A profitability constraint for energy utilization pathways in optimization modelling

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ABSTRACT

The utilization pathways of certain energy sources may become unprofitable when production costs surpass remunerations. In fact, some completed studies, which optimize energy systems as a whole from the macroeconomic perspective of a single observer, might have violated the principle of profitability. The solution to avoid this issue is to resort to an exogenous approach to the modelling of remunerations. This methodology is based on the integration of a profitability constraint into every optimization model for any energy utilization pathway. The constraint constitutes a restriction on utilization pathway's costs from the standpoint of plant operators or investors concerned. The aim of these constraints is to ensure profitable investments at the microeconomic level of each utilization pathway. Besides, integrating profitability constraints is clearly an easy task for energy system models with a single sector (data block). But if there is more than one sector, it is not straightforward to model energy and material flows across such blocks. This objective can be achieved through two sets of specific variables: the energy and material contributions to a facility and the virtual flows.

The exogenous methodology is proved in this work by applying it to the special case of bioenergy generation. A general bioenergy subsystem is modelled as a complement or add-on module of a cost minimization model describing the whole energy system. A mixed integer linear programming (MILP) approach is selected to create such a software extension called BioSPHERE. By using a sensitivity analysis, this add-on allows assessing the impact of the decrease in remunerations on a particular bioenergy subsystem. As a result, an array of macroeconomically cost-efficient bioenergy configurations of microeconomically profitable conversion units with ever lower electricity production costs and different spatial arrangements are generated. The production costs caused by the biomass contributions of each spatial unit to a given facility relate to a number of cost components that finally allow evaluating the respective utilization pathway's profitability.

KEYWORDS

Utilization pathway, profitability constraint, remuneration, sector, interface, observer, contribution, virtual flow, add-on module, bioenergy subsystem, energy configuration

1. Introduction

Ambitious goals for renewables have been laid down in the EU-28 with the adoption of the Renewable Energy Directive (2009/28/EC) by defining specific binding renewable energy targets for each member state as well as an overall European target share of 20% for the final energy consumption in 2020 (CPIH 2015). Under this energy policy context, the European Council promulgated the 2030 Energy and Climate framework in 2014 with the aim of determining a compulsory EU-wide target of 27% by 2030 without the need to meet any specific target at national level. For this purpose, an array of policies for the development of renewable energies in each European state are identified and categorized into three different basic types of support scheme. The first category encompasses price-based support instruments, namely feed-in tariffs (FIT) and feed-in premiums (FIP). According to them, administrations regulate power prices while the market decides on the quantity of electricity to be produced (Ragwitz et al. 2011). A second group includes quantity-based support policies such as quota obligations based on tradable green certificates (TGC) as well as tendering schemes. Both mechanisms leave it up to the market to decide the level of the electricity price whereas governments fix the permitted amount of power production – the quotas (Ragwitz et al. 2011). Other instruments employed such as loan guarantees, soft loans, investment grants and tax incentives fall into a third category that is associated with supplementary financial aid and fiscal incentives (CPIH 2015). The lesser relevance of the latter group allows focusing on the first two types of support policies.

FIT and FIP have been introduced by several member states in order to foster renewable energies. They are guaranteed to plant operators for a given period of time and can be either subsidized by the public budget or passed down to power consumers as a surcharge. Whereas FIT represent a fixed amount paid by the grid to plant operators in exchange for electricity under a purchase obligation, FIP are granted them as an additional variable payment provided that power is sold on the spot market in return for the electricity wholesale price. FIT have established themselves as a more suitable instrument in terms of investment security (low risk). They provide higher levels of predictability and stability as against the higher risk of FIP. Both systems permit technology-specific promotion by fostering immature techniques while differentiating by capacity classes and the kind of renewable energy source.

A number of member states have opted for quota obligations based on TGC. According to this mechanism, a minimum share of renewable energy-based electricity is fixed and allowed subsequently increasing over time. Such obligations are satisfied by submitting TGC to the competent authority. These certificates can be traded on the basis of market rules if such a minimum share cannot be met. This support policy is linked to a higher risk than price-based mechanisms owing to the uncertainty derived from certificate prices. A further quantity-based support instrument is implemented via tenders or auctions in the framework of competitive bidding procedures. Both mechanisms allow for some degree of technology-specific promotion, although in practice their suitability is lower due to the greater exposure to market competition.

1.1. Background and motivation

The price-based instruments FIT and FIP as well as the quantity-based procedures consisting of TGC and tenders/auctions can be modelled in the framework of the optimization of energy systems. These support schemes can be either endogenously or exogenously integrated into the energy system models. The endogenous approach allows modelling such mechanisms by introducing tariffs, premiums (plus wholesale prices), certificate prices as well as auction revenues as negative costs within the objective function of the model. In contrast, an exogenous procedure permits both prices (remunerations) and volumes (capacities) to be mathematically reproduced by means of specific constraints. In this way, tariffs and premiums in price-based support policies (FIT, FIP) as well as quotas and target capacities in quantity-based schemes (TGC, tenders) can be appropriately modelled because such magnitudes are legally fixed by regulators. Alternatively, undefined amounts such as the resulting energy volume and the installed capacity in price-based mechanisms (FIT, FIP) or those electricity promotion prices of quantity-based instruments (TGC, tenders) can be addressed by treating the corresponding uncertainty via scenario-based analyses.

According to diverse studies (see 1.2), the use of an exogenous approach to modelling the resultant volumes of renewable energies in an optimization analysis is in general not a complicated task. In contrast, the endogenous procedure proposed for integrating prices or remunerations as negative costs in the objective function inevitably involves the generation of some inaccuracy (see 1.2.1). This technique can then be substituted with a more advanced exogenous methodology by introducing a restriction on costs for each discrete energy utilization pathway – i.e. an energy producer attached, if any, to a raw material supply chain. Such a restriction is intended to preserve the profitability of any of these utilization pathways. For this reason, it will be subsequently referred to as profitability constraint. The total costs incurred throughout each potential utilization pathway have accordingly to be limited by the sum of remunerations granted by the network provider to the plant operator or investor concerned.

An accurate representation of the effect of such a constraint can be observed in Figure 1 for the profitable utilization pathway 1. This production chain receives a payment in the form of remunerations R1 that act as an upper bound of the corresponding expenses. This way, the restriction seeks to prevent an insufficient level of remunerations from not covering the incurred production costs – such as R2 for utilization pathway 2 (see Figure 1). This might be the case of certain immature and expensive – or even not so costly – technologies that receive comparatively low remunerations. In effect, regardless of the magnitude of production costs, a deficient amount of remunerations might always cause the non-profitability of certain technology pathways. Therefore, the underlying aim of this constraint is to avoid uneconomic investments at the microeconomic level of each utilization pathway. An observer[1] then has to

[1] The first of the two agents that are located at both ends of any interface, where any generated product (e.g. power) can be passed on to the next downstream actor in return for remunerations – e.g. between plant operators and network providers or the latter and the final consumers.

be identified that will only consider profitability from such a microeconomic point of view. In this case, the observer will be an agent at the power plant of any utilization pathway, i.e. the plant operator or the interested investor.

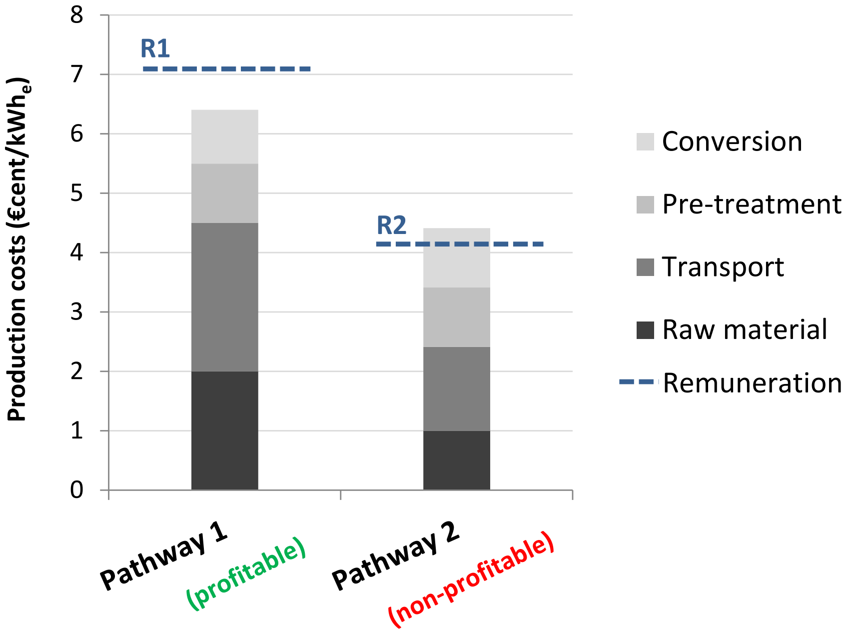

Figure 1: The role of profitability constraints as a restriction of remunerations over the production costs of utilization pathways transforming a raw material into a final energy carrier

Utilization pathway 2 turns out to be unprofitable despite its comparatively low production costs (see Figure 1). If no profitability constraint was set for this pathway, this technical option might become eligible in virtue of a cost minimization procedure, irrespective of not being profitable. This would be an outcome that can arise if a macroeconomic analysis is conducted, in which the energy system is considered as a whole without integrating any such restriction. This approach is carried out in usual optimization studies from the macroeconomic perspective of any single observer. Thus, some cost minimization analyses might include a macroeconomically cost-efficient solution but, however, a number of microeconomically unprofitable utilization pathways as well. And the same goes for profit maximization with a macroeconomically profitable energy configuration comprising certain microeconomically unprofitable pathways. For instance, it would be possible that an unprofitable utilization pathway would be wrongly selected for a short period of time; simply because this would temporarily contribute to the optimal setting of the entire energy system at an aggregated level in spite of that lack of profitability. All this might actually be the case in numerous research studies on optimization modelling accomplished in the past. Of course, it would take a huge effort to prove this error for each of them by reproducing the respective analyses once again. But in any case, this imprecision must be avoided from now on by integrating such profitability constraints in future energy system models for all utilization pathways and their respective observers. This question is the real challenge that is to be faced in optimizing energy systems.

Meeting the profitability requirement may not be easy. This is especially true for energy sources – such as bioenergy – with comparatively high production expenses – fuel and transport costs in the case of biomass – and/or relatively small remunerations. In addition to bioenergy, this issue might also occur, although to a lesser extent, in certain fossil and nuclear energy-based utilization pathways. The other renewables are not exploited on the basis of an available raw material. Therefore, they are hardly affected by this potential absence of profitability. Still, there might always be a need, for example, to set a ceiling for expenditures due to economic or political reasons. Under such circumstances, improving profitability might imply further difficulties.

1.2. Literature review

There have been several attempts to consider the previously introduced price- and quantity-based support instruments on the basis of endogenous or exogenous approaches. They managed to address both the endogenous and the exogenous modelling of feed-in remunerations as well as the exogenous method for reproducing target volumes (quotas and capacities). Hereunder, a literature review is presented, which encompasses the following studies as the most significant contributions on this topic.

(Huber et al. 2007) carries out an economic analysis of the renewable energy price support mechanisms in the Irish power generation system. The focus is set on the assessment of the effect of feed-in tariffs, quota obligations based on TGC and competitive tender schemes. The Green-X model is implemented in order to identify the potential of renewable energies in Ireland until 2020 by exogenously modelling not only the quotas and the target capacity of the quantity-based support instruments but also the resulting volume of FIT. To this effect, expenses are determined through the previous calculation of supply cost curves for this energy system exclusively made up of a conversion sector[2].

An endogenous approach to modelling FIT with the PERSEUS model is accomplished for the energy system of EU-15 by introducing tariffs as negative costs (Rosen 2008). The author performs the subtraction of FIT as negative variable costs in the objective function. But this is only applied to renewables and not to the rest of the conventional energy sources. This fact results in an incomplete assessment of the whole system, thus generating a significant error in the analysis carried out (see 1.2.1). Such a technique would turn out to be more suitable for renewable energy sources other than biomass. This is because bioenergy, in contrast to the rest of renewables, includes fuel and transport costs that may more easily jeopardize its overall cost-effectiveness and hence its profitability.

[2] Sectors are the highest aggregation level of the data structure in an energy system model. These data blocks are each bounded by two or more interfaces acting as a transition from one sector to another consecutive one. At this stage, energy flows out of a sector and into another.

(Möst et al. 2010) report on an exogenous model input of electricity commodity prices in an array of energy system models (Admire Rebus, Rebus, EIGreen, Green-X, GreenNet) drawn from a review of various research studies. Based on appropriate constraints, prices regulated by several incentive schemes are varied through sensitivity analyses via the implementation of different scenarios. Most of the above mentioned tools use marginal supply cost curves as the basis for determining both costs and potentials of renewable energies. In all cases, the energy systems described are constituted of a sole sector including the conversion technologies under consideration. This feature facilitates the integration of the respective constraints on electricity production costs (EPC), where remunerations serve as a cap.

(Shin et al. 2012) model the power system in Malaysia with a mixed integer linear programming (MILP) approach. They minimize total system costs whilst satisfying power demand and CO_2 reduction targets. They consider renewable power generation technologies in their analysis, where FIT are endogenously modelled as negative variable costs. As in the case of (Rosen 2008), the subtraction of electricity prices in the objective function is carried out exclusively for renewables (including bioenergy). In contrast, variable costs relating to conventional energy sources remain unmodified.

(Götz et al. 2012) and (Fais et al. 2014) make a significant contribution to the problem of modelling FIT in optimization analyses in their work with the TIMES model. They endogenously model FIT and electricity retail prices as negative costs and report on the exogenous modelling of quantity-based support schemes such as tradable green certificates and tendering procedures. For the case of the FIT policy instrument, the effect of the payment level (tariffs) on the demand side (surcharges) is assessed. Through such surcharges on electricity retail prices, the reapportionment of FIT payments can be accounted for. According to (Götz et al. 2012), in certain analyses conducted by (UBA 2009) and (IER et al. 2010), the effect of FIT on the development of the German energy system is taken into account. The quantity of energy supported by this mechanism is exogenously modelled by setting minimum volumes for the electricity produced from renewable energies.

(Parrilla-Martínez 2019) uses an exogenous method for modelling remunerations when optimizing the wood resources-based bioenergy subsystem of Baden-Württemberg (Germany). BIOSPHERE, a cost minimization model, is developed for this purpose and applied to this bioenergy subsystem consisting of 4 sectors – harvesting, densification, transport and conversion into bio-power. This is the only study so far that deals with the more complex case of exogenously modelling remunerations in an energy system with more than one sector. In this regard, profitability constraints for any utilization pathway are implemented in an energy system model for the first time as a novel methodology. These restrictions are constructed on the basis of an array of decision variables involving the energy and material contributions of all processes within the supply chain to a conversion unit. These contributions rely in turn on a large series of new auxiliary variables that receive the name of virtual flows.

According to the prior studies, volume and remunerations of renewables fostered by electricity promotion instruments can be exogenously modelled by means of specific constraints. The volume in price-based schemes as well as the quota and target capacity in quantity-based support instruments can be reproduced with the aid of this approach. Besides, any kind of remuneration can be exogenously modelled via a simple restriction on costs – with payments acting as an upper limit – for energy systems that only comprise a conversion sector. If an energy system consists of more than one sector, then a more complex procedure for integrating remunerations and hence their respective profitability constraints has to be taken into account. This methodological approach is used in section 2.2 in order to create an add-on module for modelling a bioenergy subsystem in the context of the whole energy system. Finally, prices and remunerations can also be endogenously modelled by subtracting them as negative costs from the total expenditures within the objective function of the model. This procedure, however, generates an unwanted outcome leading to a significant mistake that is addressed in 1.2.1.

1.2.1. Consequences of implementing the endogenous approach

Among the studies identified in the literature review, (Rosen 2008) and (Shin et al. 2012) apply the endogenous approach solely to the modelling of remunerations granted to renewable energies. These payments are accordingly subtracted from the corresponding costs of the resulting utilization pathways. On the contrary, the non-renewable energy sources are assigned the full amount of costs for each stage of their utilization pathways. If the objective function including the total expenses of the energy system is minimized, the model will primarily select renewable energy processes with artificially lower costs than the competing conventional energy producers. But this effect proves to be unrealistic as the costs apportioned to renewable energy-based utilization pathways are predominantly higher than those of mature conventional technologies. Therefore, it becomes apparent that this methodology must also be performed for the share of non-renewables in order to subject the entire system to the same conditions. In contrast to both former studies, (Götz et al. 2012) exclusively analyses a renewable energy system and thereby only applies the technique of negative costs to these energy sources – presumably in order to circumvent such an inconsistency.

Beyond that aspect, prices or remunerations arise in general at almost any stage of every utilization pathway. Therefore, there may be more than one interface – in which a generated product can be exchanged for remunerations – throughout any utilization pathway. For example, in the case of a bio-based power station and its supply chain, those of a fuel producer, a fuel transporter, a plant operator and even a grid operator. In short, the whole pathway possesses as many interfaces as phases are included from the source to the final consumer. And each agent will successively charge remunerations in exchange for each product generated. In consequence, the systematic subtraction of remunerations from those costs incurred in each of the stages might be a treatment in keeping with the essence of the endogenous approach. In this regard, (Götz et al. 2012) implements this extended methodology for exactly two interfaces. Specifically, one is where feed-in tariffs are paid by the grid to the plant operator; while the other is where retail prices are charged by the former to the customer. In this manner, (Götz et al. 2012) attempt to harmonize and correct the original method employed by (Rosen 2008) and (Shin et al. 2012). However, the application of this technique does not seem to be a suitable procedure for carrying out a real cost minimization analysis. This option is more realistic than only deducting remunerations in a single interface between e.g. plant and grid operators or these and end consumers, but it is not completely correct. In reality, the minimization of an objective function consisting of the sum of expenses originating in each stage of a utilization pathway minus the respective remunerations received from each of the next downstream agents would actually serve as a sort of profit[3] maximization – unlike the originally proposed cost minimization. The aim of (Götz et al. 2012) was initially to determine the most cost-efficient energy generation pathways, although it ended up yielding the most profitable ones. Under such an endogenous approach, expensive energy generation processes that might be assigned high remunerations could be incorrectly selected by the model as part of the most profitable but not the most cost-efficient solution.

In general, the total expenses of any utilization pathway comprise the costs arising at the power plant and in its supply chain throughout the upstream stages plus the benefits obtained by the respective agents in each of these steps. When, for example, remunerations granted to plant operators are deducted from total expenses within an objective function, two tendencies emerge:

- Remunerations are higher than the sum of utilization pathway's costs and upstream agents' benefits:

  The total expenses are removed and the remaining quantity after subtraction of remunerations from the sum of costs and benefits is a negative amount. The absolute value of this quantity corresponds to the profit realized by that plant operator. Obviously, the minimization of an objective function including such negative magnitudes is nothing more than a profit maximization such as that indirectly carried out by (Götz et al. 2012).

[3] Mention should also be made of the lack of academic precision involved in using the term "profit" – usual in business economics – for energy system analyses conducted in the framework of political economics. Notwithstanding that, the concept aims at pointing out the change of analytical approach from a pure cost minimization to a maximization of an amount equal to the difference between remunerations and costs.

- Remunerations are lower than the sum of utilization pathway's costs and upstream agents' benefits:

  In this case, the profitability of the utilization pathways involved cannot be assured. As a result, such pathways should not be selected by the model as they are not profitable for the respective plant operators. The endogenous approach does not give rise anymore to a profit maximization analysis but results in a mistake that must be avoided by identifying such lack of profitability in advance or alternatively introducing a profitability constraint. The possibility of some profitable utilization pathways offsetting other unprofitable ones must also be prevented – even though the minimized compound objective function might give a negative value as indication of the total system being profitable as a whole.

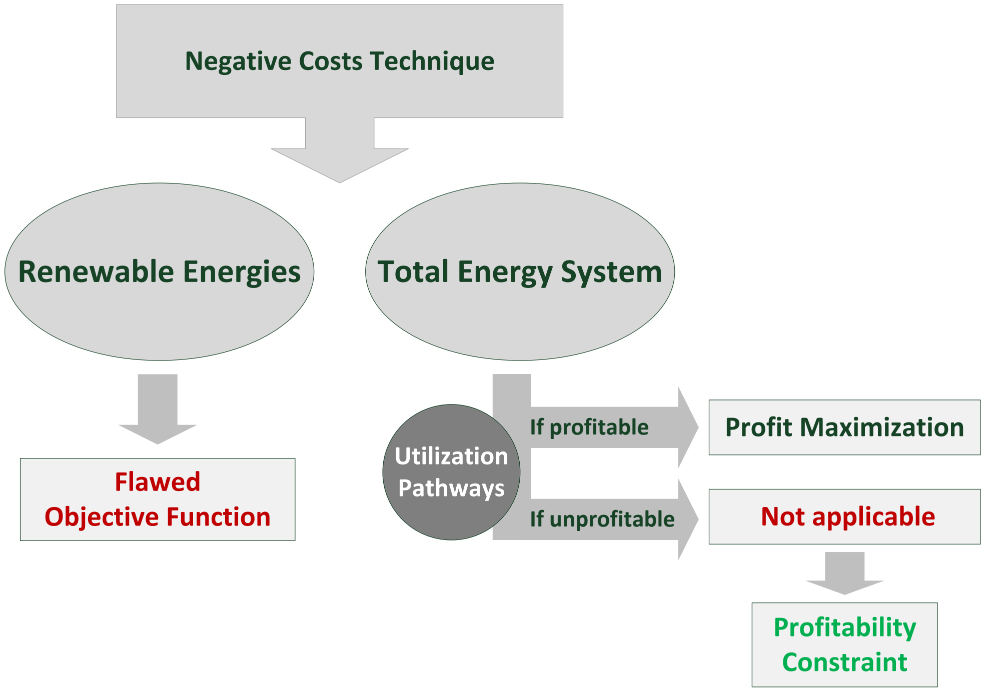

Figure 2: Consequences of the application of the negative costs technique to the portion of renewable energies only or the total energy system

In virtue of the foregoing, such a compound objective function expressed as the total system costs plus certain – depending on the chosen method not all – remunerations implemented as negative costs leads to two dissimilar results. Both differ completely from the originally intended cost minimization analysis (see Figure 2):

- A flawed objective function, if the endogenous approach is exclusively allowed for renewables and not for conventional energy sources.
- The profit maximization of the total system, when such a methodology is applied to either some or all interfaces between stages and provided that the profitability of each

utilization pathway involved is guaranteed. If certain or all utilization pathways are not profitable, the negative costs technique cannot be employed anymore. Instead, the proposed profitability constraint can be integrated for such pathways so as to successfully complete the modelling of the system.

Both outcomes diverge from the minimization of the objective function originally expressed as the sum of total expenses. In view of this, the endogenous approach introduced by the negative costs methodology fails to minimize the total system costs. In conclusion, this method cannot be considered as a suitable procedure for reducing the total amount of expenditures in the framework of a cost minimization analysis.

1.3. Objective

So as to preserve utilization pathways' profitability and eliminate the anomalies originating from the use of the negative costs technique, an exogenous approach to the modelling of remunerations is required. The objective of this paper is then to show and test such an exogenous methodology, which is based on the implementation of profitability constraints for any potential utilization pathway in a given energy system. In virtue of the conclusions from the prior literature review, integrating profitability constraints into an energy system model with more than one sector (data block) entails a certain complexity. Therefore, this aspect will be correspondingly addressed in the framework of this study. On the other hand, each possible utilization pathway has to be assigned an observer that will exclusively consider profitability for the corresponding power plant and its supply chain. This fact relies on the consideration of the expenditures and remunerations of any utilization pathway from the viewpoint of the respective observer.

Even though some completed optimization studies might have yielded unprofitable solutions, the aim of this work is not to scrutinize all previous analyses but focus on a smaller portion of any energy system – a bioenergy subsystem. The proposed analysis will exclusively concern the bio-based share, albeit the rest of the total energy system will equally be present without being explicitly considered. Such a subsystem is to be modelled as a complement or add-on module of a cost minimization model describing the whole system. This add-on will receive the name of BioSPHERE and be based on the fulfilment of the principle of profitability for any bio-based utilization pathway. The module will be developed for a general bioenergy subsystem composed of four technology sectors and *n* spatial units, where profitability will be guaranteed for each utilization pathway. As a software extension, it will include an array of auxiliary conditions involving profitability constraints for discrete utilization pathways as well as a number of sets of auxiliary equations supporting such restrictions. Based on this mathematical system, a new decision variable introducing the energy and material contributions of all processes of a supply chain to a bio-based conversion process will be evaluated. Furthermore, the activity level of any energy and material-related magnitude such as the process levels or the above mentioned contributions is to be modelled by means of an appropriate linear function of a set of auxiliary variables called virtual flows. In this manner, the ultimate objective of this paper is to shed light on the resulting spatial arrangements of profitable bio-based facilities (bioenergy configurations) on the basis of cost-efficient biomass distribution patterns.

BioSPHERE will finally be applied to the specific case of the wood resources-based bioenergy subsystem of Baden-Württemberg (Germany) in order to investigate the consequences of the change in remunerations via a sensibility analysis. To this end, this parameter will be progressively reduced from a certain level of profitability to a point where no bioenergy is produced. This way, the effect of the profitability constraints on this subsystem is to be observed for different values of remunerations.

2. Methodology

Deducting remunerations within an objective function by means of the endogenous approach induces a profit maximization that alters the intended costs minimization assessment. Besides, it is a fact that costs incurred throughout any utilization pathway might end up becoming higher than the remunerations themselves. But despite the lack of profitability, the pathway in question could be selected by the model and thus the corresponding power plant definitely installed and operated. In order to overcome this issue, the profitability of all possible utilization pathways has to be preserved even if profit does not really have to be maximized so as to focus on the goal of minimizing expenses. This way, a novel procedure is introduced to model any type of remunerations in energy systems optimization by introducing a profitability constraint for each utilization pathway. The aim of such restrictions is to set an upper limit for the total expenses incurred throughout the production chain of any of these energy generation pathways.

An important aspect in relation to exogenously modelling remunerations is the identification of an array of potential observers at each particular interface. Each of these preselected observers is allocated a specific set with all utilization pathways consisting of a power station coupled to all its possible supply chains. From all these feasible combinations, a profitable utilization pathway will finally be selected with the aid of an optimization procedure. On this basis, plant operators or investors are chosen as the necessary observers to separately assess this collection of possible pathways. These actors are assigned all remunerations and expenses arising in the corresponding power plant and its supply chain. Therefore, the ceiling on production costs will be just the level of the remunerations awarded by the network provider to the referenced observers. All this lays the foundation for microeconomically assuring the profitability not of the entire energy system but of each utilization pathway from the viewpoint of the respective plant operator or investor concerned. In order to gain insight into this methodology, the next section addresses the implication of compliance with the profitability requirement.

2.1. The fulfilment of the profitability requirement

In general, observing the profitability requirement for any kind of energy resource is correlated to the possibility of properly adjusting profits and/or reducing production costs. In this regard, when investors have to make a decision about the installation of a power plant, they are faced with the prerequisite to meet the principle of profitability. This rule dictates that the net present value of a utilization pathway be greater than or equal to zero so as to perform profitable investments at a microeconomic level. This principle can be translated into the following statement, according to which remunerations have to at least cover the total expenditures arising throughout any utilization pathway. Compliance with this condition equally aims to prevent profitable utilization pathways from compensating for other unprofitable ones by setting an upper limit to the expenditures of every observer.

The resulting inequation is in general easily satisfied for utilization pathways based on conventional energy sources such as fossil and nuclear. The same applies to most renewables such as hydro, photovoltaic, wind and geothermal energies. This is basically due to the cost reduction experienced by these renewable technologies over the last years. But it also relies on the greater political support received by them compared to that of some immature and hence expensive energy vectors such as solar thermal or ocean energies. In the case of fossil and nuclear energy, the fulfilment of the profitability requirement is linked to the relatively high energy density of the respective raw materials (primary energy carriers). This attribute facilitates their exploitation and subsequent transportation to the energy conversion units. For all aforementioned renewables, their basic energy resources, namely watercourse, radiation, wind, hot water, waves and tides, are free and then have no fuel costs assigned. Besides, there is also no need for this amount of primary energy to be either gathered or transported to the respective facility. The only expenses arising in such utilization pathways are those occurring in the conversion process itself at the prime mover. On the contrary, bioenergy represents a noteworthy exception to such renewable energies, when it comes to assessing the difficulty in meeting such a condition of profitability. This is because biomass as a raw material – irrespective of the type (forest residues, liquid manure, energy crops, etc.) – has to be collected and subsequently transported. And that generates a significant amount of expenditures that may put bioenergy pathways' profitability at risk. So as to deal with this issue, the exogenous approach to the modelling of remunerations is applied below to the problematic case of bioenergy generation.

2.2. Methodological development for a bioenergy subsystem

The proposed exogenous approach is integrated into an existing optimization model called PERSEUS (Program Package for Emission Reduction Strategies in Energy Use and Supply) that has been successfully used for the analysis of energy systems. This energy and material flow model was created in the nineties at the Institute of Industrial Production (IIP) of the

Karlsruhe Institute of Technology (KIT) on the basis of the EFOM[4] model. PERSEUS minimizes an objective function that includes the sum of the discounted costs of the target system over a given space of time. To this end, an array of auxiliary conditions must be satisfied, namely those assuring the energy and material flow balance as well as a number of constraints on capacity and process utilization.

Building on this structure, an add-on module is created as a complement to the prior energy system model. This component aims at techno-economically reproducing an elementary bioenergy subsystem where profitability has to be assured for any utilization pathway. The outcome is BioSPHERE[5] (Bioenergy Subsystem Software for Production Pathways at High Energy and Resource Efficiency), a software extension based on a multi-period mixed integer linear programming (MILP) approach. This add-on gives the base model of the whole energy system additional capabilities by introducing further auxiliary conditions. These relate to the fulfilment of the principle of profitability for discrete energy utilization pathways in the form of profitability constraints. In addition, four sets of auxiliary equations underpin the total array of such restrictions. This way, the value chains of any type of biomass for conversion into bioenergy can be integrated into the whole energy system under conditions of profitability.

The value chain of any biomass resource may encompass a multiplicity of utilization pathways consisting of a series of four consecutive stages – harvesting, densification, transport and conversion. Every utilization pathway can be described through a combination of at least four technological processes that are arranged into four succeeding sectors. These processes are assigned a capacity and located within a certain spatial unit or region for a specific timeframe. As a result, a bioenergy subsystem can be built on the basis of four technology sectors (harvesting H, densification D, transport T and conversion C) extending over a number n of spatial units or regional subdivisions $reg \in REG$ (see Figure 3). Any bio-based subsystem can then be represented by means of a directed graph, which is composed of four columns and n rows resulting in an array of $4n$ nodes linked to each other by energy flows as shown in Figure 3. These nodes include a number of technological processes for each specific sector in a given spatial unit. In virtue of this structure, all bio-based utilization

[4] 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).

[5] Not to be confused with **BIOSPHERE** (Bioenergy Optimization Software for Production Pathways at High Energy and Resource Efficiency), which is conceived as an optimization model of a bioenergy subsystem in (Parrilla-Martínez 2019). By contrast, **BioSPHERE** (Bioenergy Subsystem Software for Production Pathways at High Energy and Resource Efficiency) does not optimize but models any bioenergy subsystem making for a fraction of a bigger energy system. It serves as an add-on module that can be coupled to any previously existing optimization model of an entire energy system.

pathways can be assessed for every period of time $t \in PER$ under the premise that they compete with each other and the non-biogenic paths of the whole energy system.

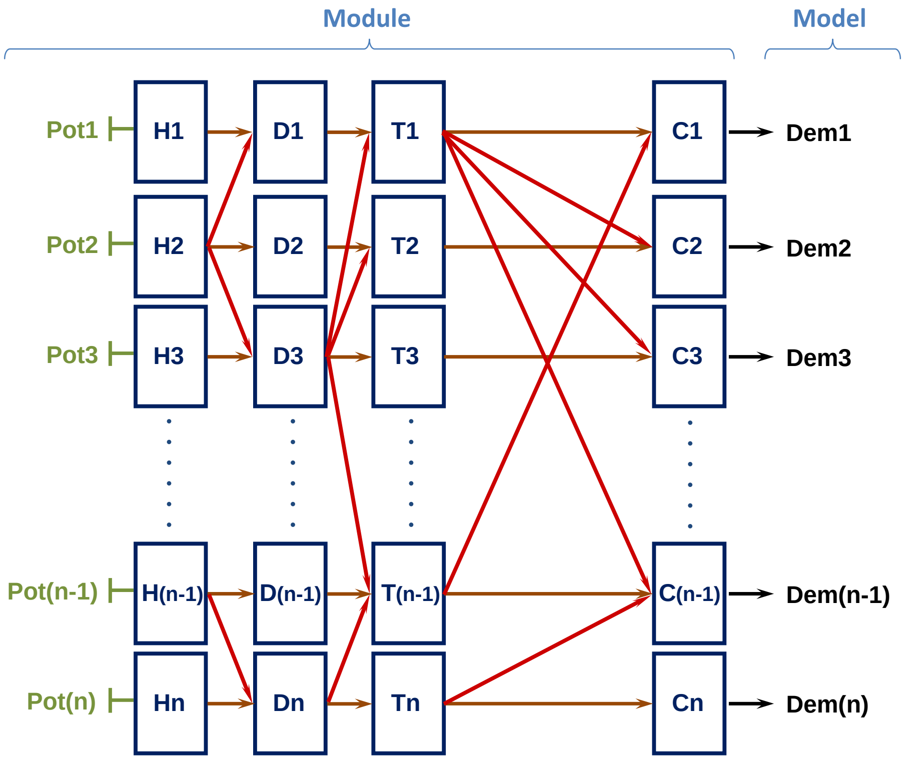

Figure 3: Structure of the add-on module BioSPHERE as a grid of nodes connected by energy flows for a bioenergy subsystem composed of four technological sectors and n spatial units

In the same vein as the technological processes, both the potential *Pot* of biomass and the energy demand *Dem* of the total energy system are spatially and temporally differentiated over the entire territory. On the one hand, the potentials of biomass are freely consumed within the bioenergy subsystem described by the add-on module. On the other hand, the energy demand – the model's driving force – has to be met for all energy carriers by covering the full energy consumption of each spatial unit. In this manner, a microeconomically profitable technology solution for the bioenergy subsystem is ensured via the introduction of profitability constraints. As the total costs of the whole energy system are minimized, macroeconomically cost-efficient biomass distribution patterns can be identified. The biogenic resource or raw material is thus apportioned among a group of biomass sinks – the power plants. These bio-based facilities are located across the total area under consideration according to a specific spatial arrangement that constitutes a bioenergy configuration.

The construction of such an add-on module based on sectors is principally the aspect that adds complexity to the issue of considering profitability constraints for every utilization pathway. This is opposed to the case of energy system models containing a single sector (conversion), as referred to in (Huber et al. 2007) and a series of studies cited by (Möst et al. 2010) in the literature review (see 1.2). The existence of more than one sector renders it more complicated to model energy flows across these consecutive blocks of data structures. Such a difficulty is basically due to the possible convergences and bifurcations of energy and material flows that can arise in certain interfaces from one sector to another. This must be carefully modelled, concretely by introducing a set of appropriate variables (see 2.2.1).

A major issue that is provided by BioSPHERE concerns assigning spatial dimension to each bio-based utilization pathway. This module reproduces a series of interconnected technological processes for a broad spectrum of capacities at a given period of time. Including the spatial dimension derives from properly linking each node with another node from the subsequent technology sector within the same or other spatial unit by means of suitable flow levels *FL* (arrows in Figure 3). In this vein, transport processes from different spatial units are allocated a certain amount of transport costs as a function of the distance among the corresponding regions. This creates the necessary effect of spatial dimension in the sense that the higher the transport costs, the longer the distances between the harvesting and densification processes and those located in the conversion sector.

Lastly, BioSPHERE can be used for investigating the impact of the change in remunerations on each individual utilization pathway within a bioenergy subsystem. This unavoidably involves analyzing the subsystem from the standpoint of plant operators and/or interested investors, who act as differentiated observers. To this end, a possible procedure is the progressive lowering of remunerations from a certain level of profitability, downwards throughout the values of a series of breakeven points, to a stage where bioenergy stops being produced. In this respect, the implementation of remunerations above such breakeven points is tantamount to removing the effect of the profitability constraints and hence even the restrictions themselves.

2.2.1. Mathematical description

As previously stated, the new restriction is based on the fulfilment of the principle of profitability for any utilization pathway when analyzed from the viewpoint of the respective observer. According to this, the expenditures incurred within the utilization pathway of a bioenergy facility $p \in C$ must not exceed the remunerations R received during its economic lifetime. To this effect, Equation 1 mathematically expresses the significance of fulfilling such a condition of profitability. The terms within both sides of this inequation are discounted to the base year and summed from the commissioning or investment year until the end of its economic life. The left-hand member is made up of four summands. The first three addends relate to the variable and fixed operation and maintenance expenses together with the investment costs of the conversion process involved. A fourth additional term accounts for the expenditures caused by the energy and material contributions of the upstream processes $i \in H$, D, T (supply chain) to the bio-based conversion process $p \in C$. Determining the cost components entailed by each of these contributions is of great importance to evaluate the total expenditures of the supply chain of $p \in C$ and thus the profitability of its utilization pathway.

Table 1: Meaning of indices, sets of indices, parameters and variables

Indices	*ec*	Energy carrier
	i, j, k	Upstream processes within the supply chain of a bioenergy generation process *p*
	n	Number of spatial units (regional subdivisions)
	p	Bioenergy generation process
	prod	Node of a bioenergy subsystem
	reg	Regional subdivision (spatial unit)
	t	Period of years
	u	Bioenergy generation unit (power plant)
Sets of indices	*BIOPROD*	Set of nodes within the bioenergy subsystem
	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* that 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* that 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
	H	Set of upstream processes within the harvesting sector
	H_p	Set of upstream processes *i* within the harvesting sector *H* that are sources of energy and material contributions $PL_{i,p}$ to a bioenergy process *p* of the conversion sector *C*
	$INVPER_u$	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 the node *prod* and convert the energy carrier *ec* into another
	$P'_{prod,ec}$	Set of processes that are contained in the node *prod* and generate the energy carrier *ec*
	REG	Set of spatial units or regional subdivisions
	PER	Set of periods of time
	SUPPROC	Set of upstream processes within the supply chain of bioenergy processes
	$SUPPROC_p$	Set of upstream processes within the supply chain of a bioenergy 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*
Parameters	α	Discount factor
	η	Efficiency of a process
	Capacity	Block size of a bioenergy generation unit *u* (MW)
	C_{fix}	Specific fixed operation and maintenance costs (€/kW)
	C_{inv}	Specific investment costs (€/kW)
	C_{var}	Specific variable operation and maintenance costs of a process (€/kWh)
	Dem	Energy demand of a spatial unit (PJ)
	Pot	Potential of biogenic resources for each spatial unit (t)
	R	Specific remuneration granted to the generation of bioenergy (€/kWh)
Variables	φ	Virtual flow (PJ)
	Cap	Capacity of a unit *u* (MW)
	Com	Number of units commissioned in each period of time *t*
	FL	Activity level of energy flows between nodes / Flow level (PJ)
	PL	Activity level of a process / Process level (PJ)
	$PL_{i,p}$	Energy and material contributions of upstream processes *i* from the *H*, *D* and *T* sectors to a bioenergy process *p*

$$\sum_t \alpha_t \cdot \begin{pmatrix} PL_{p,t} \cdot Cvar_{p,t} + \\ \left(Com_{u_p,t} \cdot Capacity_{u_p,t}\right) \cdot Cinv_{u_p,t} \\ Cap_{u_p,t} \cdot Cfix_{u_p,t} + \\ \sum_{i \in H,D,T} PL_{i,p,t} \cdot Cvar_{i,p,t} \end{pmatrix} \leq \sum_t \alpha_t \cdot PL_{p,t} \cdot R_{p,t} \qquad (1)$$

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

Besides the process level $PL_{p,t}$ of bioenergy generation, the integer number of bio-based units commissioned $Com_{u,t}$ and the corresponding capacity $Cap_{u,t}$, a further decision variable $PL_{i,p,t}$ is introduced. It determines the energy and material contributions of each upstream process $i \in H, D, T$ to a given conversion process $p \in C$. These contributions can consist exclusively of a single flow or, on the contrary, emerge as a bundle of streams with the same origin (an upstream process i) and the same end, a process p (see Figure 4). They are likewise different depending on which sector they originate from. In the example of Figure 4 for two utilization pathways (green/red), the energy and material contributions emerging from the sector H are four. Nevertheless, sector D includes five contributions and sector T only three, which are not depicted.

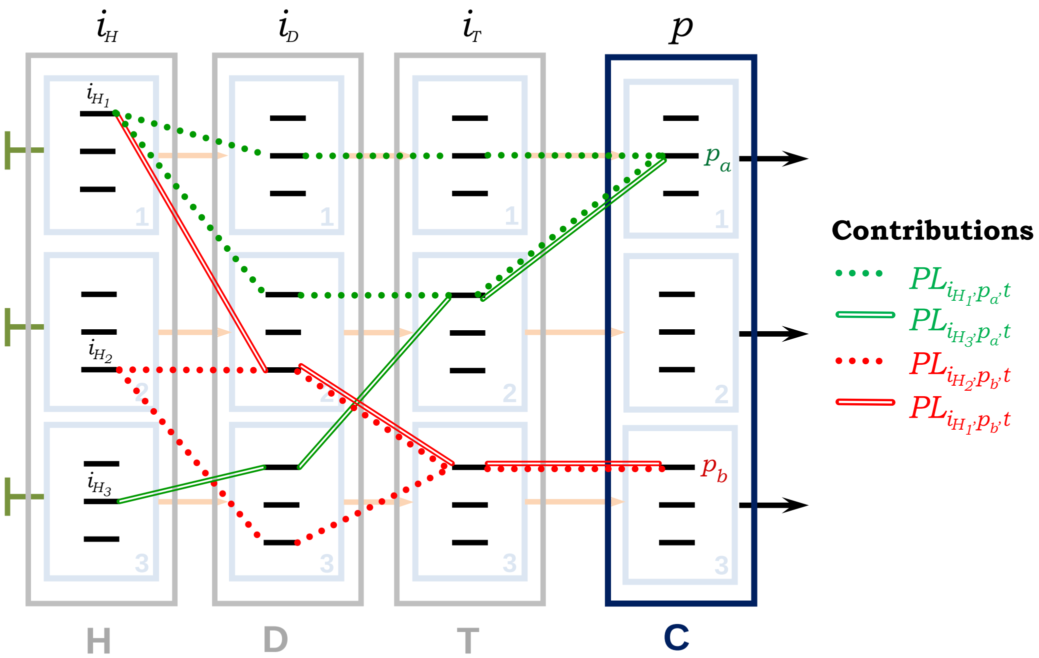

Figure 4: Breakdown of two utilization pathways (green/red) into four energy and material contributions of three processes from the sector H to two conversion processes p

However, integrating the profitability constraint of Equation 1 in the source code of BioSPHERE necessarily requires the implementation of an array of new auxiliary equations. This is due to the prior introduction of the aforementioned contributions as a further group of variables into the equation system of the problem to be solved. The auxiliary equations should link the decision variable $PL_{i,p,t}$ with themselves and both the process levels PL and (indirectly) the flow levels FL. Such sets of equations fundamentally originate from three inherent aspects relating to the bio-based subsystem and its modelling:

- the hierarchical data structure with the sector as its highest aggregation level,
- the layout of the energy and material flows between and within nodes and
- the efficiencies of the processes involved in each of the sectors.

In line with this, Equation 2 indicates that the activity level $PL_{i,t}$ of each upstream process from the *H*, *D* and *T* sectors can be broken down into the sum of all its energy and material contributions $PL_{i,p,t}$ to all the bioenergy generating processes *p*.

$$PL_{i,t} = \sum_{p} PL_{i,p,t} \quad (2)$$

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

Secondly, a triad of equations concerning the structure of the bioenergy subsystem and the correlation of process efficiencies between consecutive sectors is presented. The main idea underlying these equations is to balance energy and material flows between pairs of successive sectors such as *H-D*, *D-T* and *T-C*. Each equation shows an interdependence between the sum of all contributions $PL_{i,p}$ from upstream processes *i* of a sector to a conversion process *p* and that of total contributions resulting from upstream processes *i* of the subsequent sector to the same conversion process. To adjust both sides of the equation, each addend of the latter sum is divided by the corresponding process efficiency. Regarding the conversion sector *C*, no contributions to further sectors are defined for the processes *p*, as they simply serve as sinks of upstream processes within the supply chain. Accordingly, the lack of such contributions is made up for by the process level PL_p itself so as to complete the equation involving the pair *T-C*. Equations 3-5 display the second set of three auxiliary equations that support the integration of profitability constraints.

$$\sum_{i_H} PL_{i_H,p,t} = \sum_{i_D} \frac{PL_{i_D,p,t}}{\eta_{i_D,t}} \quad (3)$$

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

$$\sum_{i_D} PL_{i_D,p,t} = \sum_{i_T} \frac{PL_{i_T,p,t}}{\eta_{i_T,t}} \quad (4)$$

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

$$\sum_{i_T} PL_{i_T,p,t} = \frac{PL_{p,t}}{\eta_{p,t}} \quad (5)$$

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

On the other hand, linking the contributions $PL_{i,p,t}$ with the flow levels FL can be attained indirectly through a set of auxiliary variables called virtual flows φ. They stand for the smallest indivisible energy and material flows that sequentially connect four consecutive processes of the H, D, T and C sectors within a utilization pathway. They therefore constitute a basis of elements upon which any configuration of energy flows (energy configuration) can be built for any bio-based subsystem. As the smallest indivisible flow units, they indicate:

- the activity level (energy and material volume),
- the spatial arrangement of the processes (actors) along the utilization pathway and
- the breakdown of the real energy flows into their essential components or fractions.

On balance, such virtual flows determine exactly how much energy flows, from where to where and through which of the potential actors. Thus, insight can be gained into any feasible utilization pathway. In this case, who harvests and densifies the raw material, subsequently transports the resulting product and then converts it into bioenergy. But based on such features, virtual flows might also be of vital importance, beyond bio-based systems, even in the management of intelligent networks. In order to emphasize the relevance of these variables, Figure 5 graphically illustrates the disaggregation of the contributions $PL_{i,p}$ into their respective virtual flows φ by leveraging the example of Figure 4.

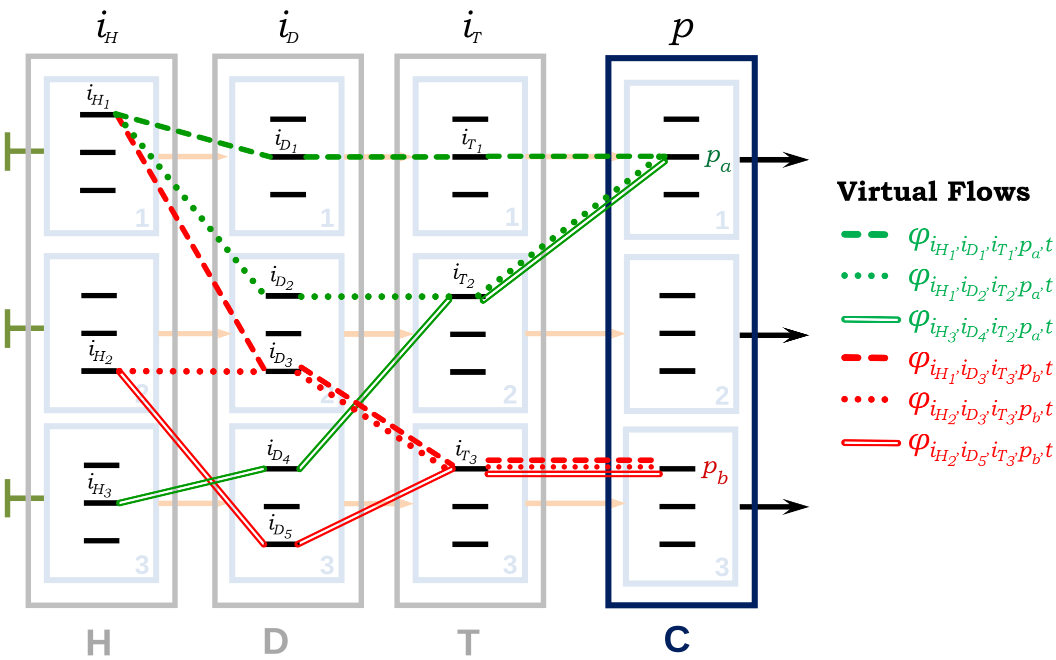

Figure 5: Disaggregation of four energy and material contributions of three processes from the sector H to two conversion processes into their corresponding virtual flows

Building on this, the activity level of any energy and material stream such as the process levels PL, the flow levels FL or the contributions $PL_{i,p}$ can be described by means of a linear combination of the pertinent virtual flows. In this manner, the breakdown of the contributions $PL_{i,p}$ from the H, D and T sectors into an array of suitable virtual flows $\varphi_{i,j,k,p}$ renders the third block of auxiliary equations (Equations 6-8). This is achieved by appropriately multiplying such virtual flows by the efficiencies of certain processes from both *D* and *T* sectors. 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 and material registered by the processes in the sector *H*.

$$PL_{i_H,p,t} = \sum_{i_D}\sum_{i_T}\varphi_{i_H,i_D,i_T,p,t} \tag{6}$$

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

$$PL_{i_D,p,t} = \sum_{i_H}\sum_{i_T}\varphi_{i_H,i_D,i_T,p,t}\cdot\eta_{i_D,t} \tag{7}$$

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

$$PL_{i_T,p,t} = \sum_{i_H}\sum_{i_D}\varphi_{i_H,i_D,i_T,p,t}\cdot\eta_{i_D,t}\cdot\eta_{i_T,t} \tag{8}$$

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

As previously stated, the flow levels *FL* between nodes can be indirectly expressed as a function of the contributions $PL_{i,p,t}$. A method of establishing this kind of relationship is the use of the virtual flows $\varphi_{i,j,k,p}$. They allow creating the fourth set of auxiliary equations showed in Equations 9-11. Thus, each flow level *FL* connecting 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 as a linear combination of the virtual flows identified above. Similarly to the previous block of equations, the multiplying factors in each term of the right-hand sides are the efficiencies η of a number of processes involved in both sectors *D* and *T*.

$$FL_{H_{reg}D_{reg'},ec,t} = \sum_{i_{H_{reg},ec}}\sum_{i_{D_{reg'},ec}}\sum_{i_T}\sum_{p}\varphi_{i_{H_{reg},ec},i_{D_{reg'},ec},i_T,p,t} \tag{9}$$

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

$$FL_{D_{reg}T_{reg'},ec,t} = \sum_{i_H}\sum_{i_{D_{reg},ec}}\sum_{i_{T_{reg'},ec}}\sum_{p}\varphi_{i_H,i_{D_{reg},ec},i_{T_{reg'},ec},p,t}\cdot\eta_{i_{D_{reg},ec},t} \tag{10}$$

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

$$FL_{T_{reg}C_{reg'},ec,t} = \sum_{i_H}\sum_{i_D}\sum_{i_{T_{reg},ec}}\sum_{p_{C_{reg'},ec}}\varphi_{i_H,i_D,i_{T_{reg},ec},p_{C_{reg'},ec},t}\cdot\eta_{i_D,t}\cdot\eta_{i_{T_{reg},ec},t} \tag{11}$$

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

3. Application to a case study

The aim of this section is to illustrate the implementation of the exogenous approach for a particular bioenergy subsystem. According to this technique, profitability will be guaranteed at the microeconomic level of any utilization pathway from the standpoint of plant operators and/or investors concerned. Such a methodology can be tested by means of an appropriate sensitivity analysis. This consists in progressively reducing remunerations from a certain level of profitability via a series of breakeven points through to the point where no bioenergy is generated. On this basis, the case of the forest residues-based bioenergy subsystem of Baden-Württemberg (Germany) is employed for proving this method. The issue of retrofitting the existing coal-fired power stations in the energy system of this federal state is selected. For such a technical enhancement, these power plants can be upgraded to co-firing forest residues at a 10% co-fire rate of the total primary energy input.

With a view to performing such a case study, the BioSPHERE add-on module is coupled to a cost minimization model that optimizes the entire energy system of Baden-Württemberg. This software extension permits assessing the impact of the variation in remunerations on the target bioenergy subsystem. By decreasing remunerations according to the above mentioned sensitivity analysis, new configurations of bio-based conversion units (bioenergy configurations) with ever lower breakeven points are identified. For each of them, the specific electricity production costs incurred by both the retrofitted coal-fired power plants and the bioenergy contributions of each spatial unit within the catchment areas are accordingly depicted in Figure 6.

The federal state of Baden-Württemberg is divided into 44 administrative units including 35 districts and 9 urban districts. Based on this fact, this kind of spatial unit is selected to model the spatial dimension of the targeted system. Regarding the temporal component, its modelling is accomplished for a single year because the spatial analysis is the real objective of the present study. In line with the foregoing, the free potentials of forest residues are also spatially distributed at district level all over the territory of the federal state. In each district, they are broken down into four specific fractions. These result from the four types of chipped forest residues arising when this resource is regarded as a by-product of timber production[6]. Specifically, these are the coniferous and the deciduous portion of forest residues harvested in woodlands that are managed by either small private or large forest owners (SPFO/LFO). Such four types of chipped forest residues present dissimilar total costs per unit mass FW[7] (see Table 2). This is due to the correspondingly diverse implementation of collection, moving and

[6] Forest residues are considered as a by-product of timber provided that costs originating from felling, extraction and debranching of trees are allocated to timber (main product). Under these conditions, forest residues are only assigned expenses incurred by moving and chipping after the split-off point at delimbing. By contrast, the term joint product is reserved for forest residues that share production costs with the other main product (timber) throughout the whole harvesting process (Parrilla-Martínez 2019).

[7] Fresh weight (35% moisture content)

chipping procedures according to differently mechanized logistic chains (Parrilla-Martínez 2019).

Table 2: Total unit costs per ton FW for the four types of chipped forest residues

Type of forest residues	**Total unit costs**
	€/t
coniferous SPFO	41.38
deciduous SPFO	26.12
coniferous LFO	37.59
deciduous LFO	23.72

These four fractions of forest residues are harvested, densified (chipped) and transported by two-container truck to the modernized power stations. With regard to the conversion phase, Table 3 introduces the list of coal-fired power plants that can be adapted to 10% co-firing of forest residues in Baden-Württemberg (BNA 2016). Twelve existing conversion units with locations in the districts of Esslingen, Heilbronn, Karlsruhe, Mannheim, Stuttgart and Ulm are taken into account. According to (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 hours per year at full load. As retrofitted coal-fired power stations can burn up to a 10% portion of forest residues, a slightly higher amount of 4,000 full load hours per year is assumed as a suitable value for modelling the co-firing technology.

As for the entire energy system, the EPC recorded for renewable and conventional energy sources in different locations of Germany are reported to vary from 4 to 15 €cent/kWh$_e$ (Kost et al. 2018). In this connection, the power gained from forest residues in co-firing-based power stations yearly operating for 4,000 full load hours will clearly incur production costs in this order of magnitude (Parrilla-Martínez 2019). Building on both propositions, an assumption is drawn exclusively for the present case study. This supposition states that the amount of bio-power generated by the retrofitted coal-fired power plants in Baden-Württemberg will be completely fed into the network of the respective regulation zone. Such a fact makes it possible to evaluate the effect of integrating profitability constraints on the basis of a progressive decrease in remunerations.

The proposed sensitivity analysis is performed by initiating the value of remunerations at a level above the breakeven points of a set of utilization pathways resulting from minimizing costs. Subsequently, this value is decreased beyond the EPC of such pathways until a successive series of lower and lower breakeven points are reached. Remunerations are thus conceived as the amount of incomes received by plant operators so that EPC can be at least covered with no, a small or even a large profit margin. In essence, the focus of this analysis will be on the formation of EPC for each utilization pathway and not on the benefit achieved by investors for each power facility.

Table 3: Coal-fired power stations eligible for co-firing-based retrofitting in Baden-Württemberg

Power plant	Location / District	Bio-based capacity	Electric efficiency
		MW	*%*
ALT HKW 1	Altbach / Esslingen	43.3	36.1
ALT HKW 2	Altbach / Esslingen	33.6	35.5
HLB 7	Heilbronn	77.8	37.5
RDK 7	Karlsruhe	50.5	36.5
RDK 8	Karlsruhe	84.2	37.6
Block 6	Mannheim	25.5	34.9
Block 8	Mannheim	43.5	36.1
Block 9	Mannheim	84.3	37.6
GAI DT 14	Gaisburg / Stuttgart	2.2	29.3
MÜN DT 12	Münster / Stuttgart	4.5	30.9
MÜN DT 15	Münster / Stuttgart	4.5	30.9
HKW Magirusstr.	Ulm	2	29.1

As the reduction in remunerations takes place, the amount of power gained from forest residues begins to gradually decrease. This occurs at the same rate as the increase in the proportion of consumption of the cheaper forest residues as against the expensive shares. As the free potentials of cheaper resources are smaller than those of the more expensive portions (Parrilla-Martínez 2019), the amount of forest residues consumed ends up shrinking significantly. Consequently, a decreasing number of coal power stations are gradually retrofitted into the co-firing mode. As a result, the remaining energy sources in the energy system of Baden-Württemberg start to progressively replace such a lessening in bio-power. In this context, the power obtained from chipped forest residues becomes increasingly cheaper and more affordable until a point where no more bioenergy is generated. The continued decline of remunerations for the utilization pathways permits gaining insight into a wide range of bioenergy configurations with different spatial arrangements and EPC.

The forest residues-based bioenergy subsystem is then subjected to the aforesaid sensitivity analysis. The corresponding variation of remunerations encompasses a number of consecutive values that range from prices above 6.7 €cent/kWh$_e$ downwards to 5.5 €cent/kWh$_e$ by varying by 0.1 €cent/kWh$_e$ from one to another (Parrilla-Martínez 2019). Thus, the subsystem evolves from different levels of profitability for remunerations higher, slightly above or as large as the breakeven points until a stage where no profitable utilization pathway is implemented. Such gradation entails passing from a phase where profitability constraints have no effect to another in which such restrictions with ever lower remunerations induce the successive generation of new spatial arrangements. From the previous collection of values, a set of four remunerations with the most significant techno-economic configurations are selected and examined below.

Based on the prior approach, an identical solution is provided for the target subsystem when remunerations are valued above or at 6.7 €cent/kWh$_e$. In this respect, Figure 6 illustrates for this value of remuneration *R* a composition of five coal-fired power plants to be retrofitted with a total capacity of 299.3 MW$_e$. These facilities include both RDK 7 and RDK 8 power stations in Karlsruhe, Block 8 in Mannheim, 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 capacity, respectively. Their specific EPC correspond to the initially arising breakeven points and are comprised between 6.07 €cent/kWh$_e$ and 6.66 €cent/kWh$_e$. These costs result from an appropriate wood resources distribution mechanism that shapes them slightly below the predefined remuneration. As an example of this, the most expensive types of chipped forest residues (see Table 2), both coniferous LFO and SPFO contributions originating largely from woodlands in the Black Forest, are allocated to the most efficient RDK 8 power plant. On the other hand, the focus of this case study (see Figure 6) is set on the catchment area of this retrofitted power station (colored unit) together with its district-specific electricity production costs (DSEPC). These expenditures account for the specific production costs of bio-power obtained from forest residues collected in a particular district of the catchment area. Each of these DSEPC is calculated on the basis of a number of bioenergy and biomass contributions, which in turn build upon certain virtual flows that link the corresponding spatial unit with the bio-based facility. Besides, the weighting of all these costs for the entire catchment area according to the bioenergy contributions of each district to the conversion unit results in its EPC. All this information on that catchment area allows illustrating its spatial evolution and cost variation as a function of the progressive decrease of remunerations *R*. Moreover, the whole free potential of forest residues in Baden-Württemberg, which is estimated at roughly 950,000 tons FW, is completely converted into bio-power without leaving any unconsumed fraction. The total production costs incurred by the energy value chain of forest residues for the total power output of 299.3 MW$_e$ add up to an annual quantity of around €77.133 million.

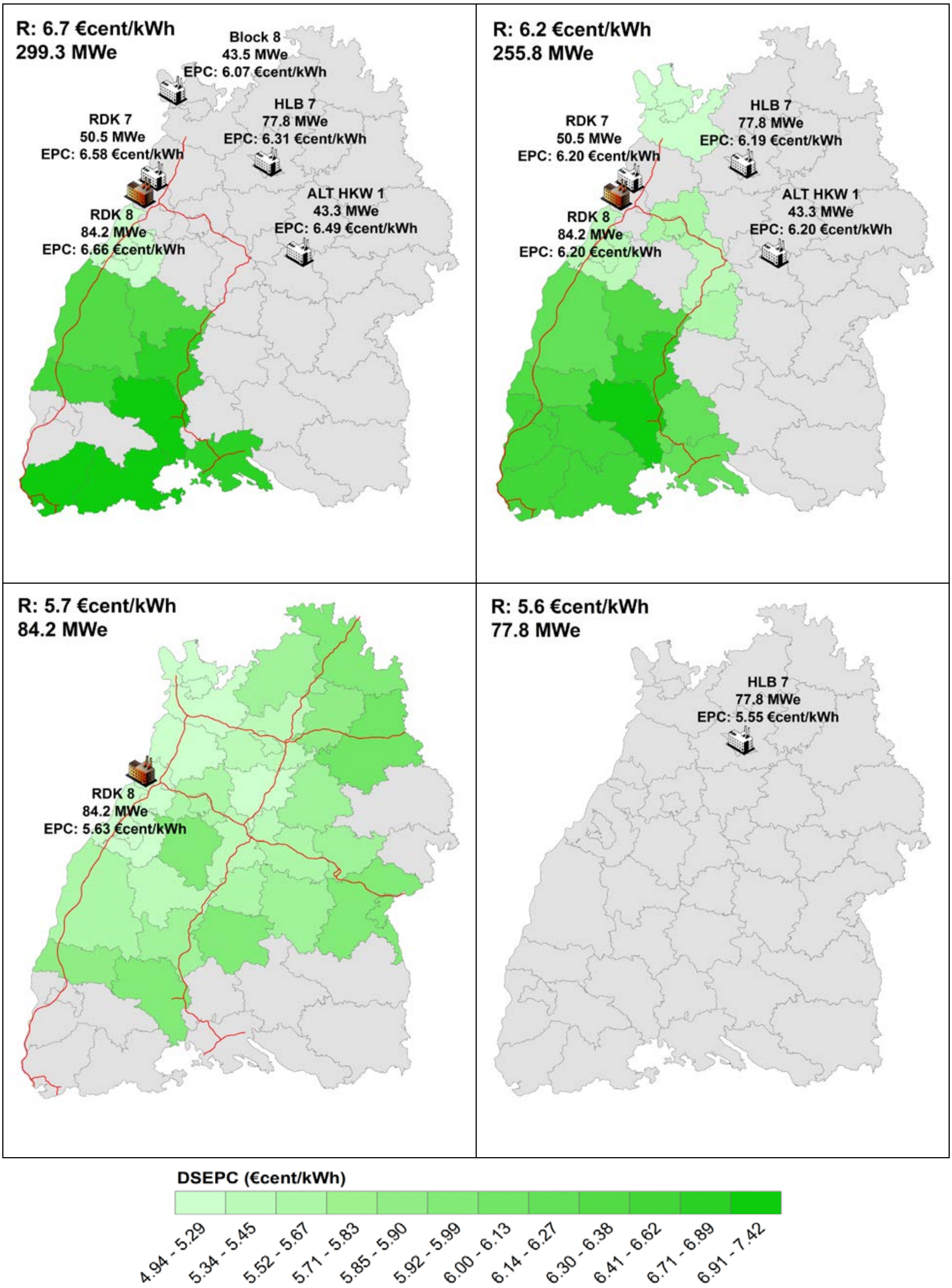

Figure 6: Location and EPC of retrofitted coal-fired power stations together with catchment area illustrating DSEPC for the RDK 8 co-firing facility as a function of the remuneration R (5.6, 5.7, 6.2 and 6.7 €cent/kWh$_e$)

When remunerations fall to 6.2 €cent/kWh$_e$, the optimization model provides a further solution for the forest residues-based bioenergy subsystem of Baden-Württemberg. The new pattern exhibits a lower magnitude (255.8 MW$_e$) for the total bio-based power capacity. Both RDK 7 and RDK 8 power stations in Karlsruhe as well as HLB 7 in Heilbronn and ALT HKW 1 in Altbach (Esslingen) rank amongst the four coal power plants to be adapted to co-firing. The corresponding specific EPC are nearly the same for each upgraded unit; only HLB 7 presents slightly lower EPC of 6.19 €cent/kWh$_e$ just below the remuneration. Concerning the catchment area of RDK 8, it expands its domain by apportioning inexpensive forest residues growing far from Karlsruhe to this conversion unit. The DSEPC in the districts of the RDK 8's catchment area become progressively lower because ever cheaper portions of deciduous SPFO and LFO chipped forest residues are allocated to this facility. Particularly, the corridors of highways 5, 8 and 81 along with certain other major roads pass through those districts supplying such economical contributions. Consequently, substantial amounts of free potentials comprising both expensive shares of coniferous SPFO/LFO chipped forest residues are not assigned to any power station. As a result, the consumed fraction of the total free potentials of forest residues accounts for approximately 80%. In a similar proportion, the yearly amount of total production costs originating in the forest residues-based bioenergy subsystem drop to around €63.419 million.

As shown in Figure 6, a further techno-economic outcome arises when remunerations are reduced to 5.7 €cent/kWh$_e$. The previous bioenergy configuration changes in such a way that only the RDK 8 facility is retrofitted into the co-firing mode. This power plant presents specific EPC with a value somewhat below the level defined by the payments. The RDK 8's catchment area encompasses a vast geographic zone covering most of the federal state. The corresponding DSEPC become cheaper and range from 4.94 to 5.83 €cent/kWh$_e$ due to the valorization of significant volumes of deciduous forest residues. Similarly to the prior case, highways 5, 6, 8 and 81 permit the channeling of wood resources from the districts in the peripheral areas to RDK 8. A marked decline in the consumed portion of total forest residues takes place with its percentage decreasing to roughly 27%. This quantity of biomass is ultimately correlated to the annual amount of total production costs, which reach the value of €18.949 million.

As a consequence of the progressive decrease in remunerations, an important amount of comparatively expensive wood resources is not collected any longer. Both coniferous SPFO and LFO forest residues are the first resources that begin not to be consumed. But when the restriction imposed by the profitability constraints intensifies, the costliest fraction of deciduous forest residues – that harvested by SPFO – also starts not to be allocated to any power station. And the same goes for the cheapest portion based on deciduous LFO chipped forest wood raw material, the last resource that is gradually gathered less and less. This way, an increasing number of districts do not supply forest residues as remunerations are progressively cut down. The trend is that expensive wood resources are consumed in the central parts of the catchment areas, while they are left unconsumed in the outlying districts of such zones. This is attributable to the fact that harvesting expensive forest residues in woodlands far away from the power plant is inevitably linked to increased transport costs that in turn raise the EPC. These potentials are then excluded from being consumed for failing to comply with the corresponding profitability constraint.

A new bioenergy configuration with the smallest size is generated when remunerations are set at 5.6 €cent/kWh_e. A single conversion unit is selected under such conditions, namely the 77.8 MW_e HLB 7 power station in Heilbronn with specific EPC of 5.55 €cent/kWh_e (see Figure 6). In this context, only a small share of the free potentials of forest residues, namely 24%, is converted into power. The implementation of a sole utilization pathway as a combination of HLB 7 and its supply chain incurs total production costs in the order of €17.284 million per year. Finally, reducing the remuneration to 5.5 €cent/kWh_e brings the forest residues-based bioenergy subsystem to a state in which wood resources are neither harvested nor densified nor transported nor converted into bio-power.

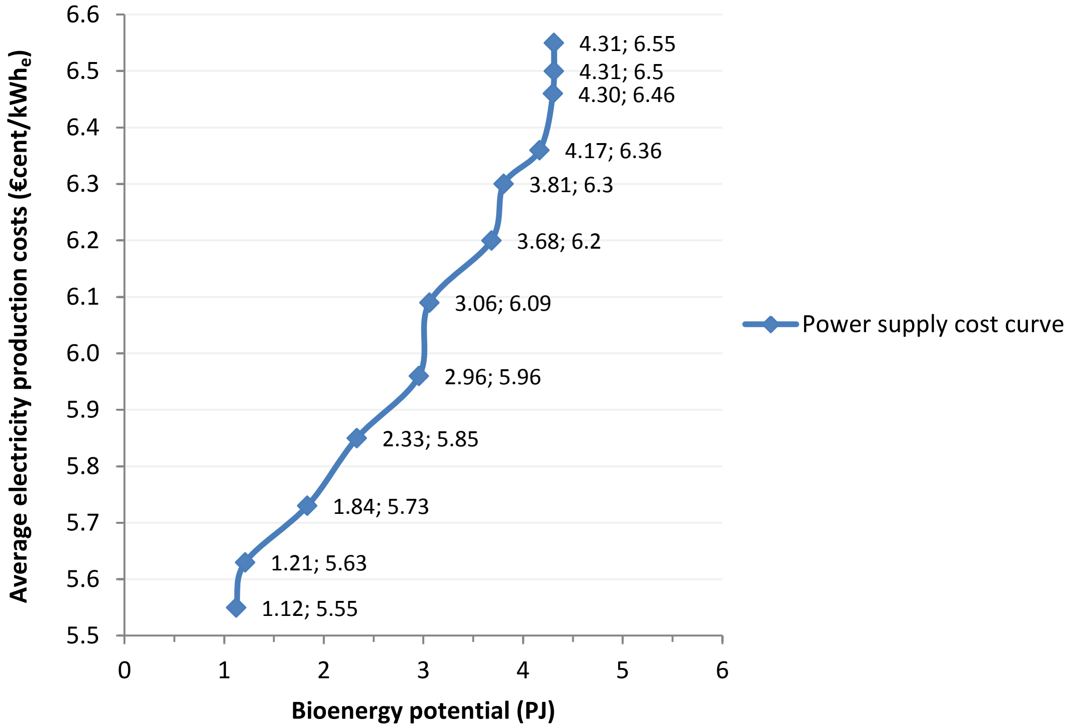

Figure 7: Power supply cost curve showing the dependence of the specific electricity production costs of a series of profitable bioenergy configurations on the amount of bio-power generated by co-firing of forest residues in a number of retrofitted coal-fired power stations in Baden-Württemberg

Thereby, on the basis of the previous sensitivity analysis, successively lower levels of EPC are reproduced by properly acting on the pertinent profitability constraints. For each techno-economic configuration, the weighted average of the specific EPC[8] entailed by the retrofitted power stations is identified as the specific electricity production costs of such a spatial arrangement. These expenditures can be correlated with the corresponding bio-power potentials so as to construct the power supply cost curve of the referenced forest residues-

[8] The values of EPC for the complete series of bioenergy configurations are taken from (Parrilla-Martínez 2019).

based bioenergy subsystem for the co-firing technology (see Figure 7). The aim of this curve is to illustrate the electricity production costs at which a succession of different spatial dispositions of bio-based facilities provide network operators with certain bioenergy potentials under conditions of profitability.

This cost-potential correlation for co-firing will be able to be integrated later into any optimization analysis of the energy system of Baden-Württemberg, when conventionally performed from a macroeconomic perspective (single observer). This kind of assessment will not require any co-firing-based utilization pathway to be subjected to a profitability constraint. The reason for this is that every bioenergy path derived from the power supply cost curve in Figure 7 would have already been proven to be profitable. Therefore, the use of such restrictions would be unnecessary in that case.

For the sake of completeness, any technology transforming forest residues into bioenergy should indeed be characterized by its respective power supply cost curve. These would be achieved as already reported by carrying out a sensitivity analysis of the exogenously modelled remunerations – i.e. by varying such a parameter in the profitability constraints. An alternative to all this would be to analyze the energy system including such technologies from the microeconomic standpoint of plant operators and/or investors (several observers) via profitability constraints. This would be the only way to guarantee utilization pathways' profitability in contrast to the macroeconomic approach.

4. Conclusions

It is a fact that the utilization pathways of some energy sources may become unprofitable when electricity production costs eventually exceed remunerations. But such a possibility is generally not easy to detect in the framework of the optimization of energy systems. In other cases, although profitability is not at stake, the prices of energy commodities may require being limited on account of economic or political motives. The solution to avoid this lack of profitability or, at best, to maintain or even enhance profits is therefore to resort to an exogenous approach to the modelling of remunerations. This methodology is based on the integration of profitability constraints for any possible utilization pathway. Such a constraint constitutes a restriction on the costs incurred throughout the production chain of each of these pathways. The corresponding ceiling on production costs is just the level of the remunerations granted to the plant operator or investor concerned. The aim of these constraints is to ensure profitable investments from the viewpoint of such specific actors at the microeconomic level of each utilization pathway. By contrast, usual optimization analyses of energy systems considered as a whole from the macroeconomic perspective of a single observer and thus without applying such restrictions may pose problems with the fulfilment of the profitability requirement.

The modelling of any energy system builds upon a number of consecutively connected sectors that comprise energy and material flows. Such a construction based on sectors (data blocks) is the aspect that adds complexity to the issue of introducing profitability constraints for every valid observer. This integration turns out to be an easy task in the case of energy systems involving a single sector (e.g. conversion). But the existence of more than one sector makes it difficult to model such energy and material streams across several successive data blocks. This difficulty is basically due to the potential convergences and bifurcations of energy/material flows, which may be formed within some interfaces, between sectors. This question has to be appropriately modelled, namely by introducing an array of specific variables: the energy and material contributions to a conversion process and the virtual flows. The former are a set of decision variables and represent the amount of energy and material provided by an upstream process within a supply chain to the corresponding facility. Such contributions can be made up of only one stream or even arise as a bundle of flows with the same origin and end in an upstream process and the pertinent conversion process, respectively. These variables permit determining the diverse cost components of a supply chain and thus, along with the conversion expenses, finally evaluating the profitability of its utilization pathway.

The latter variables have a less apparent origin and therefore a less obvious explanation also. This relays on the fact that the integration of a profitability constraint in the source code of an energy system model or its add-on module inevitably requires an additional array of auxiliary equations in order to solve the mathematical problem. These aim, among other things, at linking the decision variables of the energy and material contributions with the flow levels arranged between nodes. A technique based on a set of auxiliary variables called virtual flows can be implemented so as to indirectly create this relationship. The activity level of any energy and material stream such as the flow levels, the process levels or the contributions can then be expressed through a linear combination of the pertinent virtual flows. These auxiliary variables account for the smallest indivisible energy and material flows that sequentially connect a number of consecutive processes of successive sectors within a utilization pathway. They form a basis of elements with which to construct any possible configuration of energy flows (energy configuration) within an energy system. Their magnitude is the same throughout the complete series of the succeeding sectors. Concretely, the virtual flows show an activity level that is defined by the energy and material volume of those processes included in the sectors receiving the input of primary energy and/or raw material. And as the smallest flow units, they additionally specify the spatial arrangement of the processes involved across a utilization pathway as well as the disaggregation of the real energy flows into their essential components. In short, such variables indicate precisely what amount of energy actually flows, from where to where and through which agents. Virtual flows can also be applied to the modelling of any type of energy system. But they could be of great significance in controlling the cost formation processes in complex energy systems such as smart grids.

The usefulness of both variables is implicit in certain magnitudes characterizing any energy system model comprising more than one sector. An example is the district-specific electricity production costs analyzed in the case study of this work. These expenses represent the specific production costs of power generated in the conversion sector from primary energy or raw material that is available in a specific spatial unit (district) and processed within some upstream sectors. Such expenditures are assessed by determining their cost components on the basis of the relevant energy and material contributions and the pertinent virtual flows. The former variables connect any contributing upstream process with the power plant in question, whereas the latter link the energy and material sources with this generation station. The district-specific electricity production costs can also be weighted for any facility's catchment area. This however has to be carried out in proportion to the energy and material contributions flowing from each spatial unit to the conversion station. The weighting will finally yield the specific electricity production costs of the facility under consideration. With the assistance of both variables, all costs incurred along every utilization pathway can be calculated and subsequently integrated in its respective profitability constraint. This way, those pathways associated with elevated production costs will be excluded for not complying with the condition of profitability.

Lastly, the exogenous methodology can be used for the construction of energy and/or material supply cost curves by performing suitable sensitivity analyses for the value of remunerations. These charts have the capability to techno-economically describe, for any technology, the whole spectrum of aggregation from a single utilization pathway to the entire energy system. Such curves indicate the material and/or energy production costs incurred by a series of different techno-economic configurations in an energy system, when some downstream agents are correspondingly provided with certain profitable potentials of material or energy. These cost-potential correlations can later be integrated into any macroeconomic analysis of the same energy system on the basis of a sole observer. This approach will be possible without incurring the risk that unprofitable utilization pathways might be implemented. In any event, considering the energy system from the microeconomic viewpoint of diverse interested observers via profitability constraints would equally produce the same result under conditions of profitability.

5. Summary

Renewable energy volumes and prices regulated by electricity promotion instruments can be exogenously modelled by means of specific constraints. The resulting volume in price-based schemes (FIT and FIP) as well as the target volume (quotas/capacities) in quantity-based support instruments (TGC and tenders) can solely be reproduced through a restriction on volume. The exogenous modelling of electricity promotion prices can be implemented easily via simple restrictions on costs for those energy systems only involving one sector (e.g. conversion). If the targeted energy system is made up of several consecutive sectors, a more complex restriction must be developed. On the contrary, only prices or remunerations can be modelled endogenously, namely by subtracting them as negative costs from the total expenses within the objective function of the optimization model. Nevertheless, this practice induces an undesirable effect that alters the original purpose of the analysis and thus causes an important mistake.

The endogenous approach suggested for describing remunerations as negative costs leads at best to an unintentional profit maximization that modifies the usually envisioned cost minimization problem. But the endogenous modelling of payments may also allow for unprofitable utilization pathways that might be compensated for by other profitable ones. This would eventually result in the former pathways remaining undetected. Consequently, this method cannot be considered as a suitable procedure for reducing expenditures in the framework of a cost minimization analysis. By and large, an objective function expressed as the total system costs plus certain remunerations implemented as negative costs will yield two different outcomes. These are either a flawed objective function – when the approach is only applied to the share of renewables – or the profit maximization for the total energy system if the profitability of all utilization pathways is assured. If some utilization pathways are not profitable, the negative costs technique could not be employed.

In order to preserve utilization pathways' profitability and thus eliminate the above irregularities, this endogenous technique can be replaced with an exogenous methodology. Such an approach resorts to profitability constraints as a restriction based on the fulfilment of the principle of profitability. According to it, the net present value of each utilization pathway has to be greater than or equal to zero so as to achieve profitable investments. This equates to stating that remunerations have to at least cover the total expenditures arising throughout the entire production chain of such pathways. In meeting this condition, the purpose is equally to prevent profitable utilization pathways from offsetting other unprofitable ones. To this end, expenses are limited to a maximum value that is determined by remunerations serving as an upper bound. The profitability of any utilization pathway in an energy system is thereby ensured regardless of whether the goal may be to minimize costs or even maximize the profit. For both procedures, the exogenous approach guarantees profitability at the microeconomic level of each utilization pathway. And this happens against the backdrop of the identification of the optimal solution of the energy system when observed as a whole. In this context, an array of observers is required, each of which describes a set comprising all its possible utilization pathways within the target energy system. Such observers are located at specific interfaces, where each is assigned remunerations and all expenses incurred at any feasible combination of a power plant and a supply chain. This methodology is not concerned with the macroeconomic assessment of an energy system from the perspective of a single observer. Actually, it aims at microeconomically evaluating utilization pathways from the viewpoint of several relevant actors – namely, plant operators and/or interested investors. Nevertheless, the former is really a common method in most of the existing optimization studies accomplished in the past. And the issue is that some of these analyses might erroneously give a technology solution that is a macroeconomic optimum – a minimum cost or a maximum profit – but, however, microeconomically unprofitable.

For a better understanding of profitability constraints, such an exogenous methodology to the modelling of remunerations is applied to the special case of bioenergy generation. The intended analysis is focused on a general bioenergy subsystem as a smaller portion of any entire energy system. Thus, only the profitability of the bio-based utilization pathways will be guaranteed by means of such restrictions. Each of these biogenic pathways can be broken down into at least four consecutive technological processes – harvesting, densification, transport and conversion. Therefore, any elementary bioenergy subsystem can be constructed on the basis of four technology sectors extending over *n* spatial units. The resulting grid of *4n* nodes can be modelled as a complement or add-on module of a cost minimization model describing the whole energy system. The outcome is a tool named BioSPHERE (Bioenergy Subsystem Software for Production Pathways at High Energy and Resource Efficiency), which is based on a multi-period mixed integer linear programming (MILP) method. This software extension comprises an array of auxiliary conditions concerning the profitability constraints of discrete utilization pathways as well as four sets of auxiliary equations underlying such restrictions. On this basis, a new decision variable introducing the energy and material contributions of all processes of a supply chain to its respective bio-based conversion process is defined. This variable is included in certain terms within the left-hand side of any profitability constraint and presents a significant role in the calculation of cost components. On the other hand, some activity levels of energy and material-related magnitudes such as the process levels, the flow levels (between nodes) or the aforementioned contributions can be linked directly or indirectly to each other so as to build the four sets of auxiliary equations. The indirect approach is accomplished by expressing some of these variables as a suitable linear combination of a set of auxiliary variables called virtual flows. As a result, the model together with its add-on delivers a macroeconomically cost-efficient solution consisting of a microeconomically profitable spatial arrangement of bio-based facilities (bioenergy configuration) according to a specific biomass distribution pattern.

As a last step, BioSPHERE is used to prove the exogenous approach by implementing a particular sensitivity analysis. This add-on module allows evaluating the impact of the change in remunerations on the forest residues-based bioenergy subsystem of Baden-Württemberg (Germany). The topic of the retrofitting of the existing coal-fired power stations in the energy system of this federal state is selected as a case study. As a technical improvement, these power plants can be upgraded to co-firing forest residues at a 10% co-fire rate of the total primary energy input. Building on this framework, remunerations are progressively reduced from a certain level of profitability (above 6.7 €cent/kWh_e) via a series of breakeven points through to a point at which no bio-power is produced (5.5 €cent/kWh_e). By doing so, an array of bioenergy configurations of retrofitted conversion units with ever lower electricity production costs and different spatial arrangements are identified. No change is however perceived, as if no restriction were implemented, for those payments above the breakeven points between 6.6 and 6.7 €cent/kWh_e that first appear. In each of the settings, the specific electricity production costs entailed by both the modernized coal-fired power stations and the bioenergy contributions of each spatial unit within their catchment areas are assessed. Finally, the former expenditures are correlated with the overall bio-power potential for each spatial configuration in order to create the power supply cost curve of this bioenergy subsystem as regards co-firing.

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