeven point. The reduction in scale may in turn be linked to a lessening in size of the catchment areas that will supply exclusively the cheapest wood resources to the conversion unit. But this area of influence may also remain invariable or even larger if not enough wood resources at appropriate costs are found. As this scale reduction implies an increase in both capital and operating costs, lower electricity production costs can only be achieved if biomass potentials are supplied to the conversion unit at an appropriate level of harvesting, densification and transport costs. In virtue of this mechanism, a greater number of bio-based power plants with lower power capacity are selected, which ultimately result in the production of less bioenergy – due to lower electric efficiencies.

On the other hand, if the size of a bio-based power plant is kept constant then there exists a specific degree of freedom for the system to evolve towards lower remunerations. According to this, every bio-based facility can reduce their specific electricity production costs by obtaining cheaper potentials of biomass outside the original catchment area – i.e. that obtained at each resulting breakeven point – and in addition no longer consuming a certain amount of expensive potentials within such zone of influence. As a result of this, the respective catchment areas become larger, and hence the number of selected bio-based conversion units smaller than before. Indeed, the decrease in harvesting costs is accompanied by an increase in transport costs, which must necessarily be less than the reduction of expenses incurred by collection, moving and chipping (harvest) of biogenic resources.

Finally, when the scale of a given bio-based power plant is allowed to increase, an additional option arises. The growth in power output capacity is associated with an increase of the catchment area and consequently of their transport costs. However, the scale increase implies a reduction in both capital and operating costs that permits more expensive wood resources with even higher transport costs to be consumed. This occurs under the condition that the decrease in technology expenses is greater than the growth in harvesting and transport cost so as to be able to implement lowered electricity production costs. As a result of this mechanism, a smaller number of conversion units with greater power capacity are installed.

In general, mention should be made that the reduction of remunerations below each resulting breakeven point makes the whole bio-based system more and more costly because less inexpensive biomass and more expensive contributions of non-biogenic fuels are converted into power.

8.6. Dependence on scale

From the graphs in section 8.4 above, it becomes apparent that specific electricity production costs show a clear dependence on the scale of the bio-based power plants involved. Indeed, this is displayed and can be observed more or less easily in each of the twelve analysed scenarios. This scale dependence is however more pronounced for small and medium capacities of CHP plants based on fluidised bed gasification coupled to a gas engine than in the case of large-scaled co-firing and BIGCC-based settings. Therefore, the variation of the specific electricity production costs and their cost elements with the power output capacity from small to medium scales up to a maximum of 20 MW_e is represented in Figure 8.8 for the CHP simple scenario. This way, each of the four resources-related compound scenarios concerning the use of forest residues as a by-product or as a joint product with and without landscape wood raw material (see Table 7.1) are taken into account for this technology. In relation to Figure 8.8, mention should be made that the higher level of those electricity production costs (coloured lines) illustrated for the three resources-related compound scenarios except that involving forest residues as a by-product is mainly due to an increase in the cost components of harvesting tasks. These increased harvesting costs occur in such a way that the rest of the cost elements remain constant from one scenario to another. From direct visual inspection, it can be observed that annuity and, to a lesser extent, fixed operation and maintenance costs are the most important contributions to the resulting electricity production costs for the displayed spectrum of scales. These cost components considerably increase in value as the scale reduces unlike the other technology-based element involving the variable operating costs. In this sense, the cost components involving transport but also both harvesting and variable operation and maintenance expenses experience a low effect of economies of scale with nearly invariable magnitudes across the whole range of capacities.

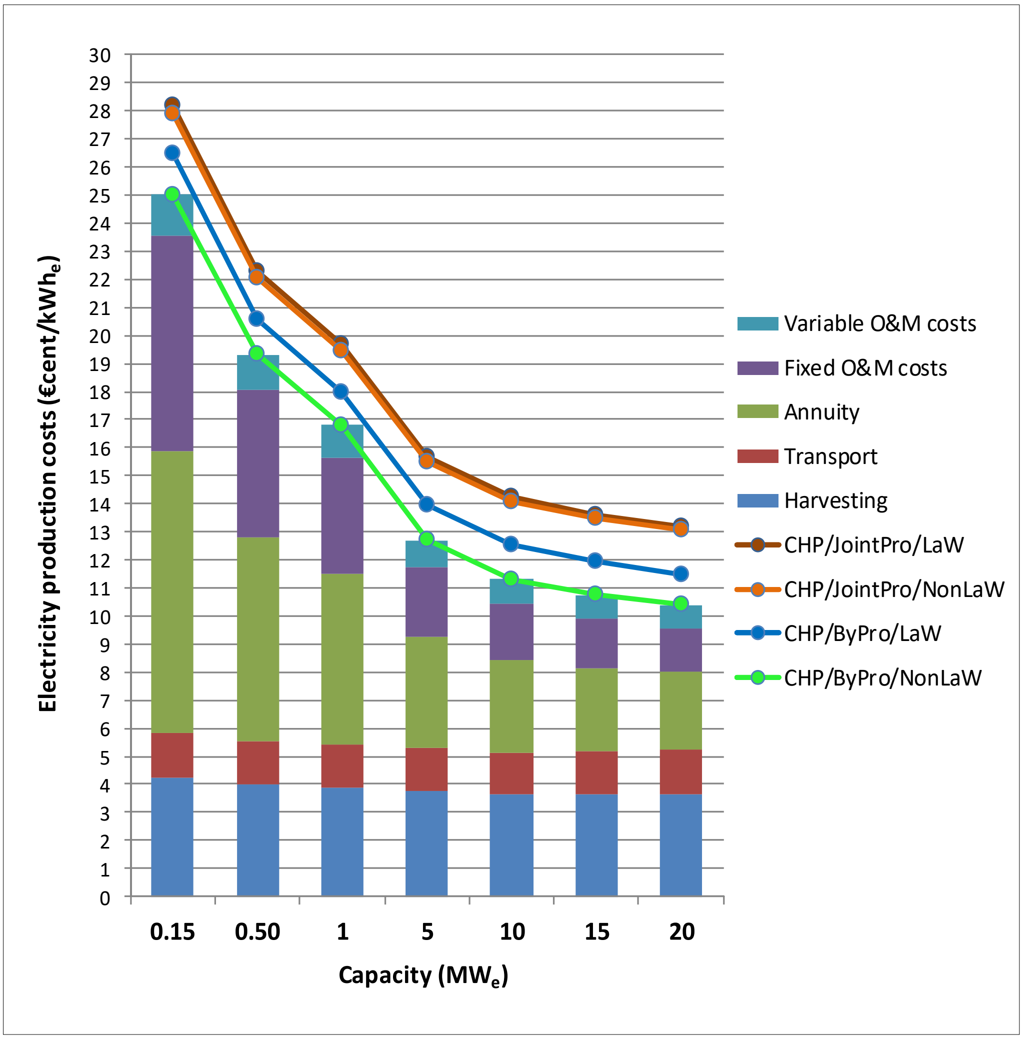

Figure 8.8: Dependence of specific electricity production costs and their cost components on scale for the four CHP compound scenarios

This strong scale dependence of the electricity production costs of gasification-based power plants for the CHP simple scenario permits drawing interesting conclusions that can easily be extrapolated to the remaining co-firing and BIGCC technologies. In this connection, it is important to recall that co-firing technology shows a reduced effect of economies of scale (see

Figures 4.1-3) with flatter costs curves as against those derived for the CHP technology. Conversely, BIGCC simple scenarios are assigned capital and operating costs with a similar scale dependence (see Figures 4.9-11) to that of CHP settings (see Figures 4.5-7) but over a wider spectrum of scales reaching up to quite larger power output capacities of around 340 MW_e. Anyhow, the evolution of the specific electricity production costs in each technology simple scenario when reducing power output capacity becomes quite similar independently of the magnitude of expenses.

In general, if scale is decreased for each technology option then the resulting electricity production costs may considerably increase to the extent that financing bioenergy production might prove to be extremely difficult – especially for small-scaled power plants. This conclusion is in turn applicable for each of the four wood resources-related compound scenarios, which elevate the electricity production costs on a regular basis regardless of the size of power output capacity. Such uniformity regarding the increase in electricity production costs through the resources-related compound scenarios actually is ascribed to the minor change of harvesting costs over the entire range of scales. In this regard, cost components involving harvesting tasks surprisingly account for almost the same value despite variation of electric efficiency. In the same vein, the cost elements referring to transport of chipped wood resources equally reproduce a practically constant evolution over the scale range. And this nearly invariable value arises as a trade-off between the reduction of electric efficiency and the decreased catchment areas – despite higher distance-specific transport costs (see Figure 3.10) – as scale gradually lessens. At any rate, the array of the three technology-related cost components clearly exhibits the well-known effect of economies of scale. Therefore, they increase noticeably with decreasing size of the power plant. In view of the above, it can be held that decrease in scale is directly correlated to a sort of amplifying effect of those cost elements relating to capital and operating expenses, whereas the rest are displayed adjusted to a nearly constant rate over the range of decreasing scales. On the basis of the foregoing, a significant recommendation can be derived, which consists in focusing on the higher cost reduction potential of technology-related cost components (capital and operating costs) in order to make bio-based power production at small scales economically more attractive. On the contrary, the impact of further improvements in small-scaled utilisation pathways via both harvesting and transport costs components turns out to be more limited owing to the lack of economies of scale.

8.7. Investments in the framework of the German Renewable Energy Act

The bidding scheme of the German Renewable Energy Act (GREA) [EEG 2017] allows stakeholders to effect investments in the wood resources-based bioenergy system of Baden-Württemberg in order to convert endogenous biogenic resources into bio-based power. Three different conversion technologies, namely a fluidised bed gasification process coupled to a gas engine, the co-firing based retrofitting of existing coal-fired power plants and a fluidised bed gasifier connected to a combined cycle with power output capacities respectively ranging up to 20, 84.3 and 340 MW_e, are the most cost-efficient technology options and therefore might also be implemented in the German energy market within the framework of the referenced act. Thus, stakeholders could invest in the bioenergy sector of the federal state while fulfilling the rules of the German Renewable Energy Act. This regulation introduces a maximum annual capacity installation of 200 MW_e for the whole of Germany; a share that can proportionally be adjusted and therefore reduced to the size and necessities of Baden-Württemberg. In this connection, a brief analysis of the installations of power plants over time on the basis of this restriction is outlined in the following subsection 8.7.1.

The identified technologies exhibit different levels of profitability when analysed in the framework of each wood resources-related compound scenario for a given remuneration. As the profitability of a particular utilisation pathway can be derived from the subtraction of whole expenditures from total remunerations, both terms must be determined prior to being able to quantify such a parameter. On the one hand, electricity production costs are affected by both structural and parameter uncertainties through those cost components involving the harvesting, transport and conversion technologies. For this reason, these uncertainties are treated respectively by means of scenarios and via sensitivity analyses (see chapter 7). On the other hand, remunerations may equally be exposed to a particular level of both mentioned uncertainties. These are due to the variability of the bioenergy policy framework of the studied region in virtue of eventual legal or political changes that may range from subventions to market premiums and correspondingly from feed-in tariff to bidding schemes. Instead of assessing both structural and parameter uncertainties on remunerations by means of respectively introducing scenarios and sensitivity analysis, it proves more effective to estimate the required value of remunerations at the corresponding breakeven point. In this manner, the identification of higher profits may act as an incentive for investors and stakeholders on the basis of such a minimum amount of received incomes. Whereas such analysis consists in the determination of the lowest remunerations via a direct inspection of electricity production costs for both co-firing and BIGCC settings – owing to their exclusive production of power –, the case of the CHP technology refers to both types of remuneration originating from the sale of power and heat. It is precisely the adequate combination of both contributions – electricity wholesale and heat retail prices – that is of particular interest and permits accordingly evaluating the minimum level of profitability for CHP facilities. Therefore, the foregoing issue is analysed in subsection 8.7.2 for the four CHP-related compound scenarios, while profitability of only power generating technologies such as co-firing and BIGCC is not considered owing to its greater simplicity.

In the same vein, the appropriateness of both centralised bio-based technologies based on co-firing and BIGCC for the replacement of the existing coal-fired and nuclear power stations during both nuclear and coal phase-outs is discussed in subsection 8.7.3.

8.7.1. Installation of power plants over time

The annual capacity expansion of the wood resources-based bioenergy subsystem of Baden-Württemberg is regulated by the German Renewable Energy Act 2017 [EEG 2017], which establishes an upper limit of 200 MW_e for the total territory of Germany. As this study only covers the region of Baden-Württemberg, an appropriate portion of this maximum capacity expansion has to be ascertained and hence apportioned to the federal state. Aiming at this objective, two criteria based upon Baden-Württemberg's dimension and energy demand are chosen. On the one hand, the proportion of the forest areas[32] in Baden-Württemberg with respect to those of Germany, which [BMEL 2014] indicates to be in the order of 12%. On the other, a second criterion points to the yearly amount of power consumed in the federal state versus that of the entire federal republic. In this regard, the statistical report [SLBW 2014] states a gross electricity consumption of 75.8 TWh in Baden-Württemberg as against 606.7 TWh for all of Germany with a resultant share of 12.5% for the federal state with respect to Germany. In this way, an average percentage of around 12% might be a reliable fraction of the total annual capacity expansion for Germany in the case of exclusively allowing for the territory of Baden-Württemberg. As a result, a maximum capacity installation of 24 MW_e might be allocated to the federal state of Baden-Württemberg for production of bio-based power from biogenic resources.

However, both co-firing and BIGCC technologies may exceed the formerly defined portion of maximum capacity for Baden-Württemberg. Therefore, the installation of medium and large bio-based power plants could exclusively be carried out by means of an amendment of the German Renewable Energy Act. This legal change should permit the installation of greater capacities than 24 MW_e as well as the allocation of the total maximum annual volume of 200 MW_e or even larger bio-based capacities to the federal state. Against this background, the projection of the installation of co-firing and BIGCC power plants over time is discarded owing to its own indeterminacy while the focus is set on the temporal evolution of CHP facilities.

Under the assumption that the whole regional capacity expansion might be employed for conversion of wood resources into bioenergy, an annual installation of a single CHP power plant with a capacity of 20 MW_e could be carried out in the bioenergy system of Baden-Württemberg. This outcome could be corroborated when modelling the targeted bioenergy subsystem with the assistance of the constraint given by Equation 5.7. The observation of this regional cap every year entails distributing the commissioning of the CHP plants over time in the case of the four wood resources-related compound scenarios described in Figures 7.1, 7.4, 7.7, 7.10. The six power plants of both scenarios (see Figure 7.1 and 7.7), where the conversion units are fed with forest residues respectively regarded as a by-product or a joint product, should be successively installed in the already identified sites throughout the time frame composed of six consecutive years – namely from 2018 up to 2023. On the other hand, the CHP facilities of Figures 7.4 and 7.10 that generate bio-based power from both aforementioned types of forest residues plus landscape wood raw material should render a different projection over time. In this regard, all the ten units in their corresponding locations

[32] Landscape areas are not considered in the estimation underlying this criterion because they were derived from the rate of forest density for each district of Baden-Württemberg (see subsection 2.2.3).

should be consecutively commissioned throughout the time span of ten years until 2027 in compliance with the requirements imposed by the German Renewable Energy Act.

8.7.2. The profitability of power plants based on the CHP technology

Investors try to obtain the highest rates of profitability when they decide on installing a bio-based power plant. The cost-effectiveness of a given investment can be appraised by taking into account the principle of profitability, which was introduced in section 5.1. According to this, total remunerations received in return for the generation of bioenergy must cover and minimally be as high as the sum of all expenses incurred throughout the entire utilisation pathway from harvesting of resources to conversion into bioenergy. Thereby, remunerations *R* for the production of bio-based power by CHP technologies are granted to plant operators provided that the technical requirements of the German Renewable Energy Act (GREA) [EEG 2017] – including the annual capacity expansion cap for the entire country – are satisfied. Therefore, the specific total remunerations conceived as the weighted average of the remuneration *R* and the heat retail price *HP* on the basis of the amount of bioenergy – power and heat – cogenerated from biogenic resources (e.g. wood resources) has to be greater than or equal to the specific electricity production costs of the installed bio-based power plant.

Based on the foregoing, the parameters R_o and HP_o are defined as the breakeven points for the remuneration and the heat retail price (€cent/kWh) in the respective cases in which only the production of power (*HP*=0) or heat (*R*=0) is remunerated. In this vein, the latter rate is directly proportional to the former – which in turn equals the specific electricity production costs – with the proportionality factor being the quotient between the electric and thermal efficiencies of the targeted CHP power plant (see Equation 8.1).

$$HP_o = \left(\frac{\eta_{el}}{\eta_{th}}\right) \cdot R_o \tag{8.1}$$

Beyond all that was previously stated, the profitability of the most cost-effective power plant in the framework of the CHP compound scenarios – namely, a conversion unit consisting of a fluidised bed gasifier and a gas engine with a power output of 20 MW_e – is graphically illustrated in Figure 8.9 after being confirmed with the assistance of the BIOSPHERE model. The four resulting straight lines regarding each resources-related compound scenario reproduce the minimal total remuneration as a weighted sum of remuneration *R* and heat retail price *HP* that must be granted to the plant operator for the combined cogeneration of heat and power in order to reach the breakeven point. Indeed, there exists the option of ensuring profitability of investments in the case that a higher total remuneration might be paid for.

$$\frac{R}{R_o} + \frac{HP}{HP_o} \geq 1 \tag{8.2}$$

According to the prior assertion, any point of the graph in Figure 8.9 involving a specific total remuneration above the breakeven straight lines of each wood resources-based scenario is definitely assigned a higher total remuneration or, in other words, a greater weighted average of remuneration and heat retail price than in any of the points contained in the corresponding straight lines. This is a graphical representation of the principle of profitability when applied to an investment in the installation of bio-based CHP facilities. The corresponding breakeven straight lines of each wood resources-related compound scenario are mathematically expressed according to the inequality expressed in Equation 8.2.

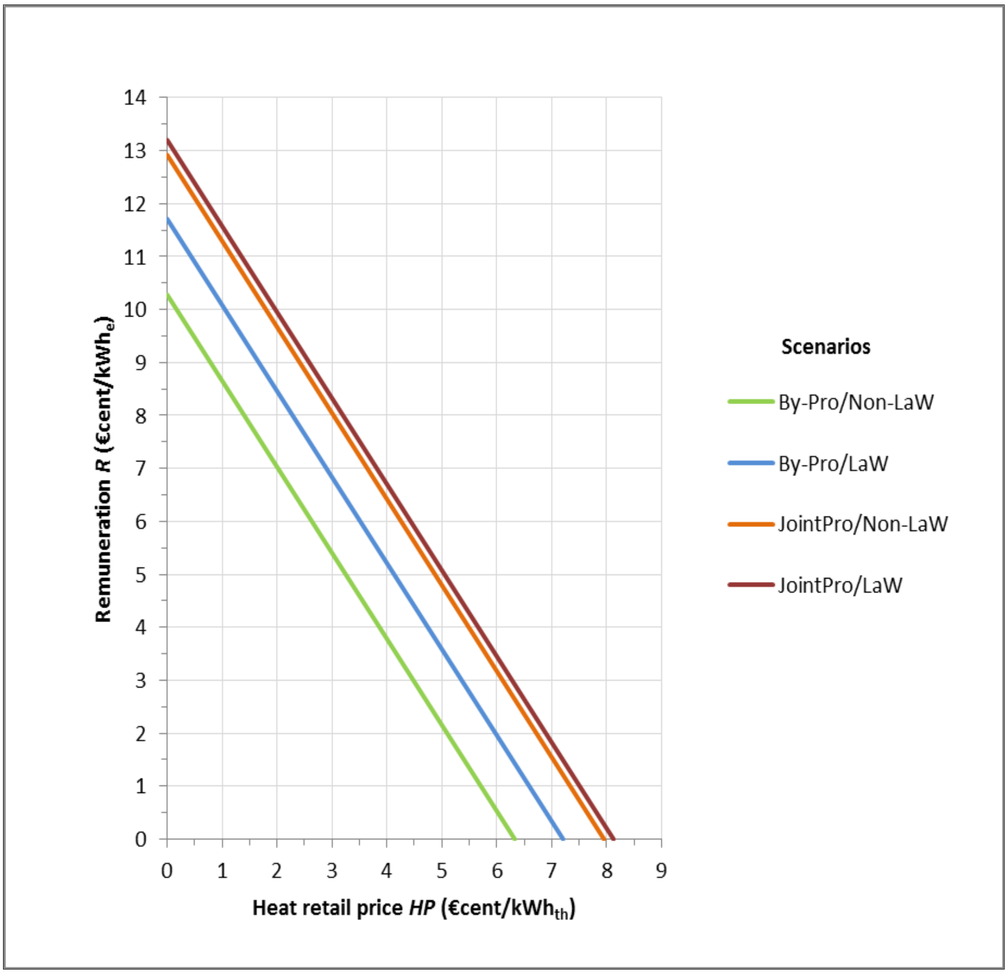

Figure 8.9: Remunerations and heat retail prices granted to a CHP facility based on a fluidised bed gasifier connected to a gas engine of 20 MW$_e$ as monetary amounts minimally required for the investment to break even within the four wood resources-related compound scenarios

In the framework of the bidding scheme of the last German Renewable Energy Act [EEG 2017], remunerations for the generation of bio-based power is made up of the revenues secured from the electricity wholesale market in addition to the corresponding market premiums. In this connection, a particular case is illustrated hereunder as an example in order to visualise the amount of specific remunerations and heat retail prices associated with the production of bio-based power by means of a gasification-based CHP plant of 20 MW$_e$. Thereby, if a specific remuneration of 7 €cent/kWh$_e$ is granted to the plant operator for production of bio-based power, a specific heat retail price of around 2 €cent/kWh$_{th}$ would be necessary – relying on the graph in Figure 8.9 – to solely reach the breakeven point for the resources-related compound scenario in which only forest residues as a by-product are harvested. However, the corresponding level of heat retail price successively becomes more and more expensive as the unit costs of chipped wood resources increase throughout the remaining resources-related scenarios until a value of roughly 3.8 €cent/kWh$_{th}$ for the most expensive scenario including forest residues as a joint product and landscape wood raw material. Whereas the latter heat price appears to be rather elevated for being cashed in exchange for heat supply, the former could be considered as a reasonable price for the energy market of Baden-Württemberg. In any case, both only represent the heat retail price at the breakeven point and hence they might still need to be increased so as to generate profitability in the respective investments. In this regard, mention should be made of the fact that a slight increase in the order of merely 1 €cent/kWh$_e$ in the remunerations would to a great extent improve the profitability of such kind of power plants across the four scenarios.

8.7.3. Suitability of centralised technologies during both nuclear and coal phase-outs

A shift in the new energy supply paradigm to meet greenhouse gas reduction targets in Germany necessarily must go hand in hand with a phase-out program for nuclear and coal power generation. While the nuclear exit has already been initiated and will supposedly take longer than a decade before completion, the imminent introduction of a coal phase-out in the German energy market is currently[33] being discussed by a recently appointed coal commission. The implementation of such plans necessarily involves the dismantling of a significant number of existing nuclear and coal power plants all over the German territory. In the case of Baden-Württemberg, the nuclear power plants[34] of Philippsburg 2 and Neckarwestheim 2 together with all the existing coal-fired power stations (see Table 6.5) – especially the largest and most important units of RDK 7 and RDK 8 in Karlsruhe, both Block 8 and Block 9 in Mannheim, HLB 7 in Heilbronn as well as ALT HKW 1 in Altbach (Esslingen) – will have to be progressively disconnected from the grid, predictably over the next decade. This measure will inevitably require the replacement of the respective power output capacities with new ones including the most efficient, carbon neutral power generating technologies.

In this context, the small-scaled CHP technology based on fluidised bed gasification coupled to a gas engine does not seem to be a good candidate for such a substitution basically on account of its relatively higher electricity production costs as against the other two considered conversion procedures. Unlike the decentralised CHP plants, both conversion techniques based on co-firing and the BIGCC technology constitute an interesting partial solution for

[33] June 2018

[34] [BNA 2018]

successfully tackling the great challenge of the energy transition in the German energy market. The comparatively low incremental capital costs of co-firing as well as the relatively high efficiencies of large-scaled BIGCC ensembles together with the valorisation of the most economical wood resources – predominantly deciduous – might lessen the resulting electricity production costs to a rather lower range of around 4.5-9.5 €cent/kWh$_e$ according to the outcomes of this study. Anyhow, this spectrum of electricity production costs will still require the introduction of energy policy support mechanisms for these centralised technologies to provide carbon neutral baseload power supply. In this sense, the promotion of both centralised bio-based technologies might positively translate to either a lower reallocation charge – with resulting savings for power consumers – or a transfer of a portion of this levy to other costly renewable energy sources.

8.8. Critical appraisal

8.8.1. Data availability

The modelling of the wood resources-based bioenergy system of Baden-Württemberg involves certain aspects that condition the quality of the solutions obtained with the BIOSPHERE model. In the first place, input data availability is a generalised problem that must be coped with in the framework of this study. Concretely, techno-economic data describing the different stages of harvesting as well as transport and conversion are largely not easy to find and require some additional harmonisation so as to integrate them into the data base of the model. In this regard, data concerning felling, extraction, debranching, moving and chipping of forest residues and landscape wood raw material appear in research literature under quite different conditions (moisture content, owner size, slope, variety). Therefore, they have to be thoroughly classified and, if possible, correspondingly harmonised. The same happens to transport data, which are extremely difficult to gather for all lengths varying from short transport distances to the longest stretches that biomass can be transported within the borders of Baden-Württemberg (around 300 km). Creating a good data base with the four techno-economic parameters that describe the most cost-effective power generating technologies for conversion of wood resources is also a complicated task. This is mainly on account of the lack of information for certain scale ranges, predominantly for higher sizes – e.g. in the case of fluidised bed gasification coupled to a combined cycle for electric capacities over 160 MW$_e$. Specifically, finding the variable operation and maintenance costs of both preselected gasification solutions exhibits a particular challenge. Besides data concerning the technological processes, also those related to the free potentials of wood resources, mainly landscape wood raw material, are markedly affected by the lack of data availability. In this regard, as no data on landscape-based resources were found, the determination of their free potential is constructed on the basis of the registered agricultural surfaces of the federal state by multiplying them with a correction factor based on the forest density at district level. Conversely, the free potentials of forest residues are indeed derived from a set of studies actually dealing with the topic in question. Despite this, a certain inaccuracy is generated for each district when defining the corresponding free potentials associated with both coniferous and deciduous portions of the four types of wood chips derived from forest residues as a by-product harvested by both small private and large forest owners (SPFO and LFO) or as a joint product in woodlands with a steepness of slope above and below 50% (S<50F and S>50F). This originates from the inadequate, but necessary use of the shares of coniferous and deciduous forest areas at district level for calculating the respective portions of all four types of wood chips from forest origin. Nevertheless, this deviation is considered as not relevant for the final results as the imprecision only takes place when analysing a single district, while it becomes negligible for larger areas. In any case, the determination of both coniferous and deciduous fractions of free potentials is conducted in keeping with a series of research studies pointing to the same orders of magnitude, at least at the level of Baden-Württemberg. This guarantees the apportionment of an appropriate dimension and scale to the amount of wood resources to be transformed into bioenergy in the federal state. On the contrary, the input data related to the power and heat demand at district level are perfectly obtainable and therefore pose less of a problem. In spite of this, their implementation in the model is not strictly required due to the fact that only a small portion of the energy demand is covered through the bioenergy produced. Hence, these data might be substituted with a high enough value in the order of the average energy demand of all districts.

8.8.1.1. Spatial and temporal dimension

The input data concerning both the free potentials of wood resources and the energy demands are easily available at district level. However, this spatial unit stands for a rather high aggregation level that is unavoidably associated with a low spatial resolution. As the spatial units of the model are equal to the administrative districts of Baden-Württemberg, the apportionment of free potentials and demands as well as the technological processes of harvesting, densification, transport and conversion to a geographic point or centroid within each district turns out to be the unique and even the best possible methodology for modelling the targeted system. In spite of former assertion, this approach may still be considered as a poor approximation to reality. Especially when dealing with decentralised conversion technologies that are characterised by small catchment areas – which might in turn consist of one district or even a fraction of it.

Besides the spatial dimension, the temporal development plays a fundamental role when it comes to reaching a comprehensive knowledge of the whole dynamics of the targeted bioenergy subsystem. Unfortunately, the input data availability associated with the chronological evolution concerning the techno-economic parameters of all processes involved as well as the free potentials and the energy demands at district level is considerably reduced – if not non-existent. This kind of information is quite infrequent in most bioenergy research publications as certain technologies are still in the demonstration and deployment stage and hence not yet mature enough so as to predict their time projection. In order to avoid this issue, a modelling approach based on temporal scenarios should exclusively permit the entire energy system of Baden-Württemberg and not only its corresponding value chain of wood resources to be analysed. Anyhow, this restriction on data availability does not prevent the wood resources-based bioenergy system of Baden-Württemberg on the cost basis of the year 2017 from being described in line with each of the free potentials for the same period of time.

8.8.2. Structural uncertainty

There exists a structural uncertainty that is linked to a particular level of indeterminacy in relation to the selection of the most cost-efficient conversion technology among a set of techniques. This is associated with the fact that the cost-efficiency of the preselected technologies proves to be higher than that of the excluded techniques. This aspect is especially valid when it comes to the comparison between gasification and combustion. The latter option, with the exception of co-firing, is systematically less cost-effective than the former and can therefore be discarded. However, less cost-efficient technologies could also be high profitable options for power production if remunerations might be high enough. In this case, the identification of further technology simple scenarios based on less cost-efficient techniques would also be necessary in order to complete the intended analysis.

Another source of structural uncertainty appears in the process of determination of the total unit costs incurred by the production of wood chips. The techno-economic modelling of the implemented harvesting and densification techniques may require the identification of an array of different states involving the collection of both forest residues and landscape wood raw material. Two of these settings introduce the employed type of cost allocation method for forest residues regarded either as a by-product or a joint product as two simple scenarios. But against this backdrop, a further intermediate level of both states could have been chosen according to another cost distribution pattern equally based on the sales value of timber and forest residues. Instead of entirely allocating the same sales value to both timber and chipped forest residues in the case of the joint product approach, a different distribution with e.g. lower sales value for forest residues compared to timber would have yielded a considerably different solution in the framework of an additional simple scenario. On the other hand, the introduction of two different states involving the harvesting or not of landscape wood raw material admits same analysis in relation to the possibility of taking into account an intermediate setting, i.e. a fraction of the existing free potentials of landscape-based wood resources as a further simple scenario.

Moreover, the scenario-based approach employed for solving the proposed problem is based on the use of the compound scenario as a tool to encompass the broad spectrum of combinations resulting from appropriately matching the different technology settings and the diverse cost allocation procedures for forest residues together with the harvesting or not of landscape wood raw material. The chosen compound scenarios account for twelve feasible options of describing the wood resources-based bioenergy system for power production purposes. To a certain extent, these scenarios predetermine the shape of the solution obtained for the model, as they are predefined on the basis of certain conditions that are supposed to dominate. In turn, they however represent a convenient method for integrating all techno-economic possibilities and therefore the entire diversity of the bioenergy system into the modelling. As the vagueness and indeterminacy involving the proposed problem represents a sort of state uncertainty with structural character, this is largely subtracted by means of this scenario-based approach.

8.8.3. Parameter uncertainty

One major point affecting the reliability of results in this study – and therefore the quality of the solution – is the parameter uncertainty. This uncertainty has an empirical and experimental nature and especially increases as a result of both power and logarithmic regression techniques implemented for the determination of the techno-economic parameters of conversion technologies. In general, it considerably impacts on the magnitude of the input data assigned to the stages of harvesting, densification, transport and conversion. Not only the techno-economic parameters – such as costs, capacity, full load hours or efficiencies – determining the different processes within each stage but also the exogenously given energy demands and free potentials of wood resources for each district are affected to a greater or lesser extent by a certain statistical variance that is finally translated into parameter uncertainty. In order to reduce or even eliminate the effect of this anomaly on the final results of the optimising bioenergy system model, an appropriate sensitivity analysis of the solutions allow them to be reproduced for variations in input data within a range of ±50%. This maximum range is selected in keeping with typical values registered in research literature for sensitivity analysis. Therefore, it seems to be enough broad so as to reproduce the corresponding variability of some of the most important decision variables such as the electricity production costs. In this respect, the specific electricity production costs of the bio-based power plants selected in the framework of this study are clearly affected by the parameter uncertainty originating from each of the cost components involving harvesting, transport and conversion technologies.

8.8.4. Model

There is an array of aspects in relation to the implemented modelling approach that must be thoroughly discussed as part of this critical reflection. Among others, the temporal restriction to a single year can be identified as one of the most significant issues. Regarding this question, it is stated in section 6.2 that electricity production costs and their components could be estimated for a defined bioenergy configuration by applying sensitivity analyses to the results obtained for a particular year, e.g. the base year. Yet, it is evident that the solution obtained for the optimisation of a bioenergy subsystem under the consideration of its temporal evolution would be more accurate than in the case of carrying out the corresponding sensitivity analysis for a single period of time. By doing the former assessment, the eventual variations of free potentials and energy demands as well as the temporal development of the incurred expenses throughout the four consecutive technological sectors could perfectly be taken into account. Anyhow, the optimisation of the value chain of wood resources for power generation in a region like Baden-Württemberg does not require such a temporal analysis unless the entire energy system is considered. Under this specific condition, another utilisation pathways – different to the generation of power – might arise and should therefore be considered. An additional matter in relation to the temporal description of the system is that the base year is not broken down into time slots. In the event of having modelled them, the introduction of seasonal variations for the free potentials of wood resources would give rise to the possibility of analysing their logistics during the four seasons of the year. This should be accomplished by including the modelling of storage processes not at power plants but at intermediate sites between them and forest and landscape areas.

A further critical point is associated with the methodological approach used for modelling heat demands on account of the lack of data in this respect. This estimation is based on an approximation consisting in the use of districts' heat demands from the industrial sector of Baden-Württemberg. These amounts are increased by an assumed factor of 2.0, thus resulting in the real total demands for heat at district level. Thereby, the contributions of both service and household sectors are equally taken into account in the whole quantity. Although these roughly calculated values are not the real amounts of districts' total heat demands, this assumption does not imply any negative consequence on the final solution of the model. This statement relies on the fact that the order of magnitude of real heat demands is much higher than the amount of bioenergy – bio-based heat in this case – that can be generated with the existing free potentials of wood resources. Besides, only the small-scaled CHP conversion units produce relatively small quantities of heat as a by-product of power, whereas co-firing and BIGCC facilities exclusively produce bio-based power.

Another concern relates to the determination of the boundaries of the targeted bioenergy system. As Baden-Württemberg is not an isolated region, further wood resources might be supplied from other neighbouring territories. The selection of the federal state responds to the need to start such an optimisation analysis from a small enough territory in order to have sufficient computing capacity. Anyhow, an analysis for a larger area than Baden-Württemberg would prove to be more interesting although also more difficult to implement in terms of work and computing effort. Actually, the analysed area should not be that of Germany but even larger. The consideration of the entire European Union would produce the right solution to the posed problem, which has been now analysed exclusively for a reduced extent.

Finally, a particularity should be mentioned when it comes to modelling the capacities of processes within the four technology sectors. The tasks of harvesting, densification and transport exhibit a certain scale effect – as reported in chapter 3 – that should be able to be reproduced, as the BIOSPHERE model incorporates the appropriate structures for that. Spite of this, the corresponding range of feasible capacities for these technologies is not actually modelled. This derives from the fact that the whole expenses incurred by the three aforementioned techniques are systematically expressed in the form of a unified amount of variable costs within most research studies. These variable costs encompass not only the real variable operating costs but also integrate both the capital expenses and fixed operating costs. This therefore prevents carrying out a true modelling of the processes within the three sectors. On the contrary, the capital costs as well as the fixed and variable share of operating costs are well enough documented for most processes of the conversion sector. In consequence, capacities are correspondingly modelled for all bioenergy facilities as a crucial part of the optimisation-based analysis.

8.9. Outlook

The present version of the BIOSPHERE model can be employed for further research lines by implementing new developments of the source code and/or the data base. In general, the model can be applied to a variety of research questions by improving upon the existing tool for considering new conversion technologies, the temporal dimension, a more detailed level of description, larger system boundaries or even the adaptation to new application areas. In any case, a trade-off between the detail level of the system and the required computing effort has to be observed so as to not exceed the available computing capacity. The series of new research possibilities are listed below following an order of increasing complexity from a light modification through to a more elaborated state of the model. Three last options do not rely on the analysis of wood resources-based bioenergy systems, but refer to three different topics in the domain of distributed generation, energy system analysis and industrial logistics.

1. **Integration of combustion technologies:** Co-firing and gasification-based technologies proved to be the most cost-effective power generating options for conversion of wood resources into bioenergy. However, optimising the utilisation pathways of the more expensive combustion technologies might yield further insight into the initiated analysis of the value chain of wood resources. The more cost-efficient technologies to be considered are presented in chapter 4, namely the Stirling engine as a prime mover and the conversion processes relying on the stoker boiler and the fluidised bed combustor. Therefore, the implementation of these technologies in the existing optimisation model would allow the construction of additional technology simple scenarios in the same way as performed in the framework of this study with co-firing and both gasification techniques (CHP and BIGCC).

2. **Inclusion of heat production:** Another possibility is to transform wood resources into heat on account of the fact that the corresponding techniques are comparatively more efficient than those of power generation. Heat is a cheaper energy carrier and additionally exhibits a different nature than power. This gives rise to preferably carrying out a separate analysis exclusively for heat generation with the assistance of further technology simple scenarios. This way, the degree of decentralisation for heat production for such a bioenergy subsystem could be ascertained for different levels of heat retail prices or total remunerations.

3. **Implementation of the temporal dimension:** Data regarding the time evolution of bioenergy systems is in general scarcely available. However, this lack of information could be coped with by means of a scenario-based approach. Based on this, a chronological development of the wood resources-based bioenergy system of Baden-Württemberg throughout the next decades might be conducted. For this aim to be achieved, certain critical aspects such as the development of the free potentials of wood resources on account of climate change as well as the evolution of remuneration involving heat and power generation from biogenic resources should be considered.

4. **Decrease of the spatial aggregation level:** An increase in the number of spatial units would definitely result in a lower aggregation level than that represented by the district. This should lead to a spatially higher resolved system and in consequence a more accurate solution for the proposed problem. In this manner, administrative units such as the community or even a group of them with similarities e.g. in relation to the type of wood resources might serve as the new spatial units of the targeted bioenergy subsystem. A new database with more detailed information concerning both the free potentials and the energy demands of less aggregated spatial units should be created via the collection and harmonisation of suitable data. As a result, one of the potential sources of error in the present study – i.e. the allocation of free potentials to the corresponding centroids – could thus be minimised.

5. **Spatial partition on the basis of a regular raster:** The transition from the prior district/community-based analysis to a supposedly more accurate sort of districting problem based on a regular raster grid would result in the maximum possible improvement of the intended modelling on the basis of the available computing capacities. The utilisation of a grid with a high enough spatial resolution raster (e.g. 10 km x 10 km) in both N-S and W-E directions would allow the different free potentials of wood resources to be appropriately assigned to each of the resulting square divisions apparently with a lower margin of error. In such a way, this approach would yield a solution with a considerable decrease in the spatial aggregation level and thereby a higher spatial resolution in the description of the system.

6. **Expansion of the scope of the system:** The enlargement of the system boundaries by maintaining the district as an adequate spatial unit would yield interesting indicators on the most cost-efficient way of producing bioenergy within larger areas than Baden-Württemberg. According to this idea, the wood resources-based bioenergy system of both southern federal states of Baden-Württemberg and Bavaria or even the entire Federal Republic of Germany as well as other neighbouring countries or prominent regions might be modelled with this extended version of BIOSPHERE by putting in practice the same methodology employed in the present study.

7. **Integration of other densification technologies different than chipping:** Although the densification of wood resources into bioenergy carriers of high energy density entails an increase in the costs of the entire supply chain, its implementation within the utilisation pathway of power generation might lessen the transport costs –especially

over long distances – due to the higher efficiency associated with carrying more mass, and therefore more energy per unit volume. This new approach would imply allowing for all technically feasible densification processes, namely pelletising, briquetting, torrefaction, pyrolysis, hydrothermal upgrading or even gasification for injecting the resulting syngas into natural gas pipelines. As a consequence, several transport modes such as the truck, the more economical long distance transport means of train and ship or the existing and future pipeline systems might be implemented after the corresponding densification stage and thereby modelled with the assistance of the extended version of BIOSPHERE for larger regions. In this regard, the additionally generated costs incurred by densification might be offset with the resulting more economical transport expenses. This effect would render the supply chain more cost-effective than in the case of chipping (transport with truck) when compared for similarly long enough journeys. Besides, the increased size of conversion plants as a result from the enhanced transportability of the densified wood resources should give rise to benefiting from economies of scale that will in turn reduce the final production costs.

8. **Modelling of technologies for production of biofuels and bio-based chemicals:** A further step could be carried out based upon the last development of BIOSPHERE achieved in the previous point. In this regard, the production of biofuels and chemicals could be separately modelled as a cost minimisation-based simulation but also integrated in the targeted bioenergy subsystem together with the generation of power. Thereby, the most cost-effective utilisation pathways could be identified for the selected territory. Furthermore, the specific production costs of the final products power, biofuels and bio-based chemicals along with their cost components could be ascertained, while gaining insight into the possible cost synergies between the three types of conversion pathways.

9. **Consideration of network operators in the modelling of utilisation pathways:** According to this study, the proposed optimisation analysis of a wood resources-based bioenergy system is systematically carried out from the viewpoint of the plant operator. This way, the incurred costs in every upstream process involved can be determined so as to subsequently introduce the corresponding profitability constraints. However, these restrictions may be equally assigned to other interfaces than that of the plant operator. In this regard, the interface characterised by the stage of the network operators can be modelled in order to include the expenses originated in the transmission lines when power is transported from a spatial unit to another. The introduction of profitability constraints at this point should permit the entire supply chain from the source to the final consumer to be evaluated while identifying more optimal solutions for the extended utilisation pathways.

10. **Distributed generation:** Beyond the conversion of biomass into bioenergy, other renewable energy sources including small hydro, photovoltaic, solar thermal, wind, geothermal and ocean energies can significantly contribute to guarantee the energy

supply of modern societies. A practical solution would involve the local consumption of this energy just where it is produced according to a decentralised autarkic pattern of a number of micro-grids that rely on appropriate energy storage systems (batteries, power to gas, etc.) for an effective off-grid operation. Nevertheless, interconnection among micro-grids proves to be of major importance so as to overcome possible blackouts and, in turn, evacuate excess energy to other micro-grids with energy demand higher than its own generation. In this context, the application of an adapted version of the BIOSPHERE model to an energy system consisted of several micro-grids would allow the energy exchange among them to be simulated for different levels of remunerations.

11. **Analysis of the entire energy system:** The modelling of any bioenergy subsystem with the assistance of BIOSPHERE can be extrapolated to that of the entire energy system of a given region as a real energy system analysis. In this case, the value chains of biomass will compete with the rest of the renewable and conventional energy sources for supplying the energy demand of the system. This competition might be altered by introducing profitability constraints not only into the bio-based utilisation pathways but also into the conventional ones. Thereby, more economical energy configurations for specifically selected actors could be identified while simultaneously avoiding eventual lacks of profitability in certain utilisation pathways.

12. **Industrial logistics:** The core concept of the BIOSPHERE model as a cost minimising tool consists in the energy and material balancing of an energy system where profitability constraints involving the remunerations and cost components associated with the contributions from upstream processes are introduced. This peculiarity enables for each process the spatiotemporal determination of the energy – or material – flows when remunerations are modelled so as to identify more economical energy configurations. But this approach may be transformed into a sort of mass flow analysis for being applied in the area of industrial logistics. As industrial goods may be produced in certain locations but subsequently processed and finally consumed in some others at different time intervals, the optimal solution for an industrial logistic system can be equally achieved via profitability constraints that permit remunerations to be modelled in order to estimate the cost components of any upstream processes within ever cheaper logistic structures.

9. Summary

The need to diversify the energy mix of Baden-Württemberg might be met through the optimal utilisation of a significant, but still unexploited amount of existing free potentials of wood resources in the form of forest residues and landscape wood raw material. Therefore, one of the goals of this study is to estimate these potentials. Subsequently, the optimisation of the value chain of wood resources exclusively for power generation purposes is carried out for this federal state. Due to the limited data availability, the district is selected as a spatial unit and then employed for this analysis because most data are exclusively obtainable at this level of spatial aggregation. In such a context, the free potentials of wood resources and the power demand at district level is allocated to a predetermined geographical point within each district. A cost minimisation analysis is carried out on the basis of a MILP approach with the assistance of the BIOSPHERE model (Bioenergy Optimisation Software for Production Pathways at High Energy and Resource Efficiency), a novel and more advanced optimisation tool built upon the existing structures of the PERSEUS optimising energy system model. The main advantage of BIOSPHERE resides in the incorporation of a new mathematical constraint based on the principle of profitability. According to this postulate, remunerations must be higher than or at least equal to the total expenses incurred throughout a given bio-based utilisation pathway. In consequence, such constraints have to be fulfilled from the point of view of each plant operator. The aim of this analysis is to determine the most cost-effective bioenergy configuration for a high enough remuneration above the breakeven point by assigning their free potentials to one or more bio-based conversion units located in predefined sites of each district. In addition, a second approach based on a series of progressive reductions of remunerations below each resulting breakeven point is performed in order to assess the evolution of the targeted bioenergy system while complying with the referenced principle of profitability.

The model provides a matrix solution that is composed of as many single solutions as processes belong to the selected utilisation pathway. As the targeted bioenergy subsystem is made up of four sectors – namely harvesting, densification into wood chips, transport with a two container truck and conversion of wood resources into bio-based power –, four single solutions are equally generated within each of them. The single solutions characterise the processes involved that make up the entire utilisation pathway as an ensemble composed of a bio-based power plant and its supply chain. Thus, each process-related single solution is assigned a 3-tuple that refers to the optimal result obtained for the location, technology and capacity of each relevant process.

The forest residues and landscape wood raw material of each district are collected with the assistance of the motor-manual as well as the partly, highly and fully mechanised logistic chains. These four logistic chains result from the suitable combination of harvesting and densification and are modelled according to two cost allocation methods for forest residues regarded as a by-product or a joint product. By contrast, only both the partly and highly mechanised logistic chains are employed for harvesting landscape wood raw material, in this case as a unique product and therefore without requiring any cost allocation technique. As a consequence, the resulting harvesting systems for both kinds of wood resources are characterised through the type of forest ownership (small or large owners), the steepness of slope in forest and landscape areas (above or below 50%) and the variety of harvested trees (coniferous or deciduous). Thus, ten different types of chipped wood resources are identified and assigned a harvested amount in tonnes. These quantities correspond to the free potentials of wood resources and are correlated with a specific unit cost that depends on the three above-mentioned characteristics. These ten types of wood chips encompass namely both landscape-based materials harvested in areas with steepness of slope lower and higher than 50% (S<50L and S>50L) as well as the coniferous and deciduous portions of the four forest-derived wood chip types produced by small private and large forest owners – when forest residues are regarded as a by-product – and in forest areas sloped below and above 50% – as a joint product – (SPFO, LFO, S<50F and S>50F).

In relation to the conversion techniques for bio-based power generation, the specific electricity production costs of an array of existing technologies are analysed under equivalent operation conditions with the singular conclusion that gasification proves to be more cost-efficient than combustion – except co-firing – for small and medium as well as large scales. In virtue of this, the modelling of the value chain encompasses a set with the following most cost-effective power generation techniques: fluidised bed gasification coupled to a gas engine or a combined cycle for small to medium or large scales, respectively, and the option of co-firing a 10% fraction of wood resources by retrofitting the existing coal power plants of the region. Subsequently, the most significant techno-economic parameters describing these bio-based technologies – namely the specific amount of capital costs as well as fixed and variable operation and maintenance costs together with both electric and total efficiencies – are calculated for the whole range of capacity via both power and logarithmic regression adjustment techniques with the aim of reproducing the best regression fit to the set of collected data.

The wood resources-based bioenergy system of Baden-Württemberg is analysed via twelve scenarios that are constructed on the basis of the three preselected technology options as well as the ten types of wood chips derived from both kinds of wood resources. The results of this scenario-based analysis allow gaining insight into the consequences of converting the estimated free potentials of wood resources – an equivalent energy content of 17 PJ – into power for high enough values of remunerations above the breakeven point. If the focus is put on the electricity production costs, the combined heat and power cogeneration process consisting of a fluidised bed gasifier coupled to a gas engine (20 MW_e) renders for an annual amount of 7,500 full load hours relatively high electricity production costs of about 10.1-13.8 €cent/kWh_e for six to ten bio-based conversion units dispersed throughout the territory. On the contrary, the conversion process based on the co-firing option yields more economical specific electricity production costs for a realistic amount of 3,000 full load hours a year. They are on the order of 6.6-11.7 €cent/kWh_e for an array of seven to twelve retrofitted power stations with bio-based capacities up to 84.3 MW_e. The fluidised bed gasifiers connected to a combined cycle with a power output capacity of 210 MW_e and 340 MW_e generate cheaper bio-based power as they benefit from economies of scale. Their specific electricity production costs are the lowest and fall to roughly 5.6-7.1 €cent/kWh$_e$ when the facilities are operated for 7,500 hours per year at full load. Regarding the cost component split of electricity production costs, the elevated contribution of harvesting costs stands out among the rest of the cost elements. Whereas the stage of harvesting accounts for around 35-50% of specific electricity production costs in both gasification-based technologies, the respective portion in the co-firing based power plants increases to around 40-55% owing to its reduced conversion-related expenses. The weight of the investment and operating costs is represented by a quite high amount of roughly 5 €cent/kWh$_e$ in the case of the more expensive fluidised bed gasifier coupled to a gas engine, 2-4 €cent/kWh$_e$ for the much more economical co-firing option and a lower value of circa 2 €cent/kWh$_e$ when a fluidised bed gasification process connected to a combined cycle is considered. If transport contributions are compared, the corresponding cost component is of approximately 1.3-1.5 €cent/kWh$_e$ for both gasification-based processes, whereas it amounts to a range between 1.2 and 2.5 €cent/kWh$_e$ for the co-firing based coal power plants.

When the small and medium-scaled technology option based on a fluidised bed gasifier combined with a gas engine is analysed, a number between six and ten bio-based conversion units are installed for the different resources-related compound scenarios. Analogously, the analysis of the co-firing technology for these four scenarios yields a similar degree of centralisation with a set of seven to twelve bio-based retrofitted power stations. As a consequence, the spatial arrangement of both types of technology follows a decentralised pattern of power production on the basis of a distributed generation scheme. On the other hand, the technology based on fluidised bed gasification coupled to a combined cycle exhibits a spatial configuration characterised by a single plant located in a central area of the targeted territory.

The progressive lessening of remunerations below each resulting breakeven point for all possible utilisation pathways within the wood resources-based bioenergy subsystem of Baden-Württemberg permits significant amounts of cost reductions to be identified. The decrease in remunerations for a given technology generates a broad spectrum of more economical bioenergy configurations with different spatial locations and capacities. The focus in the framework of this analysis is exclusively set on the co-firing technology when facilities are fed with forest residues as a by-product and operated at a usual level of 4,000 full load hours per year. Under these conditions, remunerations granted to the operators of retrofitted coal-fired power plants are gradually diminished from an initial level at the original breakeven point (6.7 €cent/kWh$_e$) to a low enough value of 5.5 €cent/kWh$_e$ at which no bioenergy is generated. This way, an array of five upgraded power stations totalling 299.3 MW$_e$ – RDK 7 and RDK 8 in Karlsruhe, Block 8 in Mannheim, HLB 7 in Heilbronn as well as ALT HKW 1 in Altbach (Esslingen) – evolves into a reduced system solely made up of HLB 7 with 77.8 MW$_e$ for a remuneration level of 5.6 €cent/kWh$_e$. The corresponding electricity production costs vary from values between 6.07 €cent/kWh$_e$ and 6.66 €cent/kWh$_e$ for the units of the former bioenergy configuration to a specific electricity production cost of 5.55 €cent/kWh$_e$ for HLB 7. When remunerations are finally cut down to 5.5 €cent/kWh$_e$, the bioenergy subsystem is brought into a state where no forest residues are consumed and hence no bio-based power produced.

In addition, this study gives guidance on the profitability of the analysed technology options when it comes to transforming wood resources into bioenergy. As the electricity production costs of a fluidised bed gasifier coupled to a gas engine are in the order of roughly 10.1-13.8 €cent/kWh$_e$, the profitability of such power plants is only viable if investments are supported with remunerations granted to the generation of power in combination with the revenues obtained from the sales of heat. As an example, a heat retail price between 2 and 3.80 €cent/kWh$_{th}$ depending on the type of converted wood resources would be necessary to merely reach the breakeven point if bio-based power is remunerated at 7 €cent/kWh$_e$. On the contrary, the specific electricity production costs of both a co-firing based facility and a fluidised bed gasification process coupled to a combined cycle range between 5.6 and 11.7 €cent/kWh$_e$ for the different wood resources-related compound scenarios. This cost range is highly improbable to be covered through the current and future levels of electricity wholesale prices. In virtue of this, some support instruments in the sense of necessarily increasing remunerations over the identified range of electricity production costs should be created in the framework of Baden-Württemberg's bioenergy system for conversion of wood resources into bio-based power. If such energy-political measures are implemented into the energy system of the federal state on the basis of the outcomes obtained in this study, the proposed centralised technologies might supply considerable amounts of carbon-neutral baseload power with total capacities of up to 340 MW$_e$.

Among the weaknesses of this study, mention should be made that the quality of the solution is mainly restricted by both parameter and structural uncertainties as well as the high spatial aggregation level chosen for this analysis. By contrast, the introduction of the new methodological approach underlying the BIOSPHERE model represents a significant strength. Actually, it eliminates a potential error in the research field of energy system analyses by considering the system from as many points of view as the number of utilisation pathways instead of a single one. Additionally, this tool provides a real breakthrough by allowing plant operators to identify certain cost reductions that remained hidden in the context of previous analyses without the employment of this technique. In this regard, the implementation of this methodology and the subsequent optimisation analysis delivers a solid starting point for gaining insight into new energy system structures that may contribute to the progress of the initiated energy transition in Baden-Württemberg and the whole of Germany.

A central conclusion of this dissertation points towards the investment in both the most cost-efficient bioenergy technologies, namely co-firing and the gasification-based combined cycle. The comparatively low incremental capital costs of co-firing as well as the great efficiencies of large-scaled BIGCC units together with the identification of possible cost reduction potentials on the basis of the valorisation of cheaper deciduous wood resources might cut down the corresponding electricity production costs to a rather low range between 4.5 and 9.5 €cent/kWh$_e$. But this spectrum of electricity production costs still requires the introduction of appropriate energy policy support mechanisms for promotion of carbon-neutral baseload power generation in the context of Germany's nuclear and coal phase-outs as part of a change in the energy paradigm. As a collateral effect, the fostering of both referenced technologies will definitely result in either a lower reallocation charge with resulting savings for power consumers or an allocation of a share of this levy to other costly renewable energy sources.

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