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(Eds.)

Challenges for Sustainable Biomass Utilisation

Proceedings of the Chilean-German Biociclo Workshop (Karlsruhe, 26.03.2009)

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PREFACE

The industrial use of woody or herbal biomass is a wide and growing field of research. Especially the energetic utilisation of such biomass and its upgrading to high value fuels or chemicals are promising. They can provide solutions to the ecologic and economic problems of the growing worldwide demand for energy and fuel. Chile is one of the world's largest producers of wood, so innovative techniques for upgrading this resource to fuels or products are of a high national interest.

A two-year research exchange between the Universidad de Concepción (Chile) and the Universität Karlsruhe (TH) (Germany) aimed at establishing contracts between researchers from both countries for supporting joint research in this field. The Biociclo Workshop was part of this exchange funded by the German Federal Ministry of Education and Research (BMBF) and the Comisión Nacional de Investigación Cientifíca y Tecnolóciga (CONICYT).

We as organizers of the workshop and editors of these proceedings are grateful for the good attendance, which is reflected by the internationality and interdisciplinarity of the workshop's participants and the scope of the contributed papers. We are glad to offer a documentation, which may foster the exchange of scientific approaches and their practical application.

We would like to thank all authors of the book and participants of the workshop. Our special thanks go to our research exchange partners:

- Dr. Alex Berg
  (Unidad de Desarrollo Tecnológico (UDT), Universidad de Concepción, Concepción, Chile)
- Prof. Dr. Claudio Zaror
  (UDT /Chemical Engineering Department, Universidad de Concepción, Concepción, Chile)

It is a pleasant duty for us to express our sincerely gratitude towards the Germany Ministry of Education and Research (BMBF) and the Comisión Nacional de Investigación Cientifíca y Tecnolóciga (CONICYT). Without their grant within their program for funding "international cooperation in education and research with Chile" such fruitful workshop on sustainable biomass utilization concepts in Chile and Germany would not have been possible.

Michael Hiete, Jens Ludwig, Christian Bidart, Frank Schultmann

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FORESTRY BIOMASS AS A FEEDSTOCK FOR ENERGY PRODUCTION IN CHILE: CHALLENGES AND OPPORTUNITIES

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Abstract: Chilean forestry industry in based on more than 2 million ha of pine and eucalyptus plantations, subject to 25 and 11 years rotation cycles. Additionally, there are 13 million ha of native forests which are not used industrially, due to strict conservation legislation. There is an urgent need to use biomass as a source of heat and power, to meet growing energy needs in the country. Both, biomass residues from current forestry activities and fuelwood from energy plantations could provide enough energy resources to meet part of future needs. Forestry activities generate around 500.000 ton biomass residues every year, whereas energy plantations settled on unused land could provide 60 million ton biomass. Government incentives and R&D would be required in order to attract investments, protect the environment, and maximise positive social impacts.

INTRODUCTION

The Chilean economy is growing at a steady rate, and is expected to do so for the foreseeable future. Over the last decade, the GNP increased at around 3.7% per year, and so did energy consumption. Currently, energy consumption in Chile is equivalent to 26 millions ton oil equivalent per year, with 1.6 ton oil equivalent per capita year. Nearly 75% of primary consumption comes from imported fossil fuels, whereas 20% is met by wood burning, mostly for heating purposes.

Despite current efforts to increase the efficiency of energy usage, energy demand is expect to grow due the fast growing economy and population. Given the significant forestry resources, energy from biomass could offer an interesting option to reduce the current vulnerability of the Chilean energy matrix.

Moreover, the Chilean forestry industry is well established and accounts for 3.5% of GNP, and 11% of total exports. This industrial sector is based on 2.1 million ha of pine and eucalyptus plantations. In this paper, a brief review of the energy potential from biomass is presented. Firstly, forestry resources and energy consumption in Chile are briefly reviewed. Then, the potential of biomass as feedstock for energy uses is discussed. Finally, key challenges are identified.

FORESTRY RESOURCES IN CHILE

Chile features a continental surface area of 756,250 km^2. Native forests cover around 13.4 million ha, representing 18% of the country's territory. As shown in Table 1, most native resources are evergreen and Nothofagus species, located in southern Chile. Standing biomass in native forests is estimated at around 1.1×10^9 m^3, whereas 12 million m^3/year are extracted for local fuelwood purposes.

On the other hand, forestry plantations cover over 2.1 million ha, mostly planted with *Pinus radiata* and *Eucalyptus globulus* species (see Table 2). It must be mentioned that all biomass supply to the Chilean forestry products industry comes from forestry plantations, featuring rotation cycles around 25 and 11 years for pine and eucalyptus, respectively.

Table 1. Predominant Native Species (UACh, 1999)

Native Forestry Species	**Covered area (ha)**
Evergreen	4.140.000 ha
Lenga (Nothofagus pumilio)	3.392.000 ha
Coigue (Nothofagus betuloides)	1.793.000 ha
Roble (Nothofagus oblicua)	1.461.000 ha

Table 2. Eucalyptus and Pinus Regional Distribution (Infor, 2006)

Region	Eucalyptus (ha)	Pinus (ha)
Coquimbo	2.634	-
Valparaiso	39065	10.903
O`Higgins	34.169	66.380
Maule	38.196	389.434
Bio Bio	240.473	610.296
Araucania	168.019	263.326
Los Rios	61.067	106.765
Los Lagos	42.184	15.237
Aysen	-	23.564
Total	625.807	1.462.341

THE CHILEAN ENERGY MATRIX

As seen in Table 3, the Chilean primary energy matrix shows that fossil fuels account for nearly 73% of total energy consumption, whereas biomass reaches less than 20%. Therefore, the country is extremely vulnerable to variations in oil, gas and coal prices and availability at international markets.

Hydroelectric resources are mostly located in Southern Chile. However, during the last century there has been a sustained reduction in rainfall due to climate change, affecting electricity generation. Additionally, Chile is periodically affected by the El Niño-Southern Oscillation. During La Niña event severe droughts reduce water availability for electricity generation, increasing the pressure on thermoelectric power generation. This trend is expected to continue and, even, become more severe.

Table 3: Chilean Primary Energy Matrix (CNE, 2007)

Primary Energy Source	Tcal /year	%
Crude Oil	106.155	41
Natural Gas	42.718	16
Coal	42.861	16
Hydroelectricity	19.576	8
Fuelwood	49.841	19

The country's electricity grid is divided into two major interconnected systems (see Table 4). The Northern grid has a total capacity around 3.2 GW mostly from thermoelectric power plants. The other serves the Central-Southern part and features 10 GW, 60% from hydroelectric and the rest from thermoelectric plants. Thermoelectric plants are fuelled by imported coal and natural. Additionally, there are 0.4 MW electricity generation capacity, from CHP fuelwood boilers in pulp and paper mills.

Table 4: Electricity Grids in Chile (CNE, 2007)

Interconnected Grid	Installed Power Capacity GW	Primary Energy Source
Northern SING	3.6 GW	99% thermo
Central SIC	10.0 GW	40% thermo 60% hydro
Others	0.1 GW	88% thermo 9% hydro 3% wind
Total	13.7 GW	

FORESTRY BIOMASS AS ENERGY FEEDSTOCK

Biomass residues from forestry plantations

As seen in Figure 1, around 14 million ton/year woody feedstock (dry basis) are harvested every year. Main products include 5 million ton cellulose, and 3 million ton saw wood and boards. Part of woody residues produced in sawmills are used as raw material for cellulose production, and the rest is used as fuel for steam generation. Cellulose mills also generate electricity for internal uses and the surplus power is fed to the national grid.

On the other hand, forestry activities also generate large amounts of residues. Pruning and thinning produce 150,000 and 100,000 ton/year biomass residues. These add to around 1 million ton residues produced during harvesting (Bidart, 2007). Part of harvesting biomass residues are burnt to reduce volume, incorporated into the soil, chipped, or used as fuelwood. Biomass residues from forestry activities that could be potentially used for energy purposes are estimated around 500,000 ton/year

Energy Plantations

Current estimations indicate that there are around 10 million ha unused or erosion stricken land available for forestry activity, mainly in Southern Chile. Energy plantations appear as an interesting alternative to stop erosion and reclaim soil. Fast growing species, such as eucalyptus or poplar, could yield around 20 ton/year per hectare. Considering a plantation area of 2 million ha, then 40 million ton/year, ie. 150,000 Tcal/year representing an energy equivalent of 3 times current biomass fuels and 35% current coal imports.

Additionally, appropriate forest management practices could enable a yearly supply around 5 ton surplus biomass per hectare, from native forests. Considering an area of 4 million ha, then 20 million ton biomass / year could be cropped, representing ie. 75,000 Tcal / year

In total, those biomass sources would provide an equivalent to 50% current coal imports.

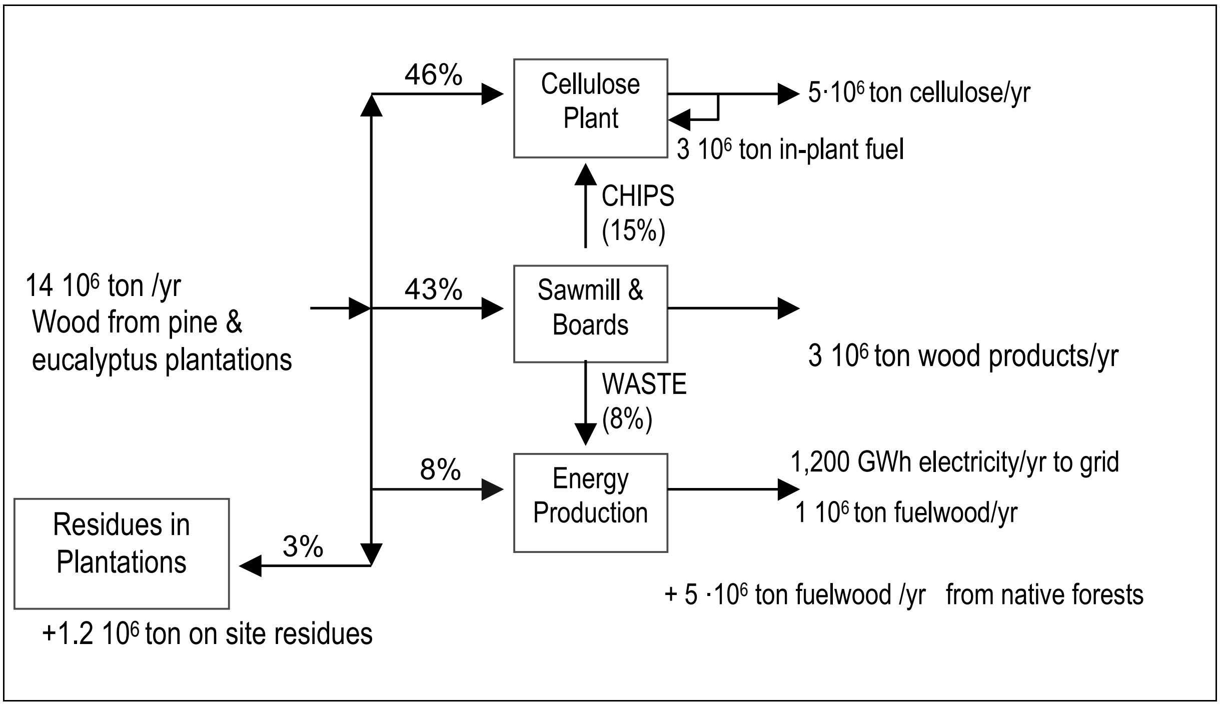

Figure 1: Forestry Sector Mass Balance

Agricultural Residues

Chilean agriculture accounts for 0.7 % GNP, with a total arable land around 700,000 ha, where 40% is used for wheat and oat crops. Almost all arable land is committed to food production (grains, fruits, vegetables), and there is little land available for energy crops. Agricultural residues are estimated around 1.5 million ton/year, representing a maximum energy potential of 45,000 Tcal /yr.

Key Challenges

In order to achieve an effective implementation of energy-from-biomass policies in Chile, Government incentives are required to promote sustainable energy plantations. For example, tax reductions and direct incentives to reforestation aimed at enhancing energy plantations, and provide long term rural employment, are a key to attract investments. Additionally, financial and technological support is essential to maximise positive social effects and minimise negative environmental impacts.

On the other hand, transport costs represent a serious problem. Indeed, most urban-industrial centres are located in Central Chile (30–37ºS), whereas available forestry land is in Southern Chile (40–50ºS), with distances in the range

400 – 2000 km. Moreover, forestry residues feature low density and high moisture content. Therefore, there is a need for decentralised processing, and/or in-situ densification or concentration (e.g. Bio-oil, charcoal, pellets).

Technological, R&D and social-environmental issues constitute key challenges that must be taken into consideration in the design and implantation of energy strategies. Some are listed below:

Technological Challenges:

- Decentralised processing, in-situ densification
- Thermal conversion technologies (pyrolysis, gasification, etc)
- Replacement of old inefficient stoves, for thermally efficient systems for cooking and heating
- Improvement of thermal insulation in construction
- Improvement of fuelwood specifications (limits to moisture content)
- Efficient environmental control technologies (air pollution control, ash management).

Research and Development Issues:

- Selection of appropriate lignocellulosic feedstock (according to growth rate, yield, energy value, environmental requirements, and chemical composition).
- Appropriate energy conversion / usage technologies (start from low complexity, and low investment costs).
- Integration of biomass energy into existing forestry practices and industrial wood processing.

Environmental and Social Issues:

- Prevent reduction of biodiversity, and negative impacts on fragile ecosystems.
- Greater controls on fertiliser use and N_2O emissions.
- Use fossil fuels only when no other alternative exists.
- Policies to favour sustainable native forest management.
- Favour labour intensive systems to maximise impact on rural employment.
- Adapt labour legislation as required.

- Financial support to small entrepreneurs, to achieve greater local social impacts.

CONCLUSIONS

There is a need for greater diversity of energy sources, to reduce imported fuel supply risks and vulnerability of hydro-electric resources. Fast growing forestry plantations may help to increase the use of biomass for energy production purposes (CHP). On the other hand, economic incentives are required to support the settlement of energy plantations, and to introduce energy conversion/use technologies. Last, but not least, social and environmental issues have to be taken into consideration in the design of energy policies.

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POTENTIAL FOR PRODUCTION AND MARKETING OF BIO-OIL BASED CHEMICALS IN CHILE

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Abstract: Chile is poor in fossil fuel resources and therefore strongly depends on imports of crude oil and natural gas with natural gas being mainly imported from Argentina. The use of biomass as fuel or chemical feedstock could help to reduce this import dependency and create value in Chile. Especially by-products of the wood industry represent a major source for potential further use. In the VIII region Bíobío alone, about 790,000 tons of sawdust are produced annually by the wood industry. A considerable part of it is not used adequately since the transport of wood dust over longer distances is economically unviable. An emerging option is the pyrolysis of saw dust to produce bio-oil.

The paper first analyzes the conversion of sawdust to bio-oil via fast pyrolysis techno-economically with the aim to determine bio-oil production costs for Chile. In the second part, options for using the bio-oil are assessed, especially utilizations for contained components and their market potential in Chile. While the sole utilization of bio-oil as a fuel does not seem economically viable, the use of its components as feedstock is seen as an interesting alternative. Potential utilizations meriting more detailed research are proposed.

INTRODUCTION

Chile is a country rich in some mineral but poor in fossil fuel resources. In 2007, 99 % of crude oil and 72 % of natural gas were imported (CNE 2007). Around 80% of the natural gas is imported from Argentina. Hence, temporal shortages or interruptions of Argentinean natural gas exports have severe impacts on Chile's strongly growing economy. In particular during peak demand in winter natural gas supply from Argentina does not meet demand and natural gas fired power plants in Chile have to switch to more costly fuel oil. The substitution of crude oil and natural gas is therefore a prevailing topic of research in Chile.

Chile is with a population of only 17 million one of the major producers of wood products (FAO 2005). The valorization of by-products of the wood industry is therefore not only from an economic point of view interesting but can also contribute to reduce Chile's energy import dependency. Combustion of the wood by-products to produce heat and power is straightforward. However, Chile's ribbon-like shape in combination with a population and forest industry which are unevenly and differently distributed over the country lead to long transport distances for either electricity or by-products rendering direct combustion in many cases less attractive. This explains why a part of the by-products is currently not used adequately and why there is a search for other use options.

One currently discussed option is the upgrading of the by-products to bio-oil using thermo-chemical processes like fast pyrolysis. Bio-oil can be either directly combusted or used for fine chemicals production. Sawdust is suited for this conversion process; it is accruing in large quantities in sawmills where around 17 wt. % of the wood is lost as sawdust. This translates to an estimated sawdust amount of 790,000 t/a for the Chilean region VIII, Bíobío (Walberg 2005). Traditionally, this sawdust is burnt on-site. In larger plants the thermal energy is used to produce process steam or to generate electricity.

The remainder of the chapter is structured as follows. First, some general information concerning wood by-products and their use is given. Then, a techno-economic analysis of bio-oil production by fast pyrolysis including the corresponding material and energy balances are presented. This step is followed by an assessment of the different use options for the produced bio-oil with a focus on its use as a feedstock for fine chemicals production. For this purpose, market potentials of chemicals contained in the bio-oil are regarded.

OPTIONS FOR USE OF WOOD BY-PRODUCTS IN A CHILEAN CONTEXT

Chilean wood industry is characterized by both natural forests and plantations of fast growing species like eucalyptus and pine trees. The wood industry is concentrated in the Chilean regions VII to X with large plants dominating the production. This localization has a strong impact on the use options for forestry by-products as the supply is limited to a few regions and concentrated in a rather limited number of places.

Direct combustion for heat and/or power production is a straightforward option to use the by-products but the concentration of the supply in a few regions and places makes it necessary to transport either the by-products or the produced power. In case of sawdust its use in existing combustion plants may induce high costs for retrofitting and its low volumetric heating value makes a transport economically and energetically unattractive. One possible solution for improving sawdust utilization is its processing with the aim to increase the heating value and to improve its handling and usability in existing installations. For processing the larger amounts of sawdust accruing at certain wood processing sites are even favorable as economies of scale can be realized.

In the following, the fast pyrolysis of sawdust to bio-oil is techno-economically analyzed. Bio-oil is a brown acidic liquid with a smoky smell and contains 20-40% water with effects on its chemical and physical stability (A.V. Bridgwater and Grassi 1991). Bio-oil is nevertheless to some extent comparable to crude oil. It is not only usable as a combustible in especially adapted engines but also as a feedstock as it contains valuable chemical compounds resp. groups of chemical compounds.

BIO-OIL PRODUCTION BY FAST PYROLYSIS

Principles of fast pyrolysis

Fast pyrolysis, principally a thermal degradation, is a thermo-chemical process that converts finely ground biomass by rapid heating to 350-800°C under the absence of oxygen to bio-oil, gas and char. Their proportions depend on the process conditions and the feedstock. Bio-oil yield is highest in a fast or flash pyrolysis which is characterized by extremely high heating rates, short residence times and rapid product quenching (A.V. Bridgwater and Grassi 1991). Fast pyrolysis has been a subject of research for at least 50 years and a variety of pyrolysis reactors were designed with the fluidized bed reactor being the most advanced and promising one. However, only small-scale or demonstration plants are in operation.

Basically, two fluidized bed reactor types can be distinguished: The first is the circulating or entrained bed reactor type, which uses a heat carrier that is entrained by a gas in a loop through the reactor. This reactor type is used already on a larger scale, e.g. in refineries. Due to high friction between the heat carrier particles and the piping energy, costs are high and feedstock particles have to be ground to 1-2 mm (Ringer, Putsche, and Scahill 2006). The second one is the fluidic or bubbling bed reactor type for which ample experience exists in the chemical and refinery industry (Ringer et al. 2006). Feedstock for this type of reactor is ground to a particle size of 2-3 mm. The feedstock passes through a heat carrier bed.

As a pyrolysis plant consists not only of the reactor but also of units for heating, quenching, storage and piping it is assumed that the investments for both reactor types are comparable (Stewart 2004). Furthermore, several studies have shown that energy consumption and production costs do not differ considerably between a fluidic bed and circulating bed reactor either.

Materials and energy balance

A materials and energy balance was calculated for the bio-oil production plant based on published data which originate mainly from the Canadian Company Ensyn Technologies Inc. The process was modeled using the Petri Net based LCA-software tool Umberto®. Figure 1 shows a snapshot of the main process steps (reactor, cyclone, quenching and auxiliaries) and associated material and energy flows. Each of the process steps was modeled in more detail in a sub-model.

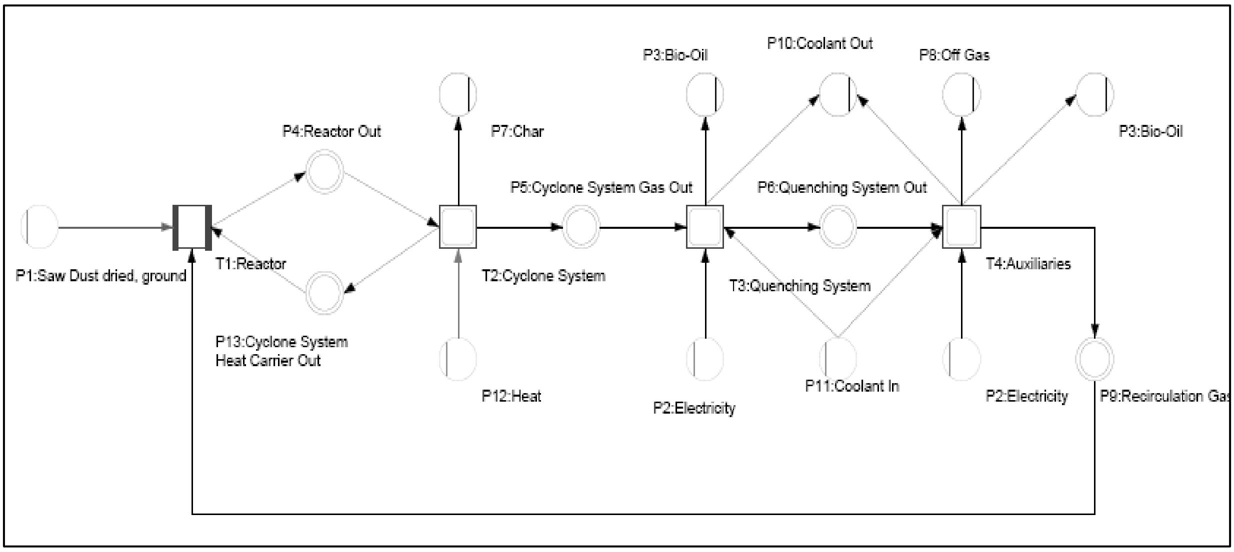

FIGURE 1: Main process steps of bio-oil production plant as a Petri Net in the software tool Umberto®

A summary materials and energy balance for the production of bio-oil in Chile is given in Table 1. The estimated bio-oil yield is 77.5%. Besides bio-oil, considerable amounts of non-condensable gases and char are produced. For producing the required process heat, about 70 kg of the produced char have to be burnt. Burning the non-condensable gases alone would provide about 80 % of the required heat. Assuming an efficiency of at least 15 % for electric power generation, non-condensable gases and char contain more energy than necessary to produce both, the necessary process heat and electric power.

TABLE 1: Summary of materials and energy balance for bio-oil production

1000 kg of sawdust yields	Processing of 1000 kg of sawdust demands
• 6 kg of ash • 108 kg of char • 110 kg of non-condensable gas • 775 kg of bio-oil	• 53 MJ (15 MWh) of electric energy • 1,600 MJ (445 MWh) of heat

Bio-oil production costs

The production costs of bio-oil are the sum of investment related costs (depreciation, imputed interests, maintenance and repair, assurance etc.) for the different parts of the plant, in particular the parts for the preprocessing of the feedstock and the pyrolysis, and operating costs (wages, energy costs, raw materials costs, consumables etc.).

For the **estimation of investment** of the plant an underlying production capacity of 75,000 t/year of bio-oil is assumed. Assuming a yield of 75% of bio-oil in case of sawdust, this equals a feedstock capacity of 100,000 t/year of sawdust (dry) and a catchment area of about 50 km around the plant. The investment for this plant including a highly-efficient fabric filter was estimated to be US$28 million (2005) based on a literature review (cf. A. V. Bridgwater and Peacocke 2000; McKeough 2005; Mullaney 2002; Östman 1999; Ringer et al. 2006; N.N. 2004) and data of a planned pellet plant in Chile. Main investment items are the pyrolysis module with US$17 million and the preprocessing module with US$9 million.

For the calculation of the bio-oil **production costs**, an interest rate of 8% and a service life of 10 years were assumed leading to an annuity factor of 15%. Annual maintenance and overhead costs were calculated as 2.5% and 2% of the investment sum respectively. Although the forestry sector is a well-established industry in Chile, prices for sawdust are relatively low with only US$19 per ton compared to US$70 per ton in Europe (Brammer, A. Bridgwater, and Lauer 2005), leading to annual feedstock costs of US$1.9 million per year. Electricity costs for both the feedstock and the pyrolysis module sum up to US$0.8 million per year. Costs for vehicles operation and labor are US$0.2 million per year each. Annual operational costs sum up to US$3.1 million per year leading to total costs of US$8.4 million per year or US$123 per ton of bio-oil produced.

The highest uncertainty exists concerning the investment for the pyrolysis unit with a high probability that learning effects on the technical side and sales volume on the market side could in future lower the price considerably. A sensitivity analysis shows that if the investment sum is reduced by 30%, production costs would be reduced by 14%. A reduction of the same percentage of the investment sum of the pyrolysis module would reduce production costs by only 9%. The reduction of feedstock and electricity costs by 30% could lower production costs by 10 % and 6 % respectively. Labor costs are only contributing with 1.5% and thus have only a minor influence on production costs.

USE OF BIO-OIL AS A FUEL

Bio-oil has a density of around 1.2 kg/l and a lower heating value of 18 MJ/kg which is less than half of that of fuel oil, but which still results in significantly lower transport costs compared with sawdust (Soltes and Milne 1988). The exact heating value and composition of the bio-oil depends on the feedstock utilized for fast pyrolysis. Bio-oil is more suitable for storage and is pumpable. As it is derived from biomass it can be burnt nearly CO_2-neutral. One disadvantage of bio-oil is the non-solubility without additives with common fuel oils and organic solvents. It is therefore not possible to use the existing fossil fuel distribution system for the distribution of bio-oil (A.V. Bridgwater and Grassi 1991). Besides, it is not as stable as diesel fuel and changes its composition over time. However, kept under 25°C and without contact to air bio-oil can be stored for up to two years. Other unfavorable properties are its water content which can be as high as 30%, its high kinematic viscosity of approximately 112 cSt at 20 °C and its strong acidity. Finally, it is less homogeneous than other fuels so that specially modified burners or engines have to be used.

If bio-oil is used in a boiler or engine, it must compete with other combustibles available in Chile like fuel oil No. 6. As the lower heating value of bio-oil is around 53% of that of fuel oil, the target price of bio-oil must be lower than the fuel oil price by at least the same percentage, i.e. cheaper than US$196 per ton at the time of the study (2007; Fuel Oil No. 6 price was US$370 per ton) (please note that prices for fossil fuels vary considerably over time and have decreased considerably afterwards).

USE OF BIO-OIL AS A FEEDSTOCK

Bio-oil contains a large number of chemical compounds. Estimates range from about 100 to 400 compounds (Diebold 2002). The main components of bio-oil are given in table 2. The chemical composition can drastically change from one feedstock to another or as a result of process modifications. Predictions of the shares of individual compounds are even more uncertain.

TABLE 2: Representative chemical composition of fast pyrolysis derived bio-oil (Bridgewater, Czernik, and Piskorz 2002)

Chemical compound	Mass %
Water	20-30
Lignin fragments: insoluble pyrolytic lignin	15-30
Aldehydes, e.g. formaldehyde, hydroxyacetaldehyde	10-20
Carboxylic acids, e.g. acetic acid, propionic acid	10-15
Carbohydrates: e.g. glucose, levoglucosan	5-10
Phenols, e.g. phenol, 3,5-dimethylphenol	2-5
Furans and furfurals	1-4
Alcohols, e.g. methanol, ethanol	2-5
Ketones, e.g. acetone, MEK	1-5

Screening of chemical compounds in bio-oil for use as feedstock

Overall there is only little information available about the shares, possible uses and economic values of the different compounds in bio-oil highlighting the need for a further analysis. Potential utilization of single chemicals, chemical groups/fractions contained in the bio-oil as well as of the whole bio-oil and of charcoal were analyzed. Overall more than 180 chemicals have been screened for their potential utilizations by their chemical abstract service (CAS) registry number. To make the different compounds and their utilizations comparable against each other an indicator framework was developed with indicators for quantity in bio-oil, price, market size, patent maturity and market applicability leading to a ranking. Table 3 shows the three best-ranked compounds respectively utilizations for the four groups: chemicals, chemical groups/fractions of the bio-oil, whole bio-oil and charcoal. A major obstacle for assessing the market potential of the compounds is that so far only two chemicals, hydroxyacetaldehyde (HAA) as a browning agent and liquid smoke as food aroma, were successfully introduced to the market. Concerning other utilizations there is only limited information available regarding their commercial viability. However, costs for separating the chemicals from the bio-oil were not analyzed in detail.

Most promising chemical compounds in bio-oil for use as feedstock

The three highest ranked compounds respectively utilizations in the indicator framework were reassessed to identify the most promising chemicals and utilizations for Chile for which a more detailed market analysis for Chile was considered fruitful.

Chemicals: Levoglucosan was selected as promising (marked by the bold letters in table 3) because of its wide range of possible utilizations and because of its abundance in the bio-oil. HAA has been analyzed to be the single most abundant chemical contained in the bio-oil and has been identified as a potential chemical for high value added applications, e.g. as a browning agent. It seems promising therefore, to look for possible market opportunities for these products in Chile. Acetol on the other hand, did not convince in terms of end-product applications.

Chemical groups/fractions: Even though there is a wide utilization area for liquid smoke in the Chilean salmon industry it was considered as not promising as liquid smoke is patented. However, the phenolic rich phase seems promising as it can be used as a phenol substitute in phenol-formaldehyde (PF) resins for the Chilean fiberboard industry. Carboxylic acids are also considered as promising due to their high market prices and their possible utilization as a silage additive.

TABLE 3: Indicator-based ranking of usages for bio-oil and components (substances in bold letters are those for which a market analysis for Chile was considered promising)

Rank	Chemicals	Groups/Fractions	Whole bio-oil	Charcoal
1	**Levoglucosan**	Liquid smoke	Preservative (for creosote replacement)	Sequestration
2	**Hydroxyacetaldehyde (HAA)**	**Phenolic rich phase**	Slow release fertilizers	Fertilizers
3	Acetol	**Carboxylic Acids**	BioLime & NOx control	Activated carbon

Market analysis for selected chemicals and chemical groups/fractions in Chile

Phenolic rich phase: The phenolic rich phase can be used as a phenol substitute in phenol-formaldehyde (PF) resins with the main market application as a glue binder in man-made wood products (Graham, 2003). PF resins are mainly used in the production of oriented strand board (OSB), plywood and wafer boards where they represent 2.5 to 10.0 wt% of the dry material. The total industrial consumption of PF resins in Chile is estimated to be 62,500 tons in 2007. The phenolic rich fraction can replace up to 40 wt% of the phenol in PF resins. Imports of phenolic resins to Chile amounted to 4.300 tons in 2007 representing a market value of US$4.2 million. As the phenolic rich phase is used as a technologically proven phenol substitute the extraction of a phenolic rich phase is highly interesting.

HAA: HAA can be used as a raw material for the production of glycolic acid. The production of glycolic acid from HAA would require special treatment though, and a rising demand on glycolic acid is not expected in the near future. HAA seems therefore unfavorable if the focus is on current markets in Chile.

Carboxylic acids: Carboxylic acids get high prices and are used as a chemical silage additive. The demand for chemical silage additives in Chile is high and has so far not been satisfied. Approximately one million tons of silage is lost in Chile every year because of a lack of required chemical silage additives. The demand for a reasonable priced silage additive in Chile is therefore expected to be very high. The carboxylic acids have been evaluated as a potential silage additive by (Jahn 2008) but it is still unclear how much of the carboxylic acid rich phase has to be used to successfully improve the silage quality. The chemical silage additives are thereby mainly used on high-risk silage with a dry mass percentage of less than 30% as under these conditions the formation of natural carboxylic acid is not sufficient to lower the pH value to the required value of about 3 to 4 (Fillipi 2007). Furthermore, when silage is covered with oxygen impermeable folia, the uppermost layer directly below the folia will not be completely free of oxygen. As this layer represents a significant part of the whole silage, losses of 20 wt% occur (Jahn 2008) which could be reduced or even avoided if carboxylic acids were added.

CONCLUSIONS

In Chile by-products of the forestry industry like saw-dust arise in large quantities in regions VII to X. As there is a strong interest in Chile to reduce dependency from fossil fuel imports and to generate added value in the country, innovative options for use of the sawdust like its fast pyrolysis to bio-oil is currently discussed. Bio-oil may replace fuel oil as combustible but can be also used as a feedstock. Chile does not provide major subsidies for green technology (Binkert 2005). Thus, if used as combustible, it competes directly with fuel oil. Our analyses show that high investments for the pyrolysis plant and hence production costs for bio-oil represent an obstacle for competitiveness as a combustible.

However, the use as a feedstock could be economically attractive as certain chemicals in the bio-oil can be used for high valuable applications in a Chilean context. Liquid smoke and HAA are examples for products being already on the market which could be extracted from the bio-oil. Intellectual property rights and a limited market make their production, however, less attractive in a Chilean context. Extraction of a phenolic rich phase and its use to replace phenol in PF resins as well as of carboxylic acids and their use as silage additive are considered as highly interesting. These options which could contribute to make the production of bio-oil economically viable in Chile need further analyses.

Considering a future perspective with most probably rising crude oil prices, continued research on the production of bio-oil in Chile and its use both as a combustible/fuel and as a source of valuable chemical products seems highly advisable.

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THE BIOMETHANE POTENTIAL IN CHILE

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Abstract: Within the last decade natural gas gained considerable importance in Chile. The contribution of natural gas within the energy system will increase in the future by predicted 3.6 % annually until the year 2015. Due to limited resources within its own country, the energy system of Chile depends on natural gas imports preferentially from Argentina. Therefore, the aim of several stakeholders from policy and industry is to reduce the share of imported primary energy within the overall energy system. In order to reach this goal, the use of domestic resources and particularly utilisation of biomass as one of the most important renewable sources of energy in Chile could play an important role. Against this background, the goal of this paper is the analysis of the technical potentials of biomethane as a substitute for natural gas. For the production of biomethane the anaerobic or bio-chemical (i.e. Biogas) as well as the thermo-chemical conversion pathways (i.e. Bio-SNG) are considered. The results of this analysis show that biomass converted to biomethane is a promising energy provision option for Chile and it contributes to the reduction of Greenhouse Gas emissions.

INTRODUCTION

Methane as the main component of natural gas is an important energy carrier and a raw material that is widely used in industry and households. The utilization of methane has spread out throughout South America, especially in the Southern cone countries. The demand for natural gas in Latin America will show an average annual growth rate of 3.6 % till the year 2015 according to estimates carried out recently by the International Energy Agency [1].

In Chile the natural gas consumption developed from 78.5 PJ in the year 1990 to 327.6 PJ in 2005. It covers 27 % of the overall primary energy demand in 2005. This contribution is predicted to increase up to 32 % in 2010 assuming that current development will continue in the next years [1, 2]. This growth is possible because of the construction of new distribution pipelines, especially from the natural gas resources in Argentina to the fast growing markets in Northern and Middle Chile [3].

Due to the increase of the natural gas demand and the lack of own resources (i.e. high share of imported gas from Argentina (about 68 % [1])) Chile is characterised by a considerable import dependency. This could have serious consequences to the overall economy because natural gas import from Argentina shows significant supply problems. One example of that was the cutting down of gas export from Argentina to Chile due to provision problems of natural gas within the Argentinean market during the energy crisis in 2004. This has lead to a number of interruptions in the natural gas supply of Chile up to now [2].

For this reason stakeholders from policy and industry in Chile started activities and programs to reduce the dependency on unreliable Argentinean natural gas imports. One of the measures under consideration is the expansion of the existing gas grid to other neighbour countries (e.g. Peru) that can supply natural gas as well [3].

Besides, the use of domestic resources for the production of methane could help to increase the energy supply security in Chile. In this context, especially the utilisation of renewable sources of energy could play an important role. The provision of a natural gas substitute is especially true for biomass since it can be used for the production of biomethane [4].

METHANE PROVISION FROM BIOMASS

For the generation of biomethane two conversion pathways are market mature respectively under development at the moment (cf. FIGURE 1) [5]:

- the thermo-chemical biomass conversion (i.e. Bio-SNG (Synthetic Natural Gas))
- the bio-chemical biomass conversion (i.e. Biogas)

The conversion technologies for Bio-SNG and Biogas differ significantly concerning e.g. biomass feedstock, conversion principle, state of technology, average installed capacity per conversion unit, available technical experiences and still given R&D demand [4].

Both conversion routes have to provide biomethane fulfilling the requirements for a feed-in into the existing natural gas grid [5]. Therefore, Biogas as well as Bio-SNG have to be upgraded by technical processes guaranteeing the same calorific value and chemical composition as natural gas. Only if this prerequisite is fulfilled biomethane can be used in any mixture with natural gas by using the same infrastructure without creating problems to the end user [4, 5].

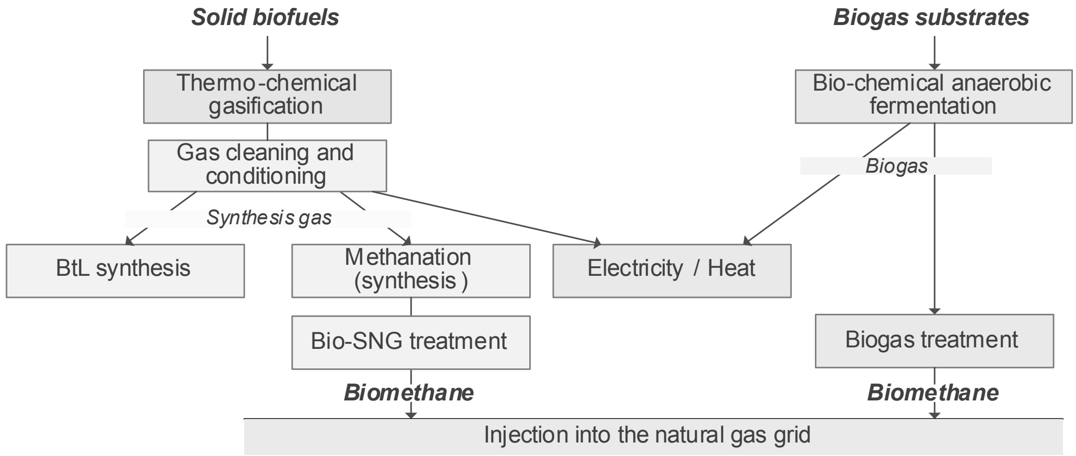

FIGURE 1: Provision pathways for biomethane

With regard to Biogas production based on anaerobic digestion, wet fermentation of biomass residues (and wastes) as well as energy crops (e.g. maize silage) is a mature technology [6]. To allow for a feed-in into the natural gas network, the produced Biogas has to be upgraded to the quality of the currently used natural gas. This can be realised by a Biogas treatment unit with e.g. pressure water absorption or pressure swing adsorption; alternatively a cleaning with Selexol or Amin is possible. All these technologies are basically available and currently under demonstration (e.g. Germany, Sweden, Switzerland). Expected plant capacities are in the range of up to 8 MW_{fuel}, whereas plants with half of this capacity are under operation in Germany so far [7]. For such plants, efficiencies of 95 - 97 % between biogas and biomethane and 50 to 85 % (depending on anaerobic degradability of the substrate) between the biomass feedstock and biogas can be expected. Thus, overall efficiencies of 47.5 - 82 % can be achieved. Additionally, the digested slurry can be returned on agricultural land and thus the nutrient cycle can be closed [6].

The production of Bio-SNG is characterised by four main steps:

- thermo-chemical gasification of lignocellulosic biomass (e.g. wood) to a synthesis gas (mainly CO and H_2),
- cleaning and conditioning of the synthesis gas fulfilling the requirements of following process steps,
- methanation of the synthesis gas into methane and
- upgrading to gas grid quality [8].

The state of technology for the production of SNG based on coal is market mature. Since 1984 in North Dakota a commercial-scale gasification plant is in operation. This plant converts lignite with a daily input of 18,500 t into SNG with an output of 4,247,520 m^3 per day [9].

The conversion of biomass into Bio-SNG is not that far developed. Currently biomass gasification based on water vapour for the production of heat and electricity is successfully demonstrated and market mature; one plant is operating for several years in Güssing/Austria [10] and another plant is in its commissioning phase. Only the subsequent methanation step has been realised in a pilot stage with a few kW thermal capacity so far. But currently, a demonstration plant with 1 MW gas capacity is in operation, whereas in December 2008 the first Bio-SNG was produced. According to "economies of scale", conversion plants in the medium- to large-scale would gain market importance for an efficient production of Bio-SNG. Thus, according to current knowledge, the expected plant capacity will be in the range of 30 to 150 and more MW_{fuel}. For such Bio-SNG plants overall efficiencies from wood to methane are expected in a range of 60 to 70 % [4, 11, 12].

Therefore, both conversion routes complement one another in an ideal way. While the bio-chemical route uses wet biomass (e.g. animal manure, maize silage), the thermo-chemical route focuses on solid biofuels (e.g. wood, straw). The former will be realized with plant capacities in the range of less than 10 MW thermal and the latter in the range of 10 to more than 100 MW_{fuel}. The product is basically the same and can be used in any mixture with natural gas.

BIOMASS POTENTIAL

Chile exhibits of a wide range of biomass resources from agriculture and forestry as well as from industry processing agricultural and forestry goods that are suitable for the production of biomethane. For the assessment of the technical biomass potentials, resources from forestry, agriculture and processing industry have to be distinguished.

The forest of Chile contains native and cultivated forest areas that can be used for the provision of wood. The overall forest area of Chile is actually about 157,000 km^2. Thereby, native forests include protected forest areas that cover a land area of approximately 39,000 km^2 [13, 14]. The cultivated forest consists of private commercial plantations, which cover over 21,000 km^2. These forest areas are used by wood processing industry and the major assortments are utilized as sawn wood or as pulp [15]. Thus, the overall technical biomass potential from forestry results from unused felling residues and from the unexploited annual growth [16].

Additional to that, there are biomass residues available from the wood processing industry that is very developed in Chile [18]. In particular, woody residues from saw-mills (e.g. bark, wood shavings, edgings), board industry (e.g. bark, scantlings, slabs) and pulp & paper industry (e.g. bark) seem to be very promising [13, 19]. Currently, wood processing industry of Chile is already exporting large quantities of wood chips and particles to North America as well as wood residues to Europe [20] that could be used on-site for energetic purposes.

Beside the use of wood from the forestry sector and the subsequent industry, there is the possibility to provide wood from plantations with fast growing trees (e.g. eucalyptus, radiata pine) on agricultural land [15]. Chile has significant land resources of fallow land (approximately 4,400 km^2 in 2005) that is not used for food or fodder production due to soil limitations [22].

Beside the potentials based on the raw material, biomass resources from agriculture (e.g. animal manure, straw, and energy crops) are available, as discussed above. For the production of Biogas residues from livestock farming and crop production can be utilized. The livestock farming has in Chile a major importance and contributes therewith considerable to the biomass potential [23, 24].

The actual overall annual biomass potential in Chile sums up to about 869 PJ (FIGURE 2). It can be used partly for the production of Bio-SNG as well as for Biogas.

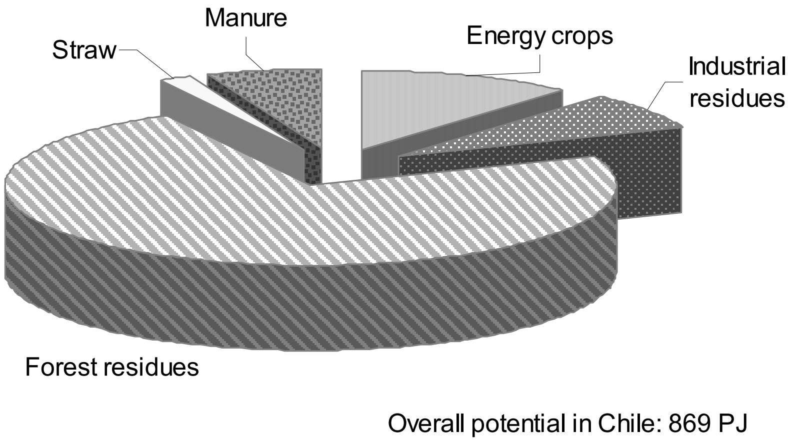

FIGURE 2: The overall biomass potential in Chile

BIOMETHANE POTENTIAL

The calculation of the resulting biomethane potential is based on the technical biomass potential with respect to the conversion efficiencies of the different technologies described above. Besides, the actual gas grid availability and density within the different Chilean regions as well as the planned future expansion of the grid is considered for the calculation. Additionally, it is assumed that conversion plants for biomethane production can be established close to the existing gas pipeline. The required substrates are obtained in a predefined catchment area along the pipeline:

- Biogas substrates $\leq$ 20 km
- Bio-SNG substrates $\leq$ 150 km [4]

The raw material availability is derived based on the existing gas grid and the defined catchment area depending on the given regional conditions.

Current biomethane potential

The overall technical biomethane potential sums up to approximately 212 PJ a^{-1} where forestry wood contributes with major share followed by residues from the wood processing industry, agricultural residues and energy crops.

Between the considered regions, differences exist with regard to the order of magnitude of the technical potential. While in the region of Biobio an overall potential of 115 PJ a^{-1} is available, in Antofagasta a potential of 0.9 PJ a^{-1} is given. These differences are due to the fact that Chile is characterised by very heterogeneous vegetation zones and thus biomass yields. Additionally, the primary production (e.g. forestry, agriculture) and the therewith connected processing industry vary between the regions significantly and have thus an unequal influence on the biomass potential.

The composition of the substrates in different regions is as heterogeneous as the distribution of the potential between the regions. For example, within the regions Valparaiso and Magallanes the biomass potential is dominated by forest residues with more than 80 % while in the region of Biobio the contribution of residues from the wood processing industry is about 40 %. Only within the region of Antofagasta the largest contribution comes from agricultural residues.

Future biomethane potential

For assessing the development of the biomethane potential in the future different foreseeable developments have to be taken into consideration. To cover the overall bandwidth of these developments two scenarios are defined covering a path with an increasing ("Increased Biomethane Supply") and a stable natural gas supply ("Stable Biomethane Supply"); the latter scenario includes the use of biomass as a raw material rather than only its conversion into an energy carrier.

The scenario "Increased Biomethane Supply" is based on the assumption that the planned expansion of the natural gas network within Chile (e.g. construction of a new pipeline to Peru) will be realised [3]. Beside this, it is assumed that within the forest sector the annual plantation harvest will increase due to the enlargement of plantations (i.e. an average of 1 hm^3 a^{-1}) [15, 25]. Thus, it is considered that production capacities of the wood processing industry will grow [13]. Furthermore, an improvement in the agricultural biomass production (i.e. better seed material, improved agricultural technology, partly irrigation) can be realized. This share corresponds to the development of the yield within the existing crop production sector of Chile (e.g. for grain) in the last 30 years [24].

No changes with regard to the pipeline extent were assumed for the scenario "Stable Biomethane Supply". Taking into consideration the development within the forestry sector for the scenario "Stable Biomethane Supply" a marginal increase of the plantation harvest is considered. Beside this, in the wood processing industry sectors a minor annual growth is assumed.

Based on these assumptions, the development of the biomethane potential can be calculated. According to this, the overall biomethane potential will increase by the year 2015 up to 429 PJ within the scenario "Increased Biomethane Supply". Similar to the current situation, the biomethane potential results also in the future mainly from wood residues from the forests. This is true for all regions except the region of Biobio, characterised by a strong wood processing industry and thus a high potential of residues from this industry. Despite the doubling of contributed biomethane from energy crops within the overall biomethane potential (conform to a biomethane yield of 10 $hm^3\ a^{-1}$), the contribution of this biomass fraction is still of minor importance in Chile. Due to the planned extent of the gas grid and the expected increase within the primary production sector (i.e. forest harvest increase, agricultural crop yield increase), it is possible to double the actual biomethane potential.

Within the scenario "Stable Biomethane Supply", the major deviations in comparison to the current biomethane potential results out of plantation harvest increase. The extent of wood processing industry contributes strongly to the biomass and therewith to the biomethane potential. Due to a relatively low yield increase, the energy crop sector is still of minor importance. In comparison to the scenario "Increased Biomethane Supply", the scenario "Stable Biomethane Supply" provides 54 % of the biomethane potential.

DISCUSSION WITHIN THE ENERGY SYSTEM

In the following, the biomethane potential is discussed in the context of the energy system of Chile. This is done with regard to the actual and future natural gas consumption.

The derived potentials of biomethane via bio-chemical or thermo-chemical conversion can substitute natural gas from fossil fuel resources. FIGURE 3 shows the current and forecast natural gas consumption as well as the technical biomethane potential of the scenarios "Increased Biomethane Supply" and "Stable Biomethane Supply". At the moment Chile consumes about 327.6 PJ of natural gas and the consumption is predicted to increase up to 510.2 PJ till the year 2015 [25]. In the scenario "Stable Biomethane Supply" a slight increase of the biomethane potential in comparison to the actual biomethane potential will occur. Therewith approximately 45 % of the future natural gas consumption of Chile (2015) could be substituted. According to the scenario "Increased Biomethane Supply" the substitution share could be raised up to 84 %.

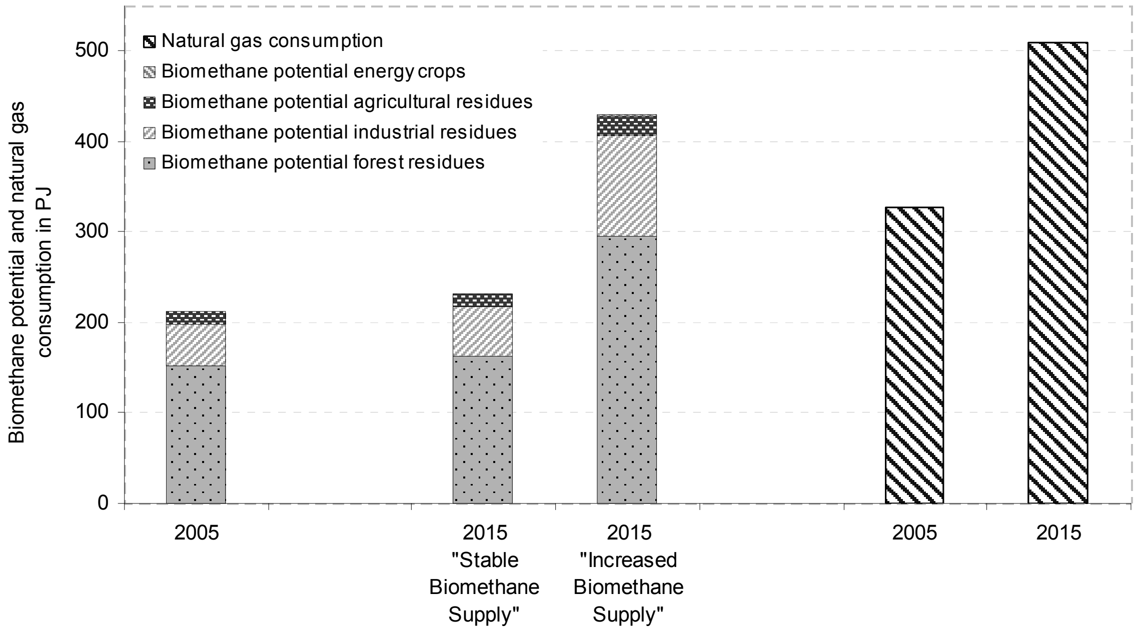

FIGURE 3: The biomethane potential and natural gas consumption in Chile

For a sustainable strategy of energy provision for Chile it is important to use options in the field of energy saving. The more the natural gas consumption can be reduced, the higher the relative substitution potential of biomethane will be.

CONCLUSIONS

The biomethane potential is based on the biomass potential from forestry, agriculture and processing industry. Within the forest sector, the national action plans are considered regarding the change of native and plantation forests. Additionally, the expected growth of the processing industry is taken into consideration. For the cultivation of energy crops only the option of growing crops on fallow land has been considered, because currently the self-sufficiency in terms of food production is below 100 % in Chile.

The results of this investigation show, that approximately 84 % of the natural gas consumption of Chile in the year 2015 can be substituted. Especially with the expansion of the gas grid infrastructure the biomass catchment area and therewith the biomethane potential could be increased substantially. The change in the forest structure contributes strongly to the technical biomass potential and therewith to the biomethane potential. Additionally, the expected growth of the wood processing industry as well as the increasing crop yield influence the technical biomethane potential.

Thus, the dependency on gas imports could be limited by the production of Biogas and Bio-SNG. Beside this, an increased added value can be expected especially in rural areas by the utilization of domestic resources.

The largest biomass potential for the conversion into biomethane in Chile is provided by the forest sector and the wood processing industry. Therefore, the regions of Biobio, Maule and Magallanes show the largest biomass potentials that could be used for the production of biomethane.

Summing up the investigation has pointed out clearly that biomass could support significantly the establishment of a more secure energy system within Chile. Additionally, the production and use of biomethane can contribute to the reduction of greenhouse gas emissions. Therefore, the production of biomethane via bio-chemical or thermo-chemical conversion is an important option for a more sustainable energy provision system in Chile in the future.

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COGENERATION USING RESIDUAL FOREST BIOMASS - A CASE OF STUDY UNDER CHILEAN ECONOMIC FRAMEWORK CONDITIONS

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Abstract: The combined heat and power systems, also known as CHP technologies, is a simultaneous generation of multiple forms of useful energy in a single an integrated system. Most of the commercial CHP technologies that use biomass as a fuel are still based on the Rankine Cycle (RC), being the Organic Rankine Cycle (ORC), Stirling engines and biomass gasification technologies still under development or in the early stage of commercialization.

In the present work an economic assessment is carried out considering biomass as a fuel for medium size biomass CHP plants (in the range of 14-25 MWe) under the economic framework of Chile, estimating the cost of production of electricity as main product.

The estimated cost of electricity production for medium size CHP ranges from 39 to 56 US$/MW$_e$h, with a cost of biomass supply at the gate of plant of 13 US$/(DMt). This estimation was obtained with a selling price of steam in the 2.5 – 3 US$/t range, considering it as a sub product, and therefore without a cost of production associated to the global balance.

INTRODUCTION

A cogeneration process is defined as a sequential or simultaneous generation of multiple forms of useful energy, usually mechanical and thermal, in a single integrated system.

Power generation as well as cogeneration by combustion can be divided into **closed thermal cycles** and **open processes** [1]. In the former, among which the steam turbine is the most important application, the combustion process and the power generation cycle are physically separated by a heat transfer from the hot combustion gas to a process medium used in a secondary cycle. Due to the separation (between the fuel-engine) the engine is solely in contact with a clean process medium.

In contrast open cycles are commonly applied for gaseous and liquid fuels used in internal combustion engines and gas turbines. The fuel is burnt either directly inside the internal combustion engine, which is operated cyclically as a four-stroke or two-stroke engine, or it is burnt continuously in an external combustion chamber and then led through an open gas turbine for expansion. The use of solid fuels in internal combustion engines is technically not feasible and their application in gas turbines is considered as complex [2].

Since biomass fuels and the resulting flue gases contain components that may damage engines, such as fly-ash particles, metals and chlorine components, the technologies for power production through biomass combustion used nowadays are based on closed thermal cycles. The main process and engine types are shown in table 1.

Table 1. Closed processes for power production by biomass combustion.

Engine Type	Range Size	Technological Status
Steam turbine	0.5 MW_e-5 MW_e	Proven technology
Steam piston engine		Proven technology
Steam screw turbine	25 kW_e-1.5 MW_e	On demonstration
Steam turbine with organic medium (ORC)	400 kW_e-1.5 MW_e	On demonstration – some commercial plants
Stirling engine	1 kW_e-100 kW_e	Under development

Many of the benefits of a CHP system stem from its relatively high efficiency compared to others, due to CHP simultaneous production of electricity and useful thermal energy. Although CHP efficiency is measured and expressed in a number of different ways, it is going to be defined as traditionally is done for a conventional Rankine cycle, as the relationship between net energy outputs (E_e) and the amount of potential energy from a fuel for power generation (Q).

$$\varepsilon = \frac{E_e}{Q} \tag{1}$$

In general, efficiency of power and CHP plants based on steam cycles are highly sensitive to scale economies. In small plants (up to 2 MW_e) electrical efficiencies leads around 8-12 %, while medium size plants (5-10 MW_e) reach around 20-25 %.

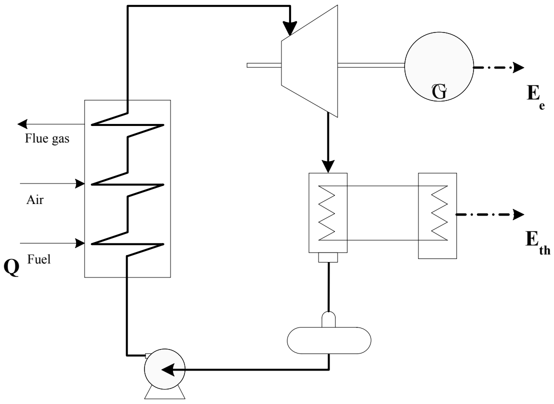

Figure 1. Flow of back-pressure plants based on the Rankine cicle. ***Source***: Adapted from *The Handbook of Biomass Combustion & Co-firing (2008).*

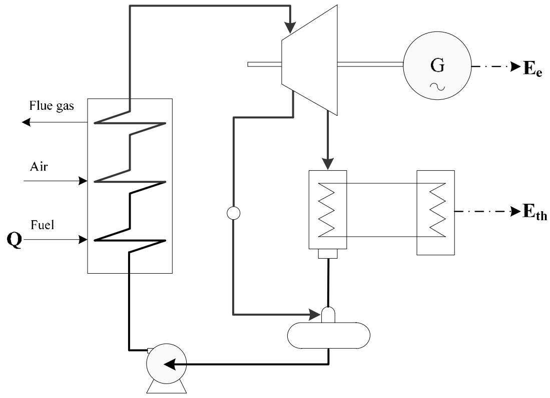

Figure 2. Extraction condensing plant with use of intermediate pressure for heat production. ***Source***: Adapted from *The Handbook of Biomass Combustion & Co-firing (2008).*

In CHP systems *the total CHP efficiency* seeks to capture the energy content of both electricity and usable steam, and is the net electrical output plus the net useful thermal output. In this way the total efficiency is defined as follows.

$$\eta = \eta_e + \eta_{th} \qquad (2)$$

For a CHP energy generation, for specific conditions, two operational modes can be distinguished. In general, small CHP plants with low electrical efficiency should be operated in a heat controlled mode, while large CHP plants are usually operated in a electricity-controlled mode. Figure 3 shows a qualitative outlook of how efficiency for heat and electricity can be achieved, in comparison with power and heat production as limits.

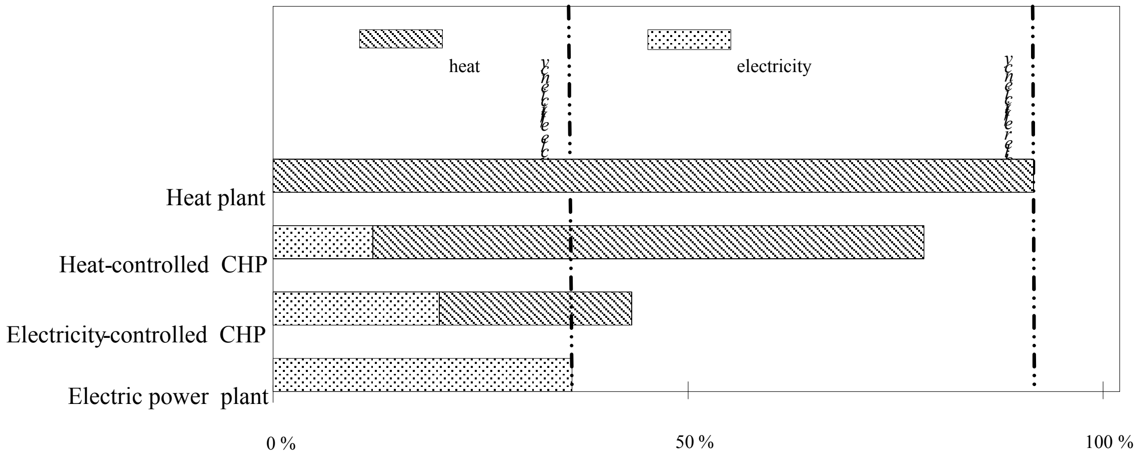

Figure 3. Share of efficiency in terms of heat and electricity production for heat, CHP and power plants.

An important operational parameter to consider is the power to heat ratio, which is defined as the relationship between the net electricity output and the net heat output:

$$\varepsilon = \frac{E_e}{E_{th}} \tag{3}$$

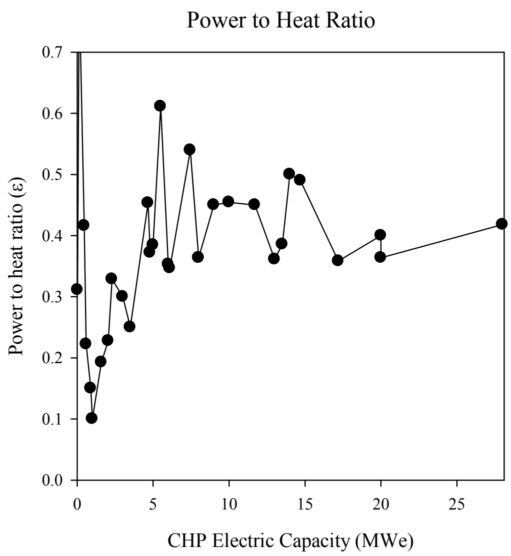

Figure 4. Power to heat ratio as a function of the plant size of biomass-fuelled CHP plants in Finland, Sweden and Denmark. ***Source***: personal compilation based on information from *Small-scale Biomass CHP Technologies- Situation in Finland, Denmark and Sweden* (2004).

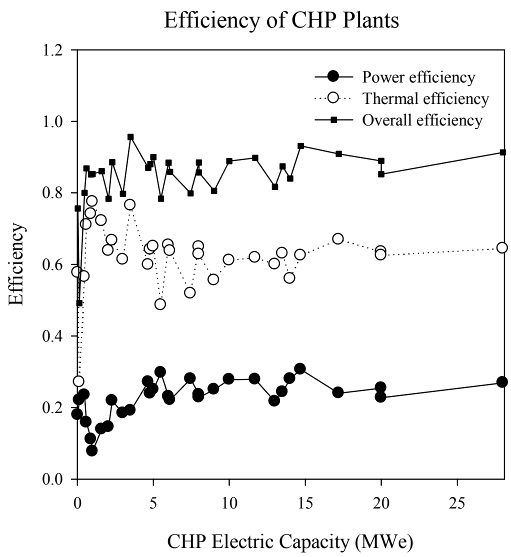

Figure 5. Power, thermal and overall efficiency as a function of the plant size of biomass-fuelled CHP plants in Finland, Sweden and Denmark. ***Source***: personal compilation based on information from *Small-scale Biomass CHP Technologies- Situation in Finland, Denmark and Sweden* (2004).

Figure 4 and 5 show the relationship between power to heat ratio and capacity for 32 plants located in Finland, Sweden and Denmark. As it is possible to see, the increasing of power heat ratio corresponds with CHP plant size.

MAIN TECHNOLOGIES FOR COMBUSTION IN COGENERATION

Pile burners is the most traditional technology for biomass combustion, where biomass is dumped on piles in a furnace and burnt with the aid of combustion air flowing from under and above the pile. Advantages of this technology are the fuel flexibility and the simple design. Important disadvantages are generally low boiler efficiency and relatively poor combustion control [1].

In the group of **grate-fired boilers**, it is possible to distinguish boilers with *stationary sloping grate*, *travelling grate* and *vibrating grate* [4]. Common to these types is a fuel feeding system which puts a thin layer of fuel on the grate and distributes it more evenly as in the case of pile burners. In a stationary sloping grate, the grate does not move, but the fuel burns as it slides down the slope. Disadvantages of this type of boiler are the difficult control of the combustion and the risk of avalanching the fuel. In a travelling grate boiler the fuel is fed in at one side of the grate and has to be burnt before it reaches the ash dumping site of the furnace. In a vibrating grate boiler the fuel is fed evenly over the whole grate. The grate makes a shaking movement and therefore has lower maintenance requirements.

Table 2. Electricity production in Chile based on combined and heat power systems fuelled by biomass. ***Source***: (1) Informe Annual 2007-Energía Eléctrica. Comisión Nacional de Estadística: (2) Declaración de Impacto Ambiental (www.seia.cl).

Plant Name	**Fuel**	**Combustion Technology**	**Power (MW_e)**	Date of Start Up
Valdivia	Forest sub product (1)	Fluidised boiler	61.0	2004
Arauco	Black liquor (1)	Recovery boiler	33.0	1996
Arauco Horcones	Forest sub product (2)	Fluidised boiler	31.0	2008
Celco	Black liquor (1)	Recovery boiler	20.0	1996
Nueva Aldea III	Black liquor (1)	Recovery boiler	20.0	2007
Nueva Aldea I	Forest sub product (1)	Travelling grate	13.0	2005
FPC	Forest sub product (1)	Travelling grate	10.0	2006
Masisa Cabrero	Forest sub product (2)	Travelling grate	9.6	2008
Cholguán	Forest sub product (1)	Travelling grate	9.0	2003
Laja	Forest sub product (1)	Stationary grate	8.7	1995
Constitución	Forest sub product (1)	Travelling grate	8.7	1995
CBB	Forest sub product (2)	Travelling grate	6.3	2006
Licantén	Forest sub product (1)	Travelling grate	5.5	2004
Total (MWe)			**236**	

In **suspension fired boilers** the fuel is fired as small particles which burn while they are being fed into the boiler, analogously to pulverised coal firing technology. A disadvantage of this system is that the fuel requires a considerable amount of pre-treatment. Its main advantage is the high boiler efficiency.

In **fluidised bed boilers** the speed of the combustion air from below the boiler is so high that the fuel becomes a seething mass of particles and bubbles. On a commercial scale one can distinguish between bubbling and circulating fluidised beds. A general feature of fluidised bed systems is that they are flexible with regard to the kind of fuel that is fired, which makes them quite suitable for co-firing different kinds of fuel.

SHORT OVERVIEW ON ELECTRICITY SECTOR AND PRICES IN CHILE

In Chile, except for the small isolated systems of *Aysén* and *Punta Arenas*, generation activities are principally developed in two electric systems. The former corresponds to Central Interconnected Grid (SIC), which covers the area from the south of *Región de Antofagasta* to *Región de los Lagos*, covering 326,412 square kilometers and supplying approximately 90% of the country's population. Its installed capacity is 9,118 MW_e and represents 70.9% of the installed capacity of the country. The second one is the Northern Interconnected Grid (SING), which covers the first and second regions of Chile (*Región de Arica y Parinacota* and partially *Región de Antofagasta*), where the principal users are mining and industrial customers. Its installed capacity is 3,569 MW_e and covers 185,142 square kilometers [5]. In each of these grids, electricity generation is coordinated by the respective independent Economic Load Dispatch Centre (CDEC) in order to minimize operational costs and ensure the highest economic efficiency of the system, while fulfilling all quality of service and reliable requirements established by current legislation.

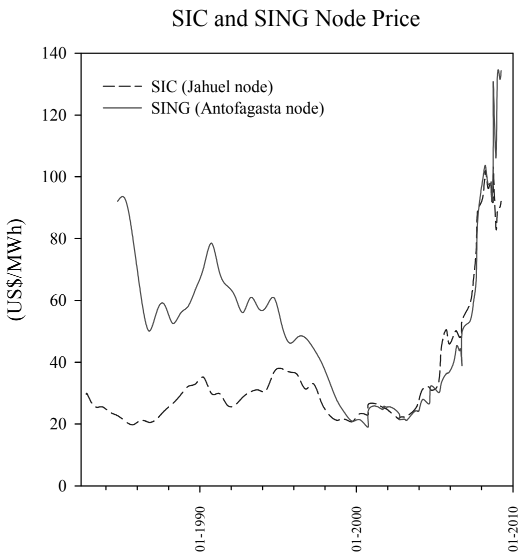

Figure 6. Energy price in the Chilean market. ***Source***: personal compilation based on information from *Comisión Nacional de Energía* (www.cne.cl)

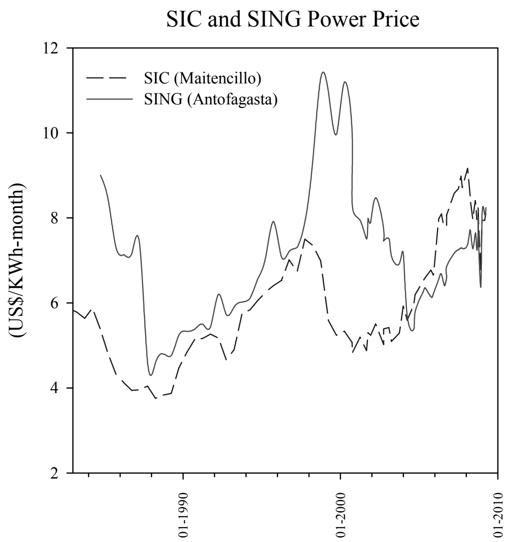

Figure 7. Energy price in the Chilean market. ***Source***: personal compilation based on information from *Comisión Nacional de Energía* (www.cne.cl)

Each generator company is required to declare availability and plant marginal operating cost every hour. These declarations are used to dispatch power plants and to set the basic marginal energy price or spot price. This price has to be used by the power generators to trade electricity among themselves to meet contracts. The spot price is heavily influenced by the opportunity cost of water in the SIC system and always equals this price. Under normal conditions the opportunity cost is equal to the operating cost of the most expensive thermal plant dispatched. If there is a water shortage the spot price becomes the outage cost. The outage cost is equal to an amount based on consumer willingness to accept compensation for a planned outage of a particular magnitude.

Regulated prices for generated electricity are determined on the basis of the expected spot price of energy over the next 4 years, and this price is fixed for six months in April and November. This node price is then converted into the regulated price of generated electricity at each of the basic substations of the system by an energy penalization factor (to reflect system losses). This gives the node energy prices. To these are added the node peak capacity charges which reflect the annual marginal cost of increasing system capacity assuming a specified reserve margin. This is paid to available generators and reflects the capital and operating costs including a 10% return of the newest technology on the system. This is similarly adjusted by a capacity penalization factor [6].

TECHNO-ECONOMIC ASSESSMENT OF CHP PLANTS – A CASE OF STUDY

Information of three prefeasibility projects was collected, which concerns investment, technology and performance, cost of labour and operation as well as fuel and administrative costs. The key aspects of all this information is summarized in the table 3.

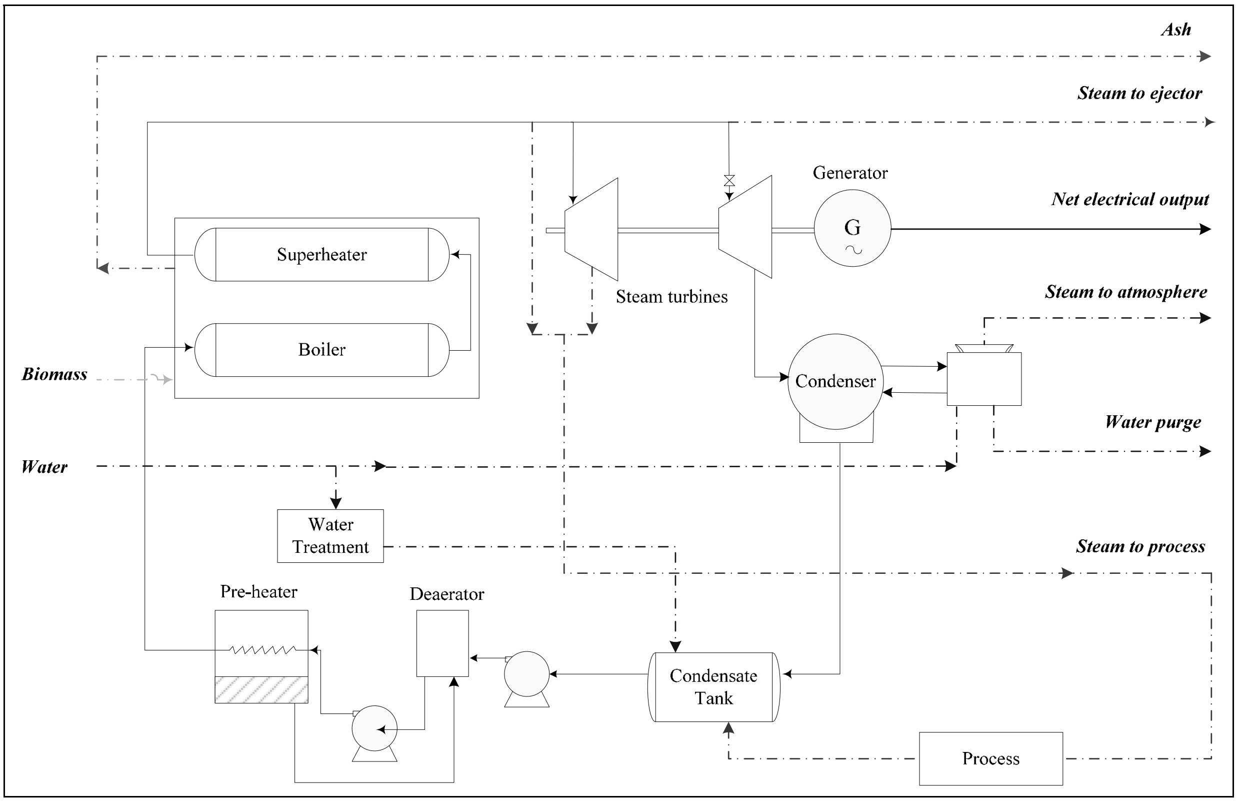

Figure 8. Common flow diagram of assessed CHP plant. ***Source***: Own elaboration with personal communications with plant managers.

A general flow diagram of the three assessed CH|P plants is shown in figure 8. The two smaller ones use travelling grate as combustion technology, while the largest one use a fluidised bed system with ad of silicate sand for improving the combustion and, in this way, the boiler efficiency. All plants use cooling towers with mechanical draft to condensate the steam from the turbine. For the requirement of water, a treatment plant is included, which covers the supply from the cooling tower system as well as from the boiler circuit.

Table 3. Key economic and performance parameters of the assessed CHP plants in Chile

Number of CHP assessed plants	: 3 with full mass and energy balance
Working hours	: 7,200 h/y
Net electrical power	: 14 MW_e, 18 MW_e and 25 MW_e
Steam to process	: flow 50 t/h; pressure 8-10 bar(g), 170-230 °C
Labor cost	: four shift of personnel
Non-Fuel costs	: water supply for boiler from 2.50 to 3.50 US$/$m^3$ water supply for cooling from 0.06 to 0.10 US$/$m^3$ ash disposal 8-10 US$/t; sand from 10 to 15 US$/t
Fuel cost	: biomass with 13 US$/(DM t)
Maintenance cost	: general maintenance as a percentage of investment
Others	: Insurance, permissions, among others

Annual operating hours in Chile typically vary from 7,200 to 8,300 for cogeneration plants fuelled by biomass, but it has been considered the lower limit, in order to estimate unitary cost under the most realistic scenario.

The cost structure was organized in five items, corresponding to *Technology*, which represent the amortization of the investment for thirty years of lifetime, *Labour*, regarding to the staff for the complete operation of the plant, *Fuel*, that for this case is only biomass at the gate of plant and under condition for its direct burn (it is not considered back fuel), with an estimated cost of supply of 13 US$ per dry tonne, for biomass recovered after harvesting and in appropriate conditions [7]. The *Non-Fuel* item is related with cost of water supply (both for the boiler circuit and for the cooling tower) and ash disposal as main items. Finally *Others* covers administrative, maintenance and overhead costs, all estimated as a percentage of the investment.

MAIN RESULTS AND DISCUSSIONS

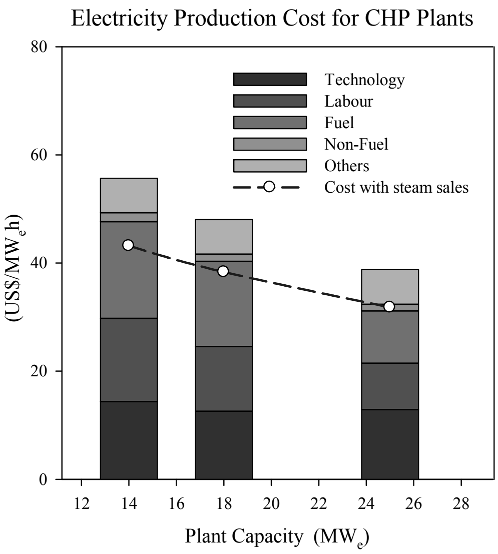

Figure 9. Electricity cost of production from assessed CHP plant fuelled by forestry biomass.

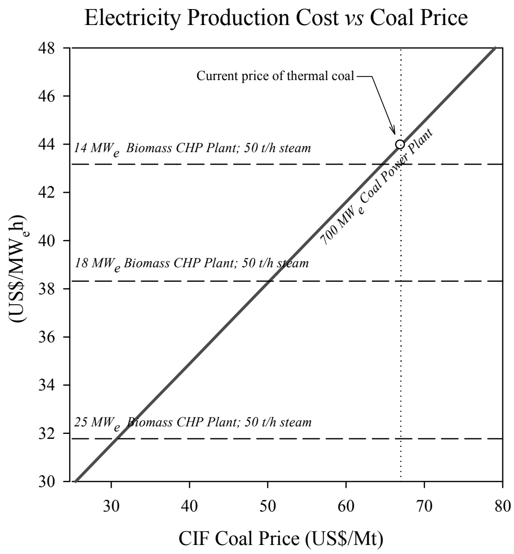

Figure 10. Electricity cost of production from coal in comparison with fuelled biomass CHP plant. ***Source***: For coal power plant, personal compilation based on information from Environmental assessment registry (www.seia.cl)

Figure 9 shows the cost structure for the production of electricity from forestry biomass for the three assessed plants. It is possible to observe that the unitary cost of electricity is very sensitive to the plant capacity, an expected result confirmed by the evaluation. The main two costs of production are concentrated on technology and fuel, representing both around 80 % of the total cost.

Due to steam is classified as sub product, with a trade price from 2 US$ to 3 US$ per tonne, its sales reduce the electricity cost of production, making it more competitive. In each case, the reduction in electricity cost range from 18 to 23 % of the original cost.

Considering the electricity production from a coal fuelled power plant, the current cost of production is around 44 US$ per MW$_e$ for a large scale plant, in which the cost of fuel represent more than 50% of the total cost of production.

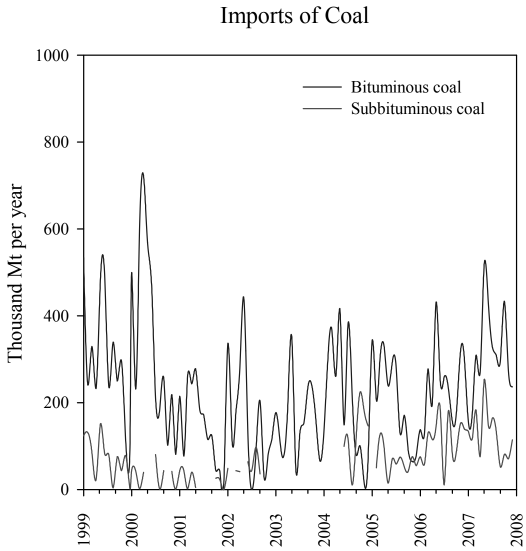

Figure 11. Imports of thermal coal to Chile the last ten years.

Source: personal compilation based on information from *Comisión Nacional de Energía* (www.cne.cl).

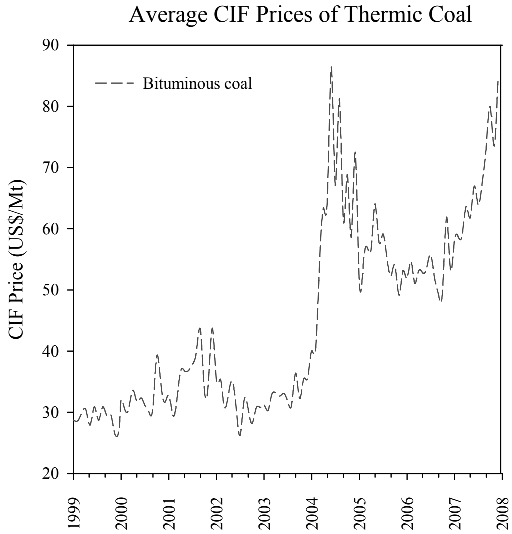

Figure 12. CIF price of coal in Chile the last ten years.

Source: personal compilation based on information from *Comisión Nacional de Energía* (www.cne.cl).

As figure 11 shows, the coal consumption for electricity production has been stable, although the price has been steadily increasing during the last years, and consequently the cost of electricity production.

Under these conditions, biomass can compete with coal electricity production only for large size plant, otherwise Clean Development Mechanism (CDM) have to be considered in order to make this kind of project financially attractive.

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OPTIMISED BIOMASS LOGISTICS FOR CONVERSION PLANTS THAT PRODUCE HEAT, ELECTRICITY AND BIOFUELS

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Abstract: Within the overall bioenergy supply chain, the biomass provision to a conversion plant is a essential part. Varying biomass and source conditions as well as conversion plant related requirements have to be considered. To provide biomass with a defined quality, the biomass supply has to be adequately designed. This provision chain consists of processes like harvest, storage, conditioning, handling and transport. According to applied process options and the supply structure a wide range of provision concepts are possible, whereas the determination of economic and environmental promising provision concepts is a complex process. A possibility to evaluate concepts is given with a multi-criteria-programming model. Such a model was developed at the German Biomass Research Centre, which allows the definition of biomass provision chains that cause minimal overall provision costs and minimal direct carbon dioxide emission under certain conditions.

The model was implemented within a comparison of two potential conversion plant sites for a 30 MW_{bf} Bio-SNG plant. The results show that the biomass provision of the plant site with a higher biomass potential is more favorable. Furthermore, the best possible biomass provision concept is characterized by process options with low losses and transport options with high load volume.

INTRODUCTION

The provision of lignocellulosic agricultural and forestry biomass to conversion plants like combined heat and power stations (CHP) to produce heat and electricity or for Biomass-to-Liquid (BtL) or Bio-Synthetic Natural Gas (Bio-SNG) plants to produce biofuel, is a crucial part of the overall supply chain. The economic supply of biomass in required quality as well as quantity to the desired destination at the right time are the objectives of the logistics as they are described in the six R-rule (Jünemann, R. 1989). To meet these objectives it is necessary to consider biomass as well as conversion plant specific issues.

The different types of biomass have various characteristics and need its particular treatment. This work considers only the solid biofuels straw, wood from short rotation coppice (SRC) and forest residues. Biomass like straw or wood from short rotation coppice is seasonally available, which makes the required logistic more complex. Harvest of agricultural feedstock is about two up to three months a year while the conversion plant demands the feedstock throughout the whole year. This leads to the need of a storage facility within the biomass supply chain. The high water content of e.g. fresh wood chips requires a drying before or within the storage process. Otherwise, there will be high dry matter losses as a result of the decomposition. The advantage of forest residues like tree tops and branches or whole trees are that they can be stored in piles at the forest road stand and dried in a natural way. The chipping of the dry material can be done the whole year round. Compared with oil or coal the low energy content of biomass, its low yields per area and its decentralized availability makes the transport more expensive.

Various requirements to the biomass provision arise from the conversion plant side. CHP plants in the scale of 5-80 MW_{bf} have a typical fuel demand from less than 10,000 t_{atro}/a up to 150,000 t_{atro}/a and are technically well established. In contrast BtL plants are viable in larger scale from 500 MW_{bf} with fuel demand of more than 1,000,000 t_{atro}/a and this technology is available in the medium to long term. These differences result in a need of technology adapted biomass provision concepts, especially if fuel requirements like chemical structure, particle size or water content are technology specific different too. In addition the biomass supply is influenced by the infrastructure of the plant site like available railways or waterways.

These aspects make it difficult to identify suitable provision concepts without further investigations into the biomass provision chain for conversion plants. This will be done in the next part of this work. Afterwards, a model for an economic and environmental optimization of the biomass provision is developed and should be understood as one approach to find the best possible biomass supply for a particular conversion plant under given circumstances.

BIOMASS PROVISION CHAIN

The biomass provision chain consists of a number of processes that are necessary to supply biomass from its source (e.g. forest stand or short rotation coppice) to a sink (e.g. conversion plant). These provision processes are: harvest, storage, conditioning, handling and transport. FIGURE 1 shows a structure of the biomass provision chain that follows the biomass flow from the source on the left-hand side to the sink on the right-hand side. The order of the particular provision processes is not defined but has to be determined due to the biomass utilization pathway. Furthermore, it can be necessary that a process has to be applied more than one time in the chain such as the transport between biomass source and a storage facility and afterwards from the storage to the conversion plant.

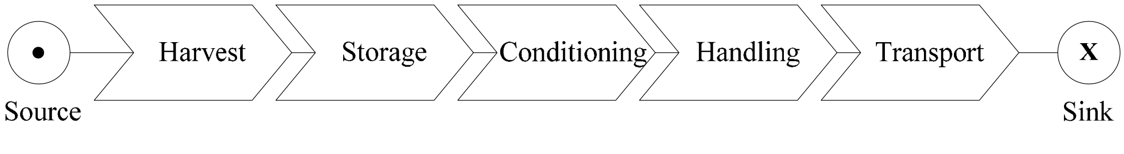

FIGURE 1: Biomass provision chain

In the following all provision processes will be described more detailed.

Harvest

As the first process in the biomass provision chain the harvest is essential to make the biomass available for its further energetic use. It includes the harvest of agricultural biomass as well as the felling of forestry biomass. The baling of straw is done with a combination of a tractor and a pulled baler. To harvest SRC different technologies like pulled whole tree bundlers or mounted chippers for tractors are tested but are still in a developmental stage. The only established technology under German conditions is an adapted forage harvester with a mounted wood harvest aggregate. Short rotation coppice with a rotation longer than four years and therefore thicker stems can be favorable harvested with forestry technology. In the forestry sector logging of trees is done with machines that fell the tree, cut of all branches and its top and cut the stem into separate parts of a defined length. Another possibility is the use of a harvester with a mounted chipper which chops the whole tree after its felling. If the branches and the tree tops should be used either a bundler collects all the residues from the ground and produces residue bundles or a mobile chipper collects and chops the residues.(Thüringer Landesanstalt für Landwirtschaft (eds.). 2006; Bayerische Landesanstalt für Wald und Forstwirtschaft (eds.). 2003; Scholz, V. 2007)

Storage

To bridge the time-related differences between availability and demand a storing of the biomass is required. Apart from the time-related aspect another important aim is to keep the biomass quality throughout the storage process. This is mainly a problem with chips from fresh harvested SRC and forest residues since its water content amounts toabout 50 %. Without a drying the decomposition process leads to massive dry matter losses and growth of mold fungus. Subject to the kind of storage facility and available technology it can be useful to combine the storage with a drying process.(Idler, C, Daries, W and Scholz, V. 2004)

A simple storage can be a pile of straw bales, branches, tree tops, whole trees or chips outside at the field or at the forest stand road. If it is uncovered a natural drying is basically possible. A more sophisticated and consequential more expensive storage is the storing of biomass in buildings or storage facilities like silos. The commodity is protected against any weather conditions and it is possible to combine the storage site with a conditioning process like drying.(Brummack, J and Polster, A. 2008)

Conditioning

Since there are distinctions between the biomass properties at the source side and biofuel properties required at the sink side a conditioning of the biomass is useful to meet the demanded needs. Furthermore, a conditioning can help to improve or enable the storage, handling or transport of the biomass. The drying process, technical or natural, makes it possible to store biomass over longer periods of time without the negative effects mentioned above and in addition drying increases the energy density based on the lower heating value. Other possibilities to increase the energy density are pelletisation, torrefaction and pyrolysis. The pelletisation is a mechanical compaction of the biomass while torrefaction and pyrolysis are thermo-chemical processes. A higher energy density per mass and volume unit improves the efficiency of the transport. For a better handling and transport forest residues can be bundled. To meet the required particle size biomass can be chopped or shredded.(Fachagentur Nachwachsende Rohstoffe e.V. (eds.). 2005)

Handling

The handling process is responsible to load, reload and transship biomass between the transport and the other provision processes. Its configuration depends on the type of biomass or rather if a bulk cargo or a piece good has to be handled. Baled straw, bundles, stems and tree residues are piece goods while chips or pellets are bulk cargo. If piece goods are transported in containers or other moveable loading units they can be handled like piece goods. Bulk cargo enables a continuous handling if conveyer belts or other conveyer technologies are applied. This is common to load ships or wagons with wood chips. The discontinuous handling of bulk and piece goods can be done by wheel loaders, folk lifts and cranes depending on the mounted equipment like buckets, forks or log grapples.(Fachagentur Nachwachsende Rohstoffe e.V. (eds.). 2005)

Transport

To move the biomass from its source to the sink and between the particular provision processes the transportation process is obligatory. Road, rail and waterway are the different possible options of transportation (air transport is not considered) which can be used by a broad variety of transport modes. The transport can be divided into multimodal, intermodal and combined transport. Multimodal transport occurs if two or more modes of transport are used on different ways (road, rail or waterway). The multimodal transport becomes an intermodal transport if only the transportation unit and not the freight itself is handled.(Bundesministeriums für Verkehr, Bau- und Wohnungswesen (eds.). 2001)

While tractors are used for short agricultural road transport mainly, the long distance transport is done by trucks. Both tractors and trucks are combined with different kinds of trailers. There are trailer, dumper and swap body solutions to transport bulk and piece goods or container and additionally road tankers for fluids. The same applies for rail transport where wagons for the mentioned purposes are available. Since diverse commodities are transported overseas as well as inland, vessels of different sizes and purposes are as well established already.(Frick, S, Müller-Langer, F and Thrän, D. 2005)

Logistic concepts

Due to the previous description it is evident that first a large number of configurations of every particular process are available and second varied orders of these processes are basically feasible. This can be seen exemplary in FIGURE 2 where possible logistic concepts are shown. Between the biomass source and the biomass sink, the conversion plant, a number of configurations are realized: The direct supply of the conversion plant (midway), the supply via storage in the first stage (upper part) and the supply via a gathering point in the first stage (bottom part). Conditioning and handling is not shown separately but handling is linked with every other process and therefore indirectly considered. Conditioning like chipping, baling or drying can be done at the gathering point or at the storage facility. Moreover the options of a transport via road, rail and waterways and its possible structure are shown as well.

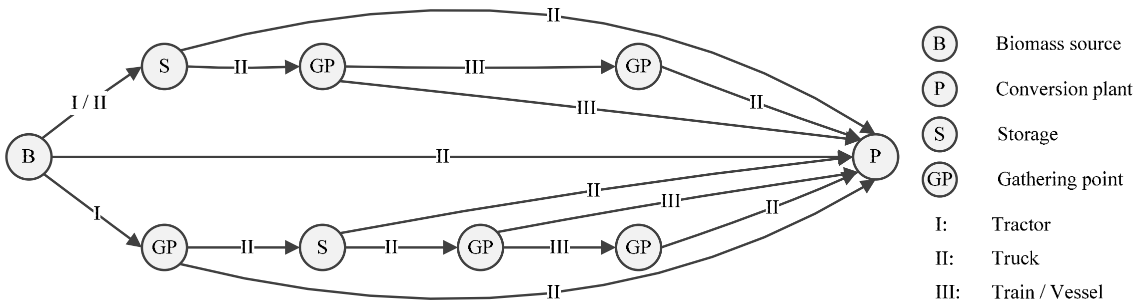

FIGURE 2: Possible logistic concepts

Attention should be paid to restrictions caused by the interdependencies between the provision processes as a result of the possible process options. A number of variations of logistical concepts are conceivable but since these restrictions have to be considered not all concepts are viable. To define economically and environmentally useful biomass logistic concepts is a complex process. Possible solution strategies of this problem are given within mathematical approaches and linear optimization models. Such a model was developed by the German Biomass Research Centre and is described in the following chapter.

OPTIMISATION MODEL

A linear optimization model allows defining an optimum solution of a specific problem while considering given circumstances. It contains decision variables, one or more target functions, a set of constraints and it is formulated as mathematical functions.

The biomass provision is a typically transshipment problem, since the transport between source and sink is divided into multiple stages. Based on a set of available provision concepts an adequate developed optimization model helps to define the economic and environmental optimized biomass provision. Such a model was developed with the aim to define a biomass provision with minimal provision costs and minimal direct carbon dioxide emission for a specific conversion plant under a set of given conditions. In addition, the costs should be considered separated into variable and fixed costs. Since more than one aim is considered and in consequence of the separation into variable and fixed costs a multi-criteria multiple-integer-programming model is required.(Domschke, W and Drexl. A. 2007)

Methodical approach

The optimization model fundamentally consists of two target functions and a set of constraints. As it can be seen in FIGURE 3 the model needs a number of information as input data and it gives information about the best possible biomass provision as output.

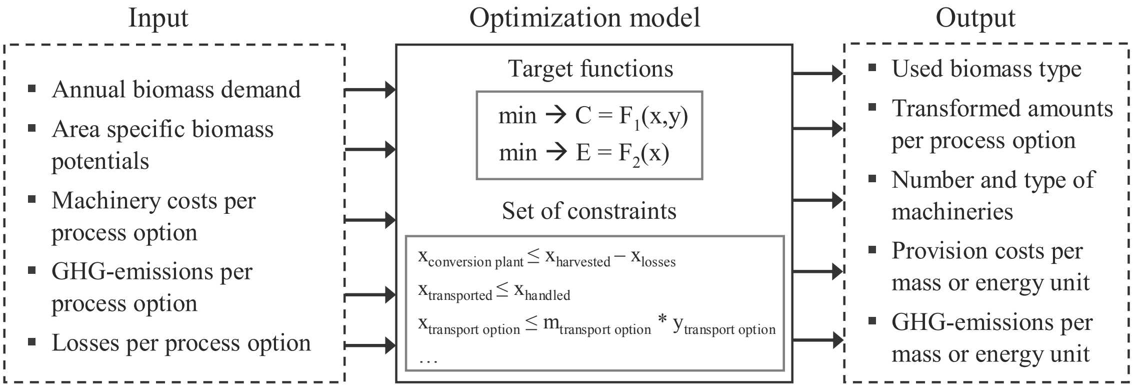

FIGURE 3: Overview of the optimization model

To consider the aim of defining the economic and environmental optimum biomass provision there is one function to calculate the costs and another function to calculate the direct CO_2 emission of the biomass provision. The overall costs are the sum of the variable and fixed costs of every provision process p, see function (1) below. The overall direct CO_2 emission result from the sum of the direct CO_2 emission of the particular processes p, see function (2).

$$\min \rightarrow C = F_1(x,y) = \sum_p (C_p(x) + F_p(y)) \qquad (1)$$

$$\min \rightarrow E = F_2(x) = \sum_p E_p(x) \qquad (2)$$

$$p \in \{Harvest, Storage, Conditioning, Handling, Transport\} \qquad (3)$$

Normally, the optimum solutions of both target functions are reached by different values of the decision variables x. As a result the minimum of the cost function is not necessarily the minimum of the emission function. In such a case the optimization model can not define an optimum solution. To handle this problem a preemptive approach was used that requires a prioritization of the target functions.(Kallrath, J. 2002) The target function with the highest priority is optimized and a given permissible deviation from that optimum must not be exceeded, while optimizing the lower priority target function. In the implemented optimization model the cost function has the highest priority and a maximum increase of 10 % of the minimum overall provision costs was defined. Function (4) shows the mathematical expression of that condition.

$$1{,}1 * F_{1\min}(x,y) \geq \sum_p (C_p(x) + F_p(y)) \qquad (4)$$

The set of constraints is a set of mathematical functions to give the optimization model a framework and to reduce the possible solutions of the model. The constraints consider the properties of the decision variables x and y, the links and interdependencies between the particular provision processes and the mass flow (balance) including losses throughout the biomass supply. Furthermore, through the constraints the provision concepts to be analyzed are determined.

Input data

As shown in FIGURE 3 the optimization model needs a number of input data, such as the annual biomass demand of an investigated conversion plant, the area specific biomass potential of the region in which the conversion plant is situated and further the machinery costs, CO_2 emission and losses per process option. These data have to be gathered and calculated to provide the model.

FIGURE 4 shows the spatial approach of the model and is based on the following assumptions:

- The conversion plant is situated in the middle of its quadratic catchment area needed for its biomass supply
- The biomass is homogeneously spread within that catchment area.
- An area specific biomass potential for the catchment area is given.

Based on that spatial structure and the annual biomass demand the size of the conversion plants catchment area can be calculated. The same approach is considered for storage facilities. It is assumed that they are homogeneously spread within the catchment area of the conversion plant and have its own catchment area, depending on storage size, as well. Consequently, it is possible to determine the average transport distance by the half of the catchment area side length of the storage as well as conversion plant.

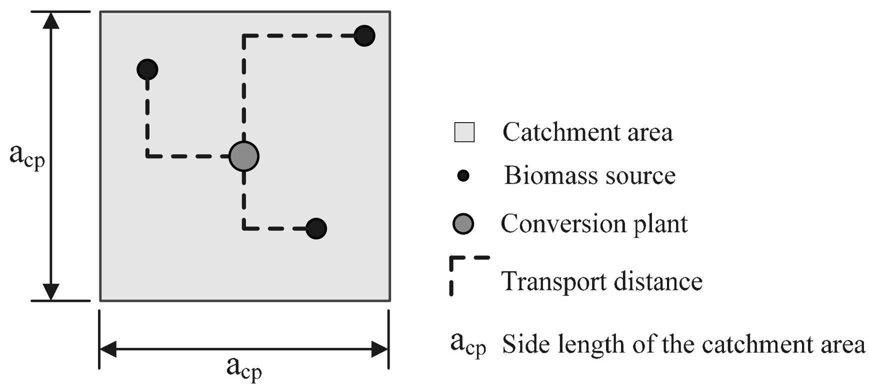

FIGURE 4: Spatial structure of the optimization model

Output data

As a result of the optimization the model gives information about the amount of the used biomass type, the number of units as well as amounts transformed for every considered process option and the provision costs as well as direct CO_2 emissions per mass and energy unit.

MODEL IMPLEMENTATION

In this chapter an example of the application of the developed optimization model is shown. The example is specified as follows:

- Conversion technology is a 30 MW_{bf} Bio-SNG plant
- Short rotation coppice (SRC) is the only biomass source
- Investigation of two different sites in Saxony and Saxony-Anhalt, Germany

Configuration

The annual biomass demand of a 30 MW_{bf} Bio-SNG plant amounts to about 56,100 t_{dm}/a, whereas an integration of the loss structure results in an amount of 66,000 t_{dm}/a. Based on this demand, the area specific biomass potential of the particular regions and the size of the storage facilities the overall transport distances can be calculated. This has been done in TABLE 1. Due to the lower area specific biomass potential the average distance of the biomass transport is about four kilometers longer in Saxony than in Saxony-Anhalt.

TABLE 1: Calculation of average transport distances
(Frick, S, Müller-Langer, F and Thrän, D. 2005)

Parameter	Saxony	Saxony-Anhalt
Area specific biomass potential (SRC) [t_{dm}/km^2*a]	41.00	69.83
Size of storages [t_{dm}/a]	500	500
Side length of catchment area of storage [km]	3.49	2.68
Annual biomass demand [t_{dm}/a]	66,000	66,000
Side length of conversion plants catchment area [km]	40.12	30.74
Average transport distances [km]	20.81	16.71

The provision chain is marked by fully-mechanized harvest, outdoor storage concepts, conventional handling technology and final transport by truck-trailer combination. Due to the high effort of gathering required data only a reasonable number of process options have been considered. TABLE 2 shows more details of the chosen process options.

TABLE 2: Considered process options
(Frick, S, Müller-Langer, F and Thrän, D. 2005 and Schmitz Cargobull AG (eds.). 2006 and Burger, F. 2004 and Spielmann, M and Bauer, C and Dones, R. 2007)

Process	Option	Description
Harvest	H FH	Forage harvester with mounted wood harvest aggregate; losses 2 %
Storage	S PwC	Simple pile with cover; losses 25 %
	S ATV	Pile with air tube ventilation system, losses 9 %
Conditioning	-	No conditioning considered
Handling	H WL	Wheel loader; losses 2 %
Transport	T FT45	Tractor with forage transport trailer; 45 m^3
	T TWT45	Tractor with two three-way tipper; 45 m^3 overall
	T SF90	Truck with sliding floor trailer; 90 m^3
	T TT60	Truck with tipper trailer; 60 m^3

Results

While defining the optimum biomass provision, for the harvest and the transport process a set of alternative process options was considered (see TABLE 2). The result of the decision is shown in TABLE 3 and represents the best possible solution of the given provision problem. Additionally the number of required units of and the amount transformed by every process option are represented as well.

For both regions Saxony and Saxony-Anhalt the optimum biomass provision applies the same process options. In the cases of available alternatives the optimization model choose the storage option with the lowest dry matter losses and the transport option with the largest load volume. The number of required transport units is different in both regions. Since Saxony-Anhalt has the higher area specific biomass potential and consequently the shorter average transport distances more trips per time unit are possible and as a result less transport units are needed. Since handling has to be done to store the biomass and to remove the biomass from storage again the transformed amount is about double as high as by the other processes. The decrease of the transformed amounts is caused by the losses of the particular process options.

TABLE 3: Chosen process options

Process	Option	Number of units [-]		Transformed amount [t_{dm}/a]
		Saxony	Saxony-Anhalt	
Harvest	H FH	5	5	65,501
Storage	S ATV	127	127	62,907
Handling	H WL	4	4	121,436
Transport	T FT45	9	8	64,191
	T SF90	4	3	56,100

Further results of the optimization are the overall provision costs and the CO_2 emission of the biomass supply. Both the costs and the emission are shown in FIGURE 5. The provision costs for a plant in Saxony amounts about to 24 €/t_{dm} compared with about 22 €/t_{dm} in Saxony-Anhalt. This difference is a result of the different transportation costs caused by the shorter average transport distance in Saxony-Anhalt. Biomass transport accounts for the largest share of the provision costs followed by harvest, handling and storage.

With about 15 kg/t_{dm} the direct CO_2 emission of the biomass provision in Saxony is slightly higher than in Saxony-Anhalt with about 14 kg/t_{dm}. Again, this difference is caused by the transportation process only. The storage process accounts for zero emission since only storing into storage and removing of the biomass from storage are producing CO_2 emission and these are considered by the handling process. Biomass harvest accounts for the largest share of direct CO_2 emission followed by transport and handling.

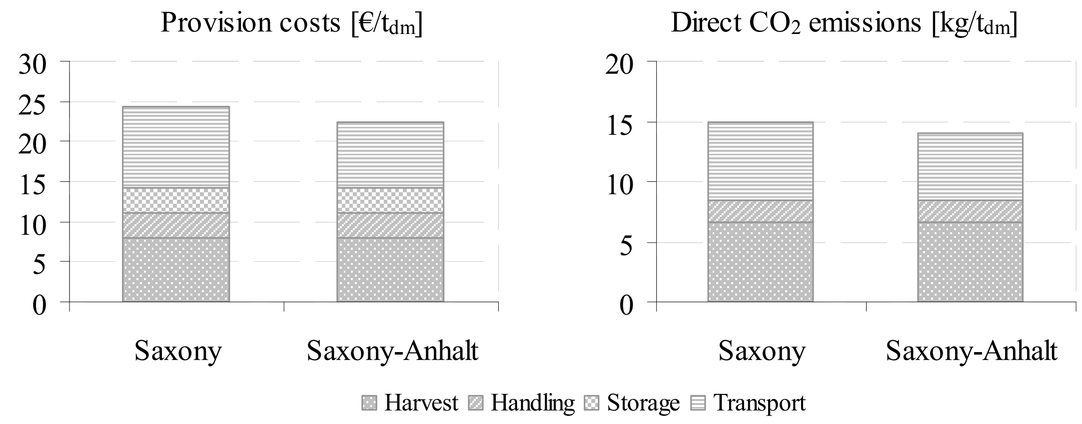

FIGURE 5: Costs and carbon dioxide emission of the biomass provision

The comparison of the two regions has shown that a higher area specific biomass potential results in lower overall biomass provision costs and lower direct CO_2 emission of the biomass provision, assumed that all other conditions are the same.

SUMMARY

To identify useful biomass provision concepts for conversion plants that produce heat, electricity and/or biofuels varied biomass source and conversion plant related requirements have to be considered. Every type of biomass has its own properties and availability. The possible conversion plant technologies demand biomass in different qualities and quantities. As a result not any biomass is necessarily suitable for any utilization path.

The processes harvest, storage, conditioning, handling and transport are elements of the biomass provision chain responsible for supplying biomass as required to the conversion plant. Subject to the applied process options and its structure it is possible to define biomass provision concepts suitable to balance the given biomass properties at the source side and the required solid biofuels properties at the sink side. To define economic and environmental useful biomass provision concepts is a complex process, due to the high number of available provision chains. A possible strategy to handle this problem is to work with a mathematical approach that considers both the economic and the environmental aspect of the biomass provision. This can be done with a multi-criteria multiple-integer-programming model. Such a model was developed at the German Biomass Research Centre and it allows considering different biomass types and different provision process options at the same time for a specific conversion plant site and technology.

The implementation of the model allows the identification of economic and environmental promising provision concepts for biomass, whereas defined frame conditions (e.g. source and sink) are taken into consideration.

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LCA OF BIOMETHANE AS VEHICLE FUEL -THE EU PROJECT BIOGASMAX

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Abstract: Fuels based on renewable resources are currently on everyone's lips as they are not based on and therefore do not deplete fossil resources. There are currently four big research projects about alternative fuels running under the 6th framework programme of the European Union. The EU promotes the development mostly for environmental reasons, but supply security is also an issue.

The project BIOGASMAX deals with the production of biogas in different European cities and regions. Biogas is produced from all kinds of waste and subsequently upgraded to biomethane (natural gas quality), distributed and eventually used as vehicle fuel. It is the responsibility of the GaBi group to conduct Life Cycle Assessment (LCA) studies of the various biomethane provision chains.

LCA of the different technologies at sites all over Europe requires an efficient data collection. A detailed evaluation framework was developed in BIOGASMAX, including automatic data upload procedures as well as a tool to provide specific online questionnaires and ad hoc calculation of indicators and charts.

From an LCA point of view, challenging methodological questions have to be answered, e.g. the evaluation of the complex and interrelated systems of "waste disposal", "(bio-)fertilizer production" and "fuel production".

INTRODUCTION AND BACKGROUND

Human activities, transport in particular, are responsible for a great share of the increase in Earth's greenhouse effect, and therefore climate change. In terms of its energy demand, the European Union is increasingly dependent on fossil fuel, which is, for the most part, imported from countries outside of the European Union. This complex situation leads to significant ecological and economical risks for society, such as:

- Constantly increasing energy needs,
- oil products produced in politically unstable regions,

– the continuous rise in the price of oil the depletion of limited resources, and
– climate change due to the emission of greenhouse gases from the combustion of fossil fuels.

The European Commission seeks to tackle these issues through a series of initiatives, including many that focus on the transport sector, which is almost completely dependent on oil. For this reason, the EC has launched a call for projects in the context of the "Biofuel Cities" initiative that focuses on biofuel-related projects.

The "Biofuel Cities" initiative is an umbrella project, linking three of the main European projects dealing with alternative fuels and their use in vehicles (see Figure 1). The BIOGASMAX project deals with the generation of biomethane, mainly from organic wastes. The BEST project assesses the production and usage of ethanol. The Hyfleet:CUTE project considers hydrogen as fuel for vehicles. Though hydrogen nowadays is not a renewable fuel, because the energy used to produce it mainly stems from fossil resources, it may be regarded as mere energy carrier, similar to electricity, which in the future might also be generated from renewable resources. It certainly is an alternative fuel and therefore integrated into the Biofuel Cities initiative. BIOGASMAX will be presented in more detail below.

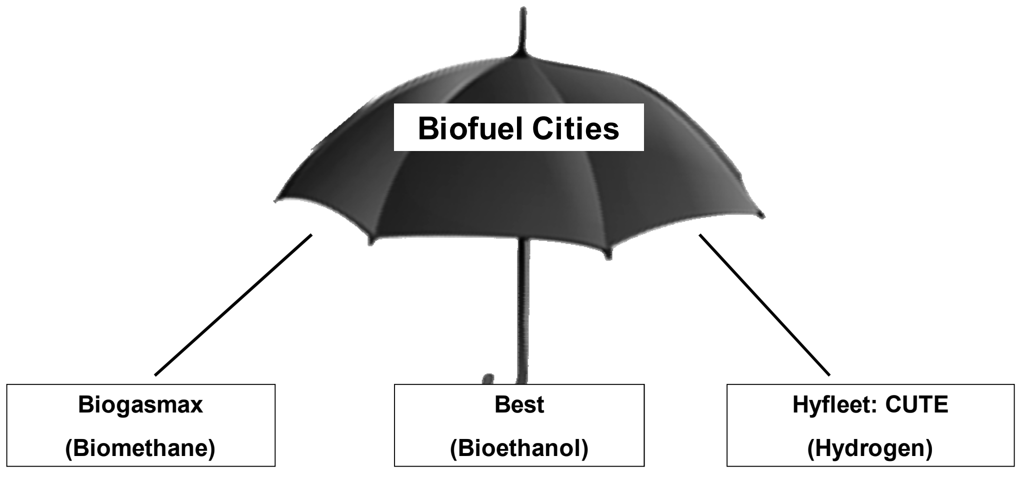

FIGURE 1: The Biofuel Cities initiative

POTENTIALS AND BENEFITS OF BIOGAS

The EC plans to substitute conventional fuels based on fossil resources by alternative fuels in the future. The target has been set at 20% of transportation fuels to be substituted by 2020. 5-8% shall be covered by biofuels, 10% by natural gas and 2-5% shall be the contribution of hydrogen (DG TREN 2003).

Biogas will be a significant part of the 5-8% within the biofuels sector. Assuming a 5% replacement in 2020 by only biogas would require about 19,000 bill. Nm^3 biogas/year corresponding to an avoidance of CO_2 emissions of around 35,800,000 t/a.

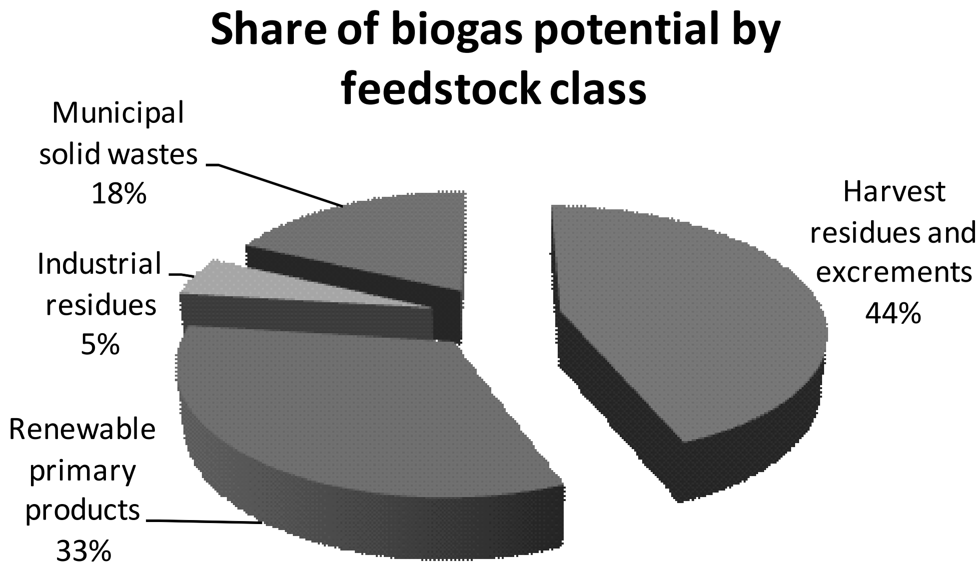

FIGURE 2: Distribution of the biogas potential in Europe

SYSTEM DESCRIPTION – THE BIOGASMAX PROJECT

BIOGASMAX is an Integrated Project (IP) of the 6th Framework Programme of the European Union. It started in January 2006 under the call: "FP6 -2004-TREN-3" with a planned duration of 4 years. It is part of the activity on Alternative Motor Fuels and of the Biofuel Cities Initiative.

The objective of BIOGASMAX is to address urban issues related to air and water pollution, as well as waste management. To this end, it uses a virtuous circle where biogas is produced from various types of waste. Cities are called upon to manage this new combination of waste disposal and fuel production while monitoring the economic and environmental impact in order to produce fuel for transport with no or little harm to the environment.

A well-to-wheel approach is followed to identify the potential for efficiency gains and cost optimisation in order to ensure market expansion. The technical reliability, cost-effectiveness, environmental & social benefits of biogas fuel are analysed, large-scale demonstrations are performed to optimise industrial processes, to experiment with and benchmark new and near-to-market techniques and to expand biogas fleets.

Ways to remove technical, operational and organisational/institutional barriers which might inhibit or prevent alternative motor fuels and energy efficient vehicles from entering the market are identified and assessed, and knowledge and results are spread to European cities and stakeholders. There is a special emphasis on dissemination of knowledge to the new EU member states.

The evaluation of the project is be carried out with respect to the EU aims "reduction of CO_2 emissions", "substitution of fossil fuels", "reduction of dependency", "reduction of other emissions", "reduction of noise, especially in urban areas", and "proper waste handling".

The benefits of the project, as can be seen in Figure 3, are derived from the combination of the benefits of:

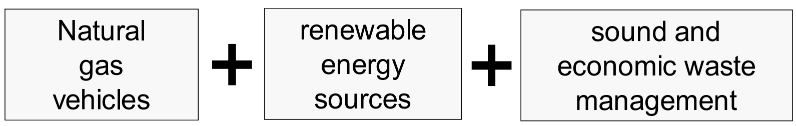

FIGURE 3: Benefits of BIOGASMAX

The research and development projects proposed in the context of BIOGASMAX are closely linked to the following four main fields of technological activities:

- Production of biogas from various types of waste;
- upgrading of biogas to fuel quality;
- distribution of fuel (to ensure the availability of biogas for transport and experiment with the injection of biogas into natural gas grids); and
- use in vehicles (increase the number of biogas-fuelled vehicles).

ROLE OF BIOGASMAX PARTNERS

BIOGASMAX includes 26 partners in Europe. Five countries (France, Italy, Poland, Sweden and Switzerland) participate in the project to demonstrate the technological and economic viability of biogas production from urban waste.

Four partners (Lille, Gothenburg, Stockholm and Rome) have quantified objectives in BIOGASMAX. Four partners in technology, evaluation and the transfer of knowledge (ISET, Nova Energy, University of Stuttgart, ENGVA) have transversal responsibilities within the project.

BIOGASMAX is divided into eight Work Packages:

- WP1: project management
- WP2: biogas production
- WP3: upgrading
- WP4: distribution
- WP5: use in vehicles
- WP6: evaluation
- WP7: transferability studies
- WP8: communication.

BIOMETHANE FROM WASTE

Figure 4 shows the principle of producing biomethane. After a few pre-treatment steps, the feedstock is digested under anaerobic conditions. The product is a mixture of methane (CH_4), carbon dioxide (CO_2), water vapour, and trace gases such as hydrogen sulphide (H_2S). The term "upgrading" refers to a process chain through which, ideally, all components except methane are removed. In practice, the upgraded biogas (called biomethane if derived from renewable sources) is about 95-99% methane, depending on the technology applied.

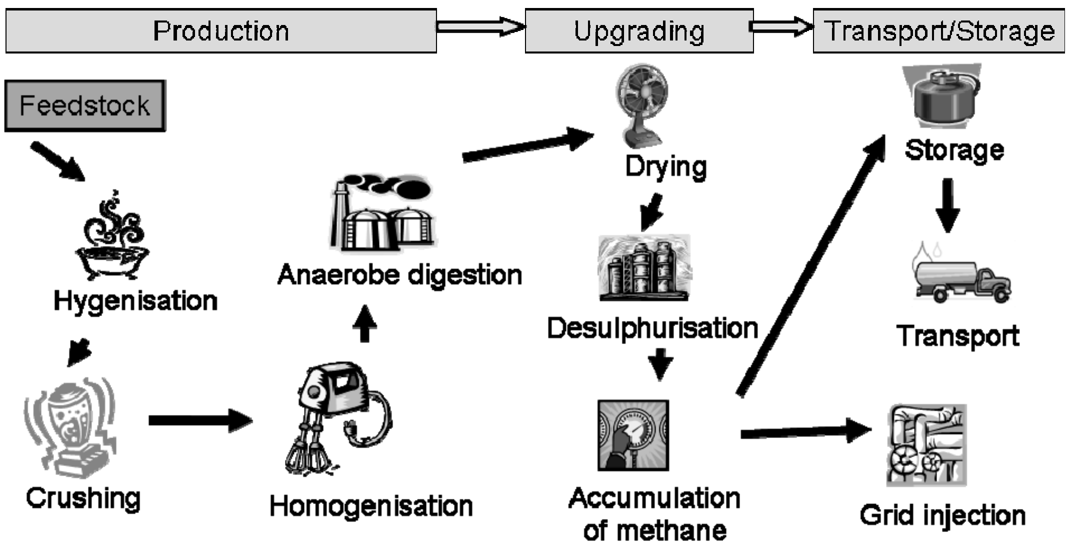

FIGURE 4: The BIOGASMAX system

One of the main advantages of biogas is the great variety of feedstock. Compared to other biofuels which rely on only one or a rather limited set of possible types of feedstock, biogas can be generated from a broad selection of substances, of which many accrue as wastes or residues like sewage sludge, food waste and by-products, municipal organic waste, agricultural residues and manure. Thus, producing biogas is an interesting way of recovering what would otherwise be only waste.

Another important point is, that biomethane has practically the same properties as natural gas, so it can be used as substitute for it. Lots of vehicles are already able to use compressed natural gas (and biomethane too). Furthermore the same infrastructure for distribution and fuelling can be used. The introduction of biomethane as a fuel doesn't require the typical introduction efforts as with many other alternative fuels. The process of market introduction may also be slowed down if it turns out to be necessary without giving up the market.

DEMONSTRATIONS

The E20 highway connecting the cities of Stockholm and Gothenburg is being outfitted with biomethane filling stations. The goal is to enable vehicles running on biomethane to make the journey between the two most important cities in Sweden. A second project is to connect Stockholm to the cities situated along the E18/E20. Gothenburg plans to build 4 biogas filling stations on the E20 highway and Stockholm 3 filling stations on the same highway.

In Rome, the upgrading of an existing waste treatment plant to an organic waste treatment centre (with a total capacity of 90,000 t/y) and a new anaerobic digestion unit (with 4 digesters) on the site with a raw biogas production estimated at 10 million Nm^3/y is planned. The plant design is in an advanced stage, but the plant itself has not been built yet.

Lille builds a new organic waste recovery centre, which will treat 100,000 tons of organic households waste and produce upgraded biogas to refuel 100 urban buses and service cars in 2007.

Bern produces 1 million Nm^3 of biomethane from sewage sludge and bio-waste digestion in order to feed 30 gas-powered buses. Biomethane is injected into the grid and distributed to filling stations also for private cars.

DATA COLLECTION

Demonstration sites in five different countries and detailed technical analyses require a sophisticated data collection system which ensures gathering of all necessary data while at the same time avoiding double collection due to overlaps of the data needs of different assessments or work packages (see Figure 5).

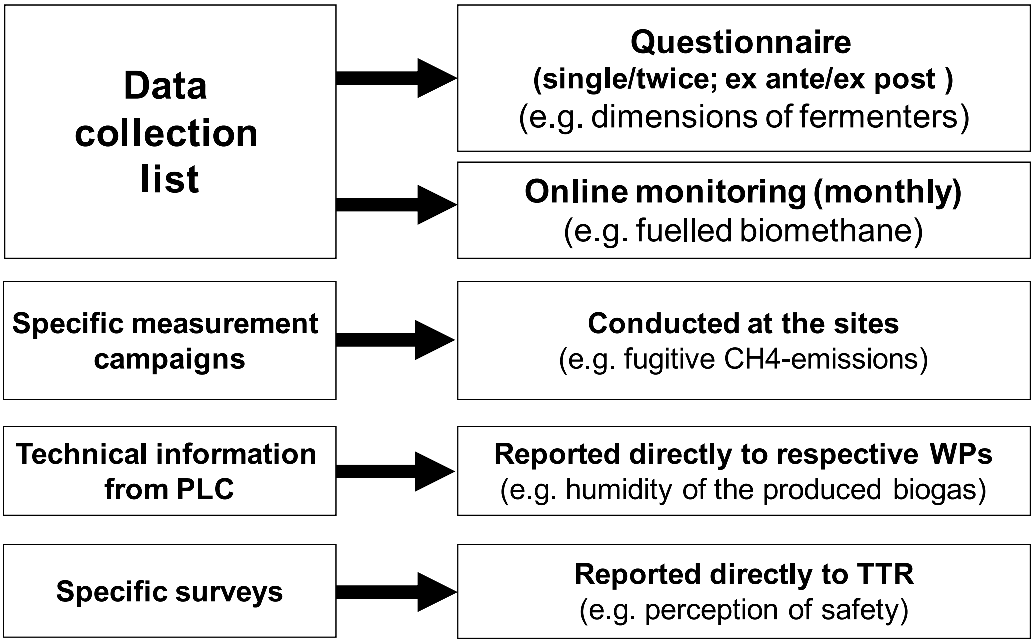

FIGURE 5: Means of data collection

The relevant and necessary technical data sets have been compiled into a data collection list and mainly divided into two groups according to their collection frequency. Frequently collected data sets are gathered via direct upload from the plants' control software (programmable logic controller, PLC) and monthly online questionnaires (using software called SoFi). Ex ante and ex post values as well as invariant parameters are collected via Excel-questionnaires. The data flow is illustrated in Figure 6.

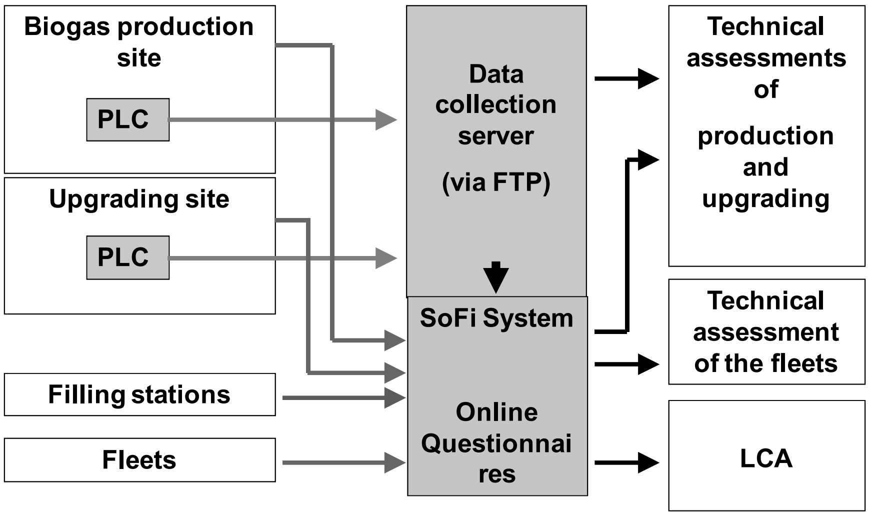

FIGURE 6: Overview data flow operating data

Advantages of SoFi are the immediate processing of the filled-in data, so mistakes can be identified by the data reporter and corrected as results can be seen immediately. It is web-based, so project-wide data collection and central evaluation is possible.

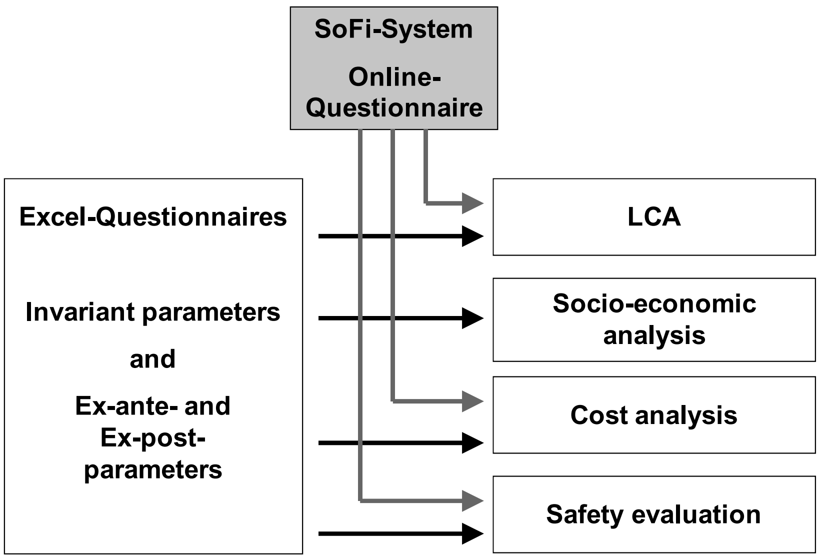

FIGURE 7: Overview data flow questionnaires

Especially the work packages dealing with production and upgrading need specific data with a short measuring frequency (minutes) to assess and optimise the production and upgrading processes. This technical data is gathered from PLCs of the respective plants and uploaded to a data collection server. Additionally, specific measurement campaigns have to be conducted at the different sites, e.g. to assess fugitive emissions.

Questions about acceptance and perception have to be asked to different groups of interviewees. Which groups can be assessed at which site is clarified in the first Excel-questionnaire. These sites then receive special questionnaires for the purpose.

The information from the questionnaires and the online monitoring tool are available as input for the different analyses (see Figure 7). These will be compiled in the evaluation report at the end of the project.

CALCULATION OF CREDITS

Figure 8 shows the material flows into and out of the BIOGASMAX system. In the case of BIOGASMAX, the use of biomethane in vehicles is seen as the main purpose of the product system and is therefore used to define the functional unit. The by-product "biofertilizer" can be handled by giving credits for avoided production and usage of industrial fertilizer according to its nitrogen, phosphorus and potassium content. However, a potentially different behaviour regarding N_2O-emissions or bioavailability is disregarded when using that approach.

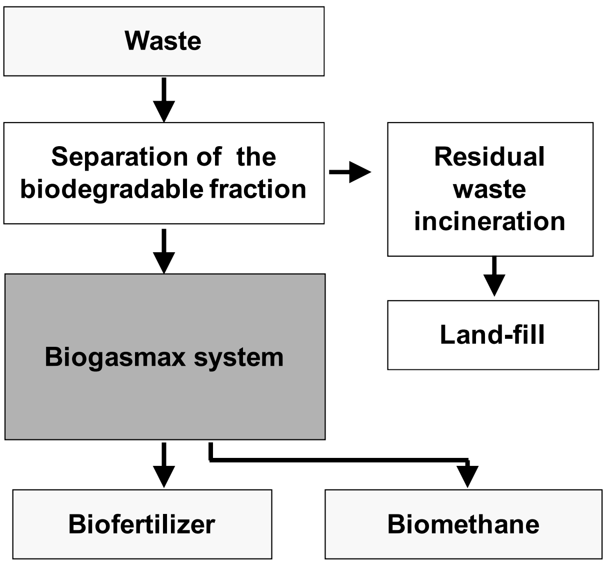

FIGURE 8: Simplified overview of the material flows

On the feedstock side it is more difficult. Mainly residues and wastes which have to be treated are used in BIOGASMAX. Their value is zero (or even below), therefore they enter the system burden-free. Using wastes as input is one of the big advantages of this approach in comparison to the cultivation of energy crops, necessary for most of other biofuels. However, by using wastes and residues as input for the processes, the demand increases and the market conditions change, resulting in increasing prices for residues as more and more biomethane producers compete for them. The approach of unburdened feedstock will become obsolete sooner or later. The residues and wastes will not be residues or wastes anymore, but become by-products of the preceding system. As far as they cannot be used in another way they will still be considered as entering the system burden-free. In case the residues can be used in another way (e.g. as fodder for pigs), this alternative, inhibited use has to be accounted for.

A BUILDING BLOCK FOR THE MAJOR LONG-TERM GOAL

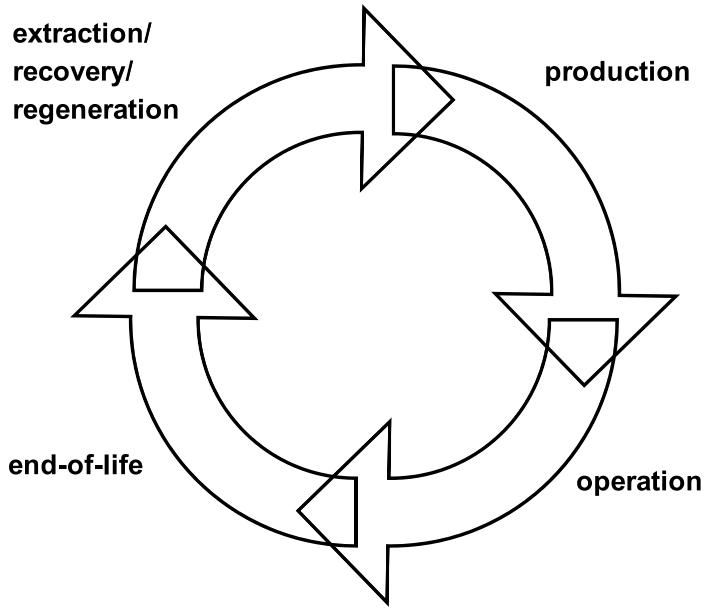

FIGURE 9:Turning waste into resources means closing loops

Summing up BIOGASMAX, the strength is turning wastes into resources and consequently closing loops (see Figure 9). In fact, it is not an infinite loop but rather an extra loop added to the life path of the preceding product. Anyway, this loop is added with no need for additional primary resources. Subsequently, closing loops means avoiding virgin production of materials (while still receiving the intended benefit), which in turn means preserving resources. Preservation resources is equal to the preservation of options for future generations. Preserving options for future generations without compromising the quality of life of the present generation is one of the definitions of sustainability. Thinking further into the future it seems to be very likely that the wastes of today (and past days) may soon become the resources of tomorrow.

ACKNOWLEDGEMENT

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ECOLOGICAL EVALUATION OF SELECTED 1ST AND 2ND GENERATION BIOFUELS – FT FUEL FROM WOOD AND ETHANOL FROM SUGAR BEETS

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Abstract: In order to reduce greenhouse gas emissions and fossil fuel consumption biomass is increasingly considered as raw material for alternative fuel production. However during biomass cultivation and processing other environmental problems can be amplified. Therefore in this contribution exemplary process chains of 1st generation ethanol and 2nd generation Fischer-Tropsch (FT) fuel are analyzed and comprehensively assessed from an ecological point of view using the methodology of life cycle assessment (LCA). The material and energy flows are modeled along the whole value chains using the software tool Umberto® together with the ecoinvent v2.0 LCI database. For life cycle impact assessment we apply the midpoint method CML 2001 for several impact categories as well as the endpoint method Eco-indicator 99 (EI 99). Exemplary results according to CML 2001 show a lower impact on climate change for the biogenic fuels compared to the fossil references. In contrast, emissions causing acidification are higher for the biogenic fuels. According to EI 99 FT fuel from short rotation wood and ethanol from sugar beets show higher overall environmental impacts than the fossil references while FT fuel from residual forest wood shows a lower overall environmental impact. The results show that single impact categories are not representative for the overall environmental effect and that different assumptions behind the methods need to be reflected and discussed.

INTRODUCTION

Declining fossil raw materials and an increasing necessity for the reduction of GHG emissions strengthen the competition for biomass and arable land. Besides electricity and heat generation in households and power plants, biomass is increasingly considered for the production of liquid fuels as well as chemicals.

Currently biodiesel and bioethanol are the biofuels with the largest production volume in the world. In 2007 approx. 10 bn litre biodiesel and 52 bn litre bioethanol have been produced worldwide. The largest amount of ethanol is produced in the US based on corn (24.4 bn litre in 2007), in Brazil based on sugarcane (18.0 bn litre in 2007) and the EU (2.3 bn litre) based on grain and sugar beets. The largest amount of biodiesel is produced in the EU based on oilseed rape (5.8 bn litre in 2007) (cf. Sims and Taylor, 2008 and Coyle, 2007). In Germany, the so-called first generation biofuels, i.e. biodiesel, plant oils and bioethanol (starch or sugar based), cover already 7.6 % of the entire German fuel demand, whereof 80% is represented by biodiesel, 19% by plant oils and 7% by bioethanol (cf. BMU, 2008). These first generation biofuels compete directly with the food industry for raw materials as well as arable land. Ethanol can be added up to 5% in fuels for conventional Otto engines and up to 85 – 100% in fuels for so-called flexible fuel vehicles. Furthermore, ethanol can be used for the production of ETBE (Ethyl tert-butyl ether) which can be added up to 15% in fuels for conventional Otto engines as a replacement for MTBE (Methyl tert-butyl ether) to enhance knock resistance. The large-scale production of so-called 2nd generation biofuels (e.g. Fischer-Tropsch (FT) fuel) is still under development. These processes use lignocellulosic raw materials e.g. straw, wood or plant residues for fuel production ("Biomass to liquid (BtL) – fuels") and therefore avoid the competition with the food industry for raw materials. However, competition for arable land occurs in case that energy crops such as short rotation wood are grown on arable land. Besides the wide variety of possible feedstocks whole plants can be processed for 2nd generation biofuels production which might result in higher fuel yields per area. As fuel properties can be adapted to particular engines (e.g. via variation of pressure, temperature, choice of catalyst during fuel synthesis) BtL-fuels are often referred to as "designer fuels".

In 2007 approx. 400,000 ha sugar beets were cultivated in Germany with an average yield of 63 t_{wet}/ha*a compared to the average yield of wheat and rye which accounts for approx. 7 and 4 t_{wet}/ha*a respectively (cf. Statistisches Bundesamt, 2008). Related to the cultivated area ethanol from sugar beets shows significantly higher reduction potentials regarding primary energy demand as well as greenhouse gas (GHG) emissions in comparison to ethanol based on grain (cf. Reinhardt et al., 2006). The average stock of wood in German forests accounts for approx. 320 m^3/ha with an annual growth of 13 m^3/ha*a whereby residual forest wood accounts for approx. 1 t /ha*a (cf. Polley and Kroiher, 2006). Short rotation plantations are cultivated in Germany currently only on a pilot scale, i.e. a total area of less than 1,000 ha.

The ecological assessments of process chains for biomass utilization can contribute to identify sustainable biomass utilization paths against the background of limited arable land together with a limited availability of biomass. In this contribution we compare exemplary process chains of 1st and 2nd generation biofuels from an ecological point of view using the methodology of life cycle assessment. We consider the production of 1st generation ethanol from sugar beets and of 2nd generation FT fuel from residual forest wood and short rotation wood as they are promising pathways for a further increase of biofuels production in Germany. Regarding life cycle impact assessment we apply two different approaches, the midpoint method CML[1]2001 and the endpoint method Eco-indicator 99 (EI 99) in order to analyze the influence of different approaches for the assessment of biomass utilization pathways.

METHODOLOGY FOR THE ECOLOGICAL EVALUATION OF PROCESS CHAINS

The ecological evaluation of the considered process chains is carried out following the methodology for life cycle assessment (LCA). According to the international standards ISO 14040 and 14044 the life cycle of a product is modeled as a so-called product system consisting of different unit processes along the value chain (cf. DIN EN ISO 14044, 2006 and DIN EN ISO 14040, 2006). All inputs and outputs of the product system i.e. energy, raw materials inputs and emissions are quantified and summarized within the so-called life cycle inventory (LCI) which is the basis for the subsequent life cycle impact assessment (LCIA). LCA studies can be sub-divided into four main steps: *goal and scope definition*, *life cycle inventory analysis*, *life cycle impact assessment* and *interpretation of the results*.

Goal and scope definition and life cycle inventory analysis

Within our study the process chains for the production of 1st generation ethanol and 2nd generation FT fuel are compared from an ecological point of view to each other as well as to fossil gasoline and diesel respectively. Thereby, possible ecological advantages and disadvantages of the considered process chains are identified. For our analysis a cradle to grave analysis including biomass production, biomass transport, processing of the biomass to ethanol and FT fuel as well as fuel use in passenger cars is carried out. For life cycle inventory analysis a detailed modeling of mass and energy flows is carried out using the software tool Umberto® together with the ecoinvent v2.0 LCA database (cf. ecoinvent Centre, 2007). The life cycle inventories comprise information on resource consumption, land use and emissions for each process step along the value chain. By-products, i.e. surplus electricity generation during FT fuel production is accounted for as credits for the substitution of electricity from the German electricity mix (cf.VIK, 2008). All results are referred to 1 GJ of fuel as the functional unit.

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Life cycle impact assessment

Life cycle impact assessment is supposed to identify and to judge the extent and significance of environmental effects throughout the life cycle of a product. For life cycle impact assessment LCI results (e.g. SO_2, HCl emissions) are assigned to the corresponding impact categories (e.g. acidification). Through so-called characterization models the LCI results are converted to indicator values (e.g. SO_2 emission equivalents). Optionally indicator values of different impact categories can be normalized, weighted and grouped (cf. DIN EN ISO 14044, 2006). There are problem-oriented approaches, e.g. the CML 2001 method (cf. Heijungs et al., 1992) as well as damage-oriented approaches, e.g. the EI 99 method (cf. Goedkopp and Spriensma, 2001) available for life cycle impact assessment. The former determine the contribution of LCI results to environmental problems which are so-called midpoints within the cause-and-effect chain. The latter determine the contribution of LCI results to environmental damages which are so-called endpoints within the cause-and-effect chain. Within our study we apply two different methods for life cycle impact assessment in order to determine the influence of different approaches for life cycle impact assessment on the results of our assessment. The above mentioned and in the following described methods are provided by ecoinvent Centre (2007) and are used in our study together with the LCA software Umberto®.

The CML 2001 method

The life cycle impact assessment method CML 2001 was developed by the Center of Environmental Science of Leiden University (CML) together with The Netherlands Organisation for Applied Scientific Research (TNO) and the Fuels and Raw Materials Bureau (Bureau B&G). The method is described within the operational guidelines to perform life cycle assessment according to the ISO standards (cf. Heijungs et al., 1992 and Guinée et al., 2002). By means of this midpoint method contributions of a product system to different environmental problems are determined. These environmental problems are represented through impact categories. For life cycle impact assessment the life cycle inventory results are assigned to the appropriate impact categories and are converted via characterization models to the corresponding indicator values. According to Guinée et al. (2002) there are three groups of impact categories: Baseline categories (group A) which are most commonly used in LCA studies, study-specific impact categories (group B), which are included depending on goal and scope definition and related data availability and other impact categories (group C) which need to be further developed before they can be used within LCA studies (cf. TABLE 1). Within this contribution we analyze the impact categories climate change and acidification which are currently most commonly used in studies on ecological assessment of biofuels as well as the impact category land use competition. For the impact category climate change the characterization model GWP (global warming potential) is used to convert greenhouse gas emissions (e.g. CO_2, CH_4, N_2O) to the indicator value CO_2-equivalents and for the impact category acidification the characterization model AP (acidification potential) is used to convert acidifying emissions (e.g. SO_2, NO_X, NH_3) to the indicator value SO_2-equivalents. For the impact category land use competition the indicator value corresponds to the occupied area during one year and is expressed as m^2*a disregarding the land use type. Therefore no information on the impact on e.g. biodiversity or soil quality is given by this indicator. The characterization models are further described in Guinée et al. (2002).

TABLE 1: Impact categories of the CML 2001 method according to Guinée et al. (2002)

Group A (Baseline impact categories)	**Group B (Study-specific impact categories)**	**Group C (Other impact categories)**
Impacts of land use (land competition)	Impacts of land use (loss of life support function)	Depletion of biotic resources
Freshwater aquatic ecotoxicity	Impacts of land use (loss of biodiversity)	Odour (maldourous water)
Marine aquatic ecotoxicity	Freshwater sediment ecotoxicity	Desiccation
Terrestrial ecotoxicity	Marine sediment ecotoxicity	…
Climate change	Impacts of ionizing radiation	
Stratospheric ozone depletion	Odour (malodourous air)	
Human toxicity	Noise	
Acidification	Waste heat	
Eutrophication	Casualties	
Depletion of abiotic resources		
Photo-oxidant formation		

The Eco-indicator 99 method

The damage-oriented method EI 99 determines the environmental effects and induced impacts of a product system on human health, ecosystem quality and resources. The damages for human health, ecosystem quality and resources are modeled through so-called damage factors. Via normalization and weighting of the damage factors a single value (EI 99 points) is obtained as a result (cf. Goedkopp and Spriensma, 2001). Damage modeling includes rather subjective assumptions. To cope with this subjectivity the EI 99 method provides damage models for three different cultural perspectives i.e. individualist, egalitarian and hierarchist whereby according to Goedkopp and Spriensma (2001) the hierarchist perspective is chosen as a default which includes only facts that are backed-up by scientific and political bodies. Main characteristics of the three versions for damage modeling are described in Goedkopp and Spriensma (2001). By evaluating a process chain with the EI 99 method the LCI results are allocated to one of altogether ten impact categories whereby every impact category belongs to one of the three damage categories human health, ecosystem quality and resources (cf. TABLE 2). The damage to human health (HH) is quantified as DALY/a (Disability Adjusted Life Years per year), damages to ecosystem quality are quantified as PDF*m^2*a (Potentially Disappeared Fraction times area and year) and damages to resources (minerals and fossil fuels) are quantified as MJ/a (surplus extraction energy for future extraction) (cf. Goedkopp and Spriensma, 2001). The damages are weighted and normalized to the whole damage in Europe. For our analysis the overall environmental impact of the process chains according to EI 99 using the damage model of the hierarchist perspective together with the average weighting factors (HH:EQ:R = 4:4:2) is determined. Furthermore the contributions to individual impact categories as well as the respective contributions of several process steps along the value chains are identified.

TABLE 2 : Damage categories HH, EQ, R and corresponding impact categories of the EI 99 methodology according to Goedkopp and Spriensma (2001)

Human Health (HH)	Ecosystem Quality (EQ)	Resources (R)
Respiratory effects	Land use	Mineral extraction
Ozone layer depletion	Acidification and eutrophication	Fossil fuel extraction
Ionizing radiation	Ecotoxicity	
Climate change		
Carcinogenesis		

CHARACTERIZATION AND MODELING OF THE PROCESS CHAINS

As starting point for the ecological evaluation the process steps and base configurations for each process chain, concerning biomass provision, biomass processing and fuel use in passenger cars are determined. In this chapter the process chains are characterized in terms of detailed descriptions of the sub-processes, important parameters and assumptions as a basis for the modeling of the mass and energy flows with Umberto. Besides to the biogenic process chains the production and use of conventional gasoline and diesel are considered as reference processes for ethanol and FT fuel respectively.

Modeling of material and energy flows with Umberto®

The modeling of the considered process chains is carried out with Umberto®, a petri-net based software tool. The Umberto® models are built-up hierarchically for each of the described process chains. FIGURE 1 shows the generic superior Umberto® material and energy flow network. The process steps along the value chains (biomass production, biomass transport, process plant and fuel combustion in passenger cars) are further specified in different subnets. FIGURE 6 and FIGURE 8 show exemplarily the subnets for the process plant for FT fuel production and the process plant for ethanol production respectively. The build-up models provide the life cycle inventories for subsequent life cycle impact assessment. Furthermore the LCIA methods CML 2001 and EI 99 provided by ecoinvent Centre (2007) and implemented in Umberto® are applied to the different Umberto® models for subsequent ecological assessment.

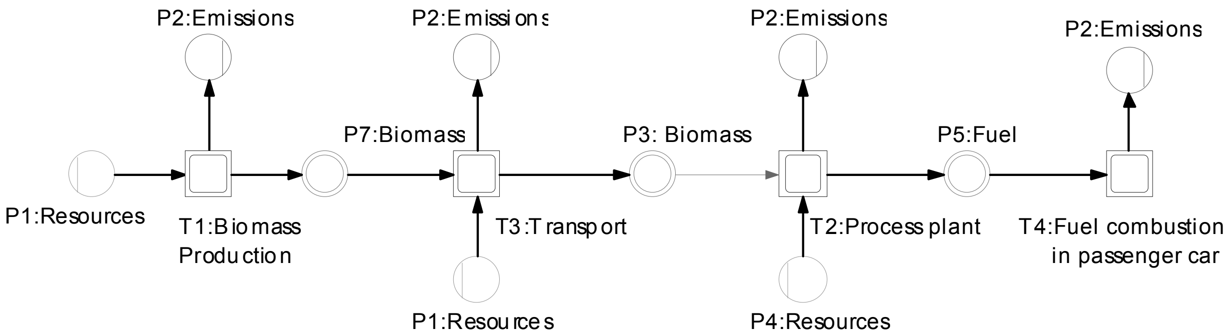

FIGURE 1: Generic superior material and energy flow network modeled in Umberto®

Biomass provision

In contrast to the production of fossil fuels raw materials for biogenic fuels need to be cultivated, harvested and gathered from large forest or agricultural areas. This includes e.g. different technical processes, application of fertilizers or plant protection agents. During the production of necessary auxiliary materials as well as field and forest working processes resources are required and emissions occur. Therefore, detailed analyses of the supply chains for biomass are very important in the context of an ecological assessment of biomass utilization paths. For our analyses the provision of seedlings for short rotation plantations as well as the provision of sugar beet seeds is neglected as for the former no data is available. After harvesting the biomass is transported to the process plants. We assume that the transport is carried out via truck and the transport distance to the process plants is 100 km. For LCIA the presented process steps for biomass provision are modeled in Umberto®.

Sugar beets

Sugar beets cultivation requires high soil quality with constant water and nutrient supply, loose soil structure and relatively warm climate. Sugar beets have a high nutrient requirement (N, P, K, Mg) and are susceptible for weeds. Therefore the application of fertilizer and plant protection agents is necessary for conventional as well as integrated sugar beets cultivation. Sugar content in sugar beets accounts for approx. 17 % of the wet mass (cf. Lewandowski, 2001). Characterization and modeling of sugar beets cultivation with Umberto® is carried out based on ecoinvent Centre (2007) and refers to the integrated production of sugar beets in Switzerland (cf. Nemecek and Kägi, 2007). For our analysis it is assumed that Swiss conditions are transferable to Germany. The major process steps for the provision of sugar beets at the process plant are shown in FIGURE 2. Before sowing the sugar beets in March the soil is prepared via tillage and fertilization. During sugar beets growth the soil is maintained via hoeing and application of plant protection agents. The sugar beets are harvested in October using harvester, tractor and trailer. The transport distance of the harvested sugar beets to the farm is assumed to be 1 km. After harvesting catch crops are cultivated on the field until February in order to avoid nutrients leaching off the soil and to prevent soil erosion (green manure). The life cycle inventory includes all field work processes, the production and provision of plant protection agents and fertilizers, transport of sugar beets from the field to the farm as well as the processes for production and cultivation of green manure. According to Nemecek and Kägi (2007) the sugar beets yield is $72.3t_{wet}$/ha*a with a water content of approximately 77% and a gross calorific value of approx. 16.4 MJ/kg_{dry}. For the production of sugar beets the land use type *arable, non-irrigated* is assumed.

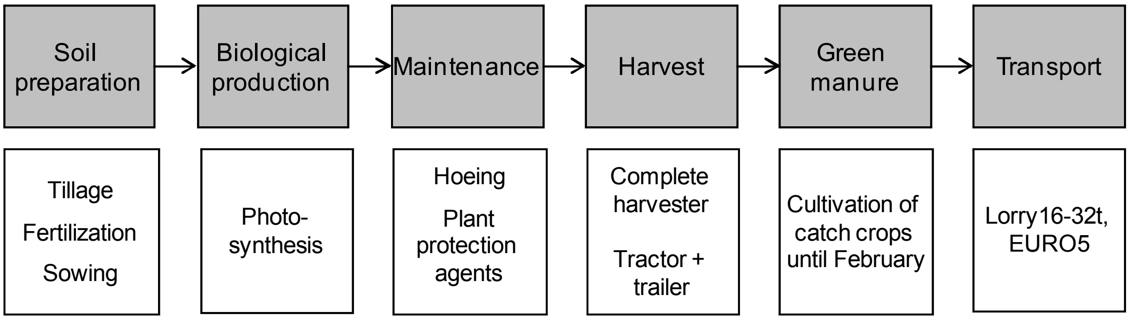

FIGURE 2: Process steps for the provision of sugar beets

Short rotation wood

Typical short rotation trees in Central Europe are poplar and willow. A loose soil structure and sufficient water supply are of particular importance for short rotation tree plantations. Also with unfavourable conditions (e.g. less deep soils, cooler humid climate) in particular poplar can constitute comparably high yields. For the cultivation of willow and poplar only low fertilizer and plant protection agent applications are needed (cf. Lewandowski, 2001). Characterization of poplar cultivation is based on Rödl (2008) and refers to short rotation plantations with a cultivation time of 16 years and a rotation time of 4 years. According to the information given in Rödl (2008) the modeling is carried out with Umberto® using the corresponding modules from ecoinvent Centre (2007). The major process steps for the provision of short rotation wood chips at the process plant are shown in FIGURE 3. Before planting the seedlings the soil is prepared via tillage and application of plant protection agents. Poplar seedlings are planted in spring. During poplar growth the soil needs to be maintained only during the first year via hoeing. The poplars are harvested using harvesters with mobile choppers. After a cultivation time of 16 years the soil is recultivated using rotary cultivators.

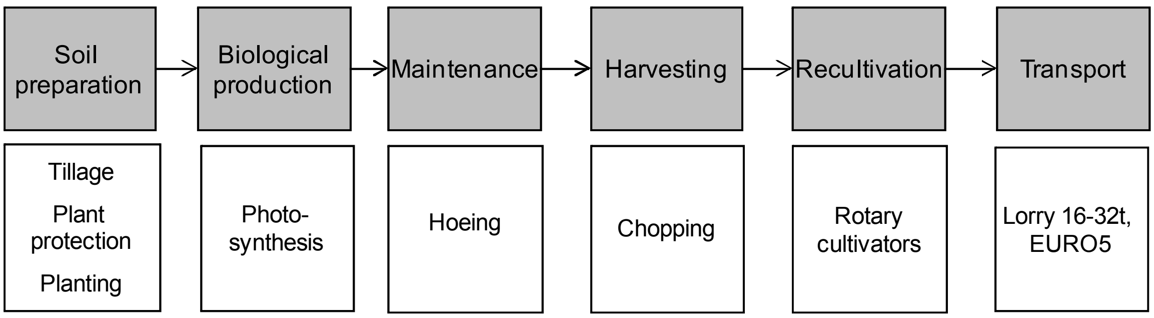

FIGURE 3: Process steps for the provision of wood chips (short rotation wood)

The life cycle inventory includes all field work processes as well as the production and provision of the herbicide Round-up. The typical water content of short rotation wood is 50% and the gross calorific value for 18.5 MJ/kg_{dry} (cf. Lewandowski, 2001 and Rödl, 2008). According to Rödl (2008) the average yield for poplar from short rotation plantations without fertilization accounts for 16 $t_{wet}/ha*a$. For the production of short rotation wood the land use type *forest, intensive, short-cycle* according to ecoinvent Centre (2007) is assumed. Using EI 99 this category corresponds to the occupation of arable land and is evaluated equally to the cultivation of sugar beets. According to Rödl (2008) short rotation plantations have a positive influence on biodiversity unlike the cultivation of agricultural crops. For comparative analysis we additionally chose the land use type *forest, intensive* which exhibits the lowest impact according to EI 99 and corresponds to forest land occupation.

Residual forest wood

According to Werner et al. (2007) residual forest wood (branches < 7cm diameter, brush wood, rough wood) accounts for approx. 16% of the above-ground tree mass, industrial wood for approx. 33% and round wood for approx. 51%. Therefore harvesting 6.3 m^3 of a hardwood tree results in 1 m^3 residual wood (cf. Werner et al., 2007). For the provision of residual forest wood at the forest road different processes are applied, e.g. power sawing, forwarding, mobile chopping which are further described in Kaltschmitt and Hartmann (2001). Characterization and modeling of the provision of residual forest wood in Umberto® is carried out based on ecoinvent Centre (2007) and described in Werner et al. (2007). The major process steps for the provision of residual forest wood at the process plant are shown in FIGURE 4. Besides process steps for wood harvest and wood chipping process steps for forest maintenance are taken into account. According to Werner et al. (2007) for the production of 1 m^3 of hardwood 2,120 m^2*a are required. As residual wood is regarded as a by-product of industrial and round wood production 6% of the environmental effects of forest maintenance, wood harvest as well as required area are assigned to residual wood. This allocation of environmental effects is based on the revenues of the three wood assortments round wood (82%), industrial wood (12%) and residual wood (6%) (cf. Werner et al., 2007). The gross calorific value of the wood chips with bark accounts for 18.4 MJ/kg_{dry} (cf. Hartmann et al., 2007). Equally to short rotation wood the water content of residual forest wood is assumed to be 50%. The density of the bulk volume is assumed to be 478 kg_{wet}/m^3. As land use type the land use category *forest, normal* is assumed.

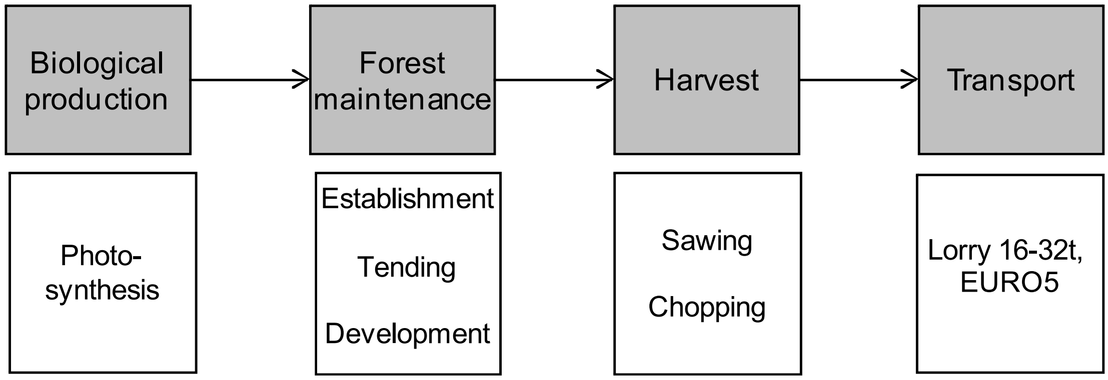

FIGURE 4: Process steps for the provision of wood chips (residual forest wood)

Production and use of FT fuel from wood

FT fuel belongs to the so-called BtL-fuels which are produced from lignocellulosic biomass. After preparation of the biomass the biomass is gasified to synthesis gas (mainly H_2 and CO) which can be further processed to various synthesis products, such as methanol or FT fuel. Within our study the production of FT fuel for a central arrangement is analyzed (all process steps take place at one production site). The characterization of the process chain is carried out according to Leible et al. (2007) and Kerdoncuff (2008). The major process steps for the production of FT fuel from wood are shown in FIGURE 5. The wood chips are dried from 50% water content to 15% water content. After pre-heating, the wood is mixed with hot sand and is heated within 1 s to 500°C which results in a thermal degradation of chemical bonds and vaporization of the water. Product of this fast pyrolysis is a so-called slurry of pyrolysis oil and coke as well as pyrolysis gas which is burned for heating-up the pyrolysis sand. The Slurry is gasified with O_2 in an entrained flow gasifier, O_2 is provided from an air separation plant. For subsequent Fischer-Tropsch (FT)-synthesis the raw synthesis gas is cleaned and conditioned. Via CO-conversion the mol ratio of H_2 to CO is adjusted to 2:1 and CO_2 is removed via selexol washing. During FT-synthesis the cleaned and conditioned synthesis gas is converted in a fixed bed reactor with a cobalt catalyst to hydrocarbons with different chain lengths. After water separation the liquid synthesis products are distilled into the fractions wax, diesel and gasoline. In order to increase the fuel recovery rate the waxes are converted to diesel and gasoline via hydrocracking. Process parameters of the synthesis are adjusted to maximize diesel recovery. As FT-synthesis is an exothermal reaction, released heat is recirculated to cover the heat demand within the process. Gaseous synthesis products are used in a gas and steam cogeneration plant for electricity production. Thereby the required power for the plant as well as surplus electricity is generated. Surplus electricity is assumed to be fed into the public network. For ecological evaluation this is accounted for as credits for the substitution of electricity from the German electricity mix (cf. Kerdoncuff, 2008). Per t of dry wood 0.145 t FT fuel are produced. With a gross calorific value of 43.9 MJ/kg for FT fuel per t of dr wood 6.4 GJ fuel are produced.

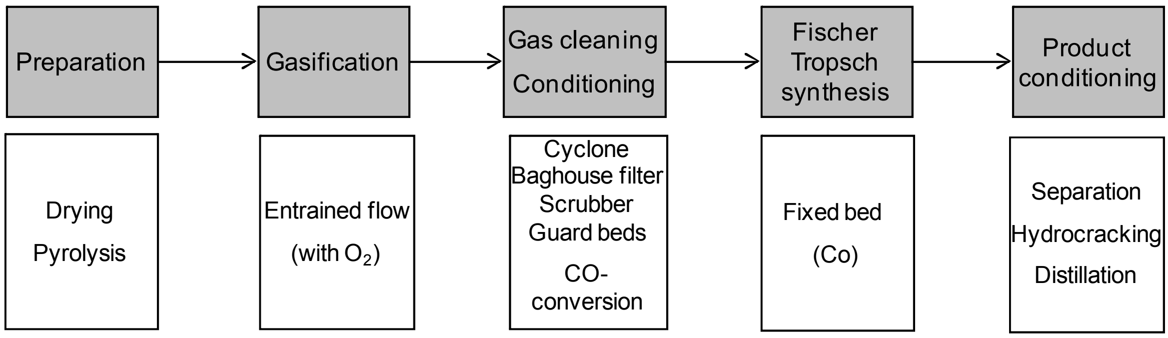

FIGURE 5: Process chain for the production of FT fuel from wood

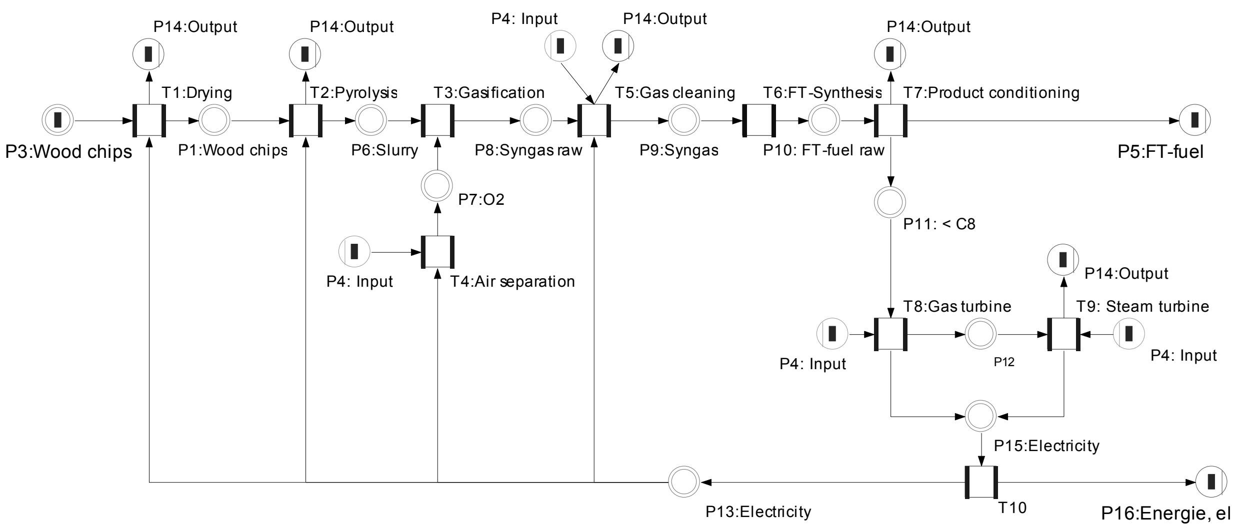

FIGURE 6: Subnet for the process plant for FT fuel production modeled in Umberto®

According to Kerdoncuff (2008) the heat demand of the process plant is covered via burning of pyrolysis gas, heat from exothermic FT-synthesis as well as the cooling of raw synthesis gas. Because of a lack of data availability plant infrastructure, provision of auxiliary materials, emissions from pyrolysis gas burning as well as waste disposal are not included for life cycle inventory analysis. The Umberto® model for the production of FT fuel from wood is shown in FIGURE 6. Modeling of FT fuel use in passenger cars is carried out based on emission data in PROBAS (2008).

Production and use of ethanol from sugar beets

Sugar beets molasses or syrup can directly be converted via fermentation to ethanol. Therefore the conversion of sugar beets to ethanol is in comparison to the conversion of grain to ethanol particularly efficient (cf. Schmitz, 2003). The characterization of the process chain is carried out according to Jungbluth et al. (2007). In FIGURE 7 the major process steps for the production of ethanol from sugar beets are shown. Sugar beets are cut into thin slices before they are extracted with hot water in a reverse flow. The remaining beet chips (25% dry matter) contain approx. 2% sugar. The sugar containing raw juice is fermented in a series of tanks at 33 – 35°C by yeasts to ethanol. For nutrient supply phosphorous and nitrogen are added as phosphoric acid and urea respectively. The ethanol concentration is rising up to 14% before the fermentation is stopped. Hydrated ethanol (95%) is recovered via rectification and is thereby separated from the so-called vinasse. Via molecular sieve separation ethanol is dewatered to 99.7% ethanol. For our analysis we assume that the beet chips are burned in a cogeneration unit in order to cover heat and electricity demand of the process. The use of vinasse as a second by-product is neglected.

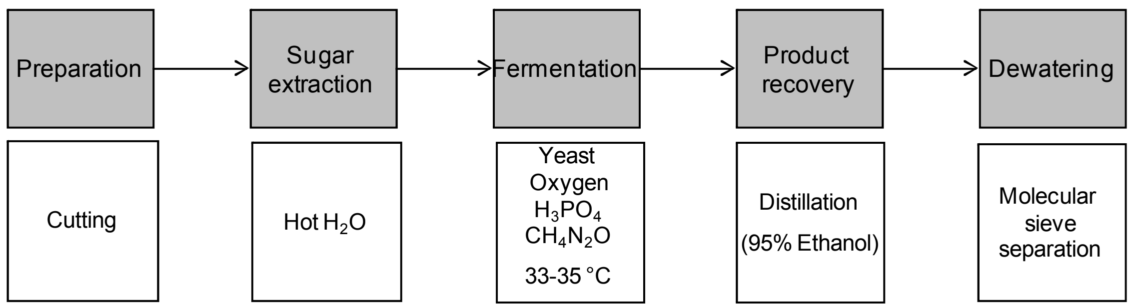

FIGURE 7: Process chain for the production of ethanol from sugar beets

Modeling of sugar beets fermentation to 95% ethanol, the ethanol dewatering to 99.7% ethanol as well as the cogeneration of beet chips in Umberto® is based on ecoinvent Centre (2007). For life cycle inventory analysis supply chains for the provision of electricity and heat are considered. Analog to the production of FT fuel from wood the provision of auxiliary materials as well as the disposal of wastes and the production infrastructure are neglected. The Umberto® model for the production of ethanol from sugar beets is shown in FIGURE 8. Per t_{dry} of sugar beets 0.38 t ethanol (99.7%) are produced. With a gross calorific value of 28.1 MJ/kg for ethanol per t of dry sugar beets 10.5 GJ fuel are produced. Modeling of ethanol use in passenger cars is carried out based on emission data in PROBAS (2008).

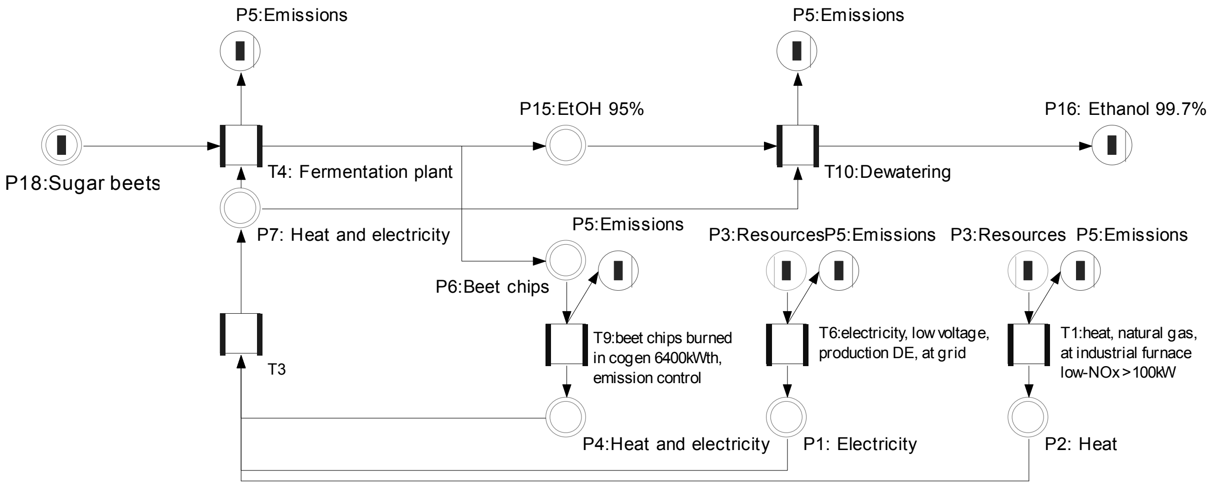

FIGURE 8: Subnet for the process plant for ethanol production modeled in Umberto®

Production and use of fossil reference products

The modeled process chains for the production and use of biogenic fuels are compared from an ecological point of view to the production and use of fossil reference products. For bioethanol low-sulphur gasoline and for FT fuel low-sulphur diesel are considered. The production processes for these reference products are modeled based on ecoinvent Centre (2007) and characterized in Jungbluth (2007).

TABLE 3 : Emissions from fuel combustion in passenger cars as kg/kg fuel according to PROBAS)

	Conv. gasoline	Bioethanol	Conv. diesel	FT fuel
CH_4 fossil	3.29E-04	3.93E-5	1.88E-05	1.92E-05
CO fossil	7.09E-02	1.17E-02	4.89E-03	4.99E-03
CO_2 fossil	3.26E+00	-	3.20E+00	-
N_2O	1.10E-04	1.15E-04	1.57E-04	1.60E-04
NH_3	-	1.15E-04	1.96E-05	2.00E-05
NMVOC	4.99E-03	2.99E-04	7.64E-04	7.80E-04
NO_X	5.17E-03	1.20E-03	4.90E-03	5.01E-03
PAH	n.s.	3.18E-10	8.29E-09	8.46E-09
SO_2	3.10E-04	-	3.31E-03	-
Particulates	2.05E-09	7.59E-06	1.73E-04	1.77E-04

For the production of 1 t of low-sulphur diesel 1.11 t and for the production of 1 t of low-sulphur gasoline 1.15 t crude oil are necessary. For life cycle impact assessment all relevant elementary flows (resources and emissions) for the production processes are taken into account. A detailed characterization of the production processes as well as products can be found in Jungbluth (2007). With an assumed gross calorific value of 43 MJ/kg for diesel and 43.5 MJ/kg for gasoline (cf. VIK, 2008) 38.7 GJ diesel and 37.8 GJ gasoline are produced per t of crude oil. Modeling of fuel combustion in passenger cars is based on PROBAS (2008). During the combustion of bioethanol and FT fuel according to PROBAS (2008) no SO_2 as well as fossil CO_2 emissions occur. The remaining emissions listed in TABLE 3 are for the combustion of FT fuel in the same order of magnitude as for conventional diesel. Fossil CH_4, fossil CO, NMVOC and NO_X emissions from the combustion of bioethanol underlie emissions from conventional gasoline combustion while N_2O, NH_3, PAH and particulates emissions exceed emissions from conventional gasoline combustion (cf. TABLE 3).

COMPARATIVE ECOLOGICAL EVALUATION OF THE PROCESS CHAINS

Based on the modeled mass and energy flows of the investigated process chains the life cycle inventories are established. Based on the life cycle inventories the ecological assessment of the process chains is carried out. In this chapter the most important characteristics of life cycle inventory analysis are shown and the results according to CML 2001 as well as EI 99 are discussed.

Main characteristics of life cycle inventory analysis

Life cycle inventory analysis provides all information on inputs and outputs in terms of resources and emissions as well as land use for each product system. In this section the most important parameters of each process chain are given. In TABLE 4 the biomass yields per ha are given as well as the fuel yields per t_{dry} of biomass as well as per ha. The highest biomass yield per ha as well the highest fuel yield per t of biomass results for the production of ethanol from sugar beets. Besides product yields the required energy for fuel production in terms of heat and electricity are important parameters of life cycle inventory analysis. The energy balances of the production processes are shown in TABLE 5. For the production of ethanol from sugar beets 80.4 kWh electricity and 1,692 MJ heat are required. From beet chips combustion in a cogeneration plant 35 kWh electricity and 1,212.9 MJ heat are generated per t of dry biomass. The deficiency is provided by electricity from the German electricity mix and heat from natural gas burning.

TABLE 4: Specific yields for biomass and products

Biomass	Biomass yield		Product	Product yield	
	[t_{wet}/ha]	[t_{dry}/ha]		[GJ/t_{dry}]	[GJ/ha]
Sugar beet	72.31	16.63	Ethanol	10.6	176
Short rotation wood	16.00	8.00	FT fuel	6.4	51
Residual forest wood	17.94[2]	8.97	FT fuel	6.4	57

Fossil CO_2 emissions from this additional energy demand are the main contributors to process immanent GHG emissions of ethanol production from sugar beets:

[2] Required area for residual forest wood according to economic allocation

per dry t of sugar beets input 67 kg CO_2 are emitted. For electricity production gaseous synthesis products from FT synthesis are separated and burned in a gas and steam cogeneration plant. Per t of dry biomass input 0.137 t gaseous synthesis products are obtained and 484 kWh electricity are generated. To cover the electricity demand of the plant 457 kWh are needed per t of dry wood input. Therefore 27 kWh surplus electricity are generated. Gas combustion in the gas turbine results in 1.55 kg NO_X emissions per t of dry wood input (1.53 kg NO and 0.2 kg NO_2). These NO_X emissions are responsible for considerable acidifying emissions from FT fuel production (cf. FIGURE 10) as well as contributions to the EI 99 impact category respiratory effects (cf. FIGURE 13).

TABLE 5: Energy balance of the production processes

Process	Electricity [kWh/t_{dry} biomass]			Heat [MJ/t_{dry} biomass]		
	Production	**Demand**	**Balance**	**Production**	**Demand**	**Balance**
Ethanol from sugar beets	35.0	80.4	-45.4	1,212.9	1,692.7	-479.8
FT fuel from wood	484	457	27	Production = Demand		0

In terms of biomass provision significant CO_2 and NO_X emissions are caused by fossil fuel combustion during agricultural and forest processes as well as N_2O and NH_3 emissions during sugar beets cultivation due to fertilization (cf. TABLE 6). Fuel use in passenger cars is characterized in terms of GHG emissions by fossil CO_2 emissions from fossil fuel combustion and in terms of acidifying emissions by NO_X emissions from the combustion of all types of fuels as well as by SO_2 emissions from fossil fuel combustion (cf. TABLE 3).

TABLE 6: Characteristic emissions from biomass provision

Biomass	Emissions [kg/t_{dry} biomass]			
	CO_2 fossil	**N_2O**	**NH_3**	**NO_X**
Sugar beets	77	0.63	1.07	0.76
Short rotation wood	88	0.003	0.002	0.80
Residual forest wood	23	0.001	0.001	0.21

Ecological evaluation of the process chains using the CML 2001 method

In this section the environmental impacts according to CML 2001 are presented. For life cycle impact assessment according to CML 2001 we analyze the impact categories climate change, acidification and land use competition.

Climate change

For the impact category *climate change* the CO_2 emission equivalents are calculated for the different process steps along the whole value chain. For the considered process chains primarily fossil CO_2 as well as N_2O and CH_4 emissions contribute to this impact category. In FIGURE 9 FT fuel and bioethanol are compared to conventional diesel and gasoline respectively. The results are shown as kg CO_2-equivalents per GJ fuel. The main contributions for the biomass utilization paths are caused by the biomass provision. This is mainly due to fossil CO_2 emissions from agricultural and forest processes as well as N_2O emissions during sugar beets cultivation. Altogether the biogenic fuels show lower impacts on climate change in comparison to fossil fuels mainly because of the lack of fossil CO_2 emissions during fuel combustion in passenger cars. Additionally, credits are recorded for surplus electricity production during FT fuel production. The production of FT fuel from residual forest wood shows the lowest impact on climate change followed by the production of FT fuel from short rotation wood.

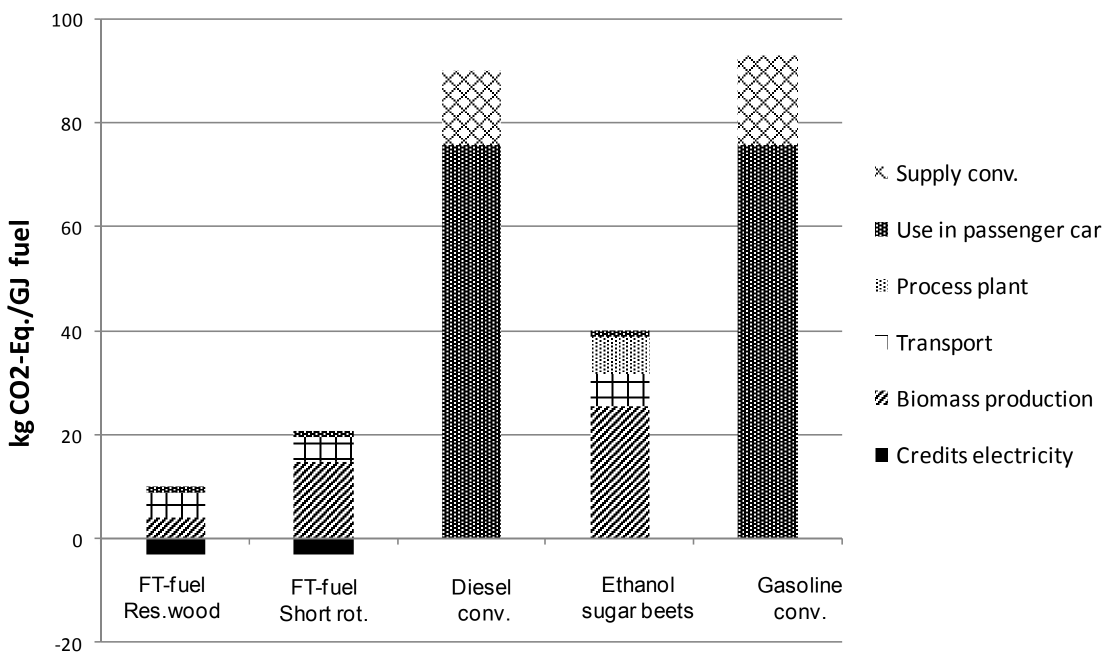

FIGURE 9: Results for the CML 2001 impact category *climate change*

Acidification

For the impact category *acidification* the SO_2 emission equivalents are calculated for the different process steps along the whole value chain. For the considered process chains primarily NO_X as well as NH_3 and SO_2 emissions contribute to this impact category. In FIGURE 10 FT fuel and bioethanol are compared to the fossil references. The results are shown as kg SO_2-equivalents per GJ fuel. The main contributions for the biomass utilization paths are caused by the provision of sugar beets mainly due to NH_3 emissions during cultivation and NO_X emissions from agricultural processes as well as NO_X emissions from FT-fuel production due to the combustion of gaseous synthesis products in a gas turbine. Furthermore, NO_X emissions from agricultural and forest processes for the provision of residual forest wood and short rotation wood as well as from fuel combustion in passenger cars show relevant contributions. Altogether biogenic fuels have higher impacts on acidification compared to the fossil references. Amongst the biogenic fuels the production of FT fuel from residual forest wood exhibits the lowest impact on acidification.

Land use competition

For the impact category *land use competition* the required area is determined as m^2*a for the production of 1 GJ fuel. In FIGURE 11 the biogenic fuels FT fuel and ethanol are compared to conventional diesel and gasoline respectively. Only the biogenic fuels contribute considerably to this impact category whereas the highest requirement for area results for the production of FT fuel from short rotation wood, followed by the production of FT fuel from residual wood. This area results from the biomass yields per ha together with the fuel yield per t of biomass. Because of the high biomass yield per ha and the high fuel yield per t of biomass, ethanol from sugar beets exhibits the lowest requirement for area amongst the three examined biomass utilization paths.

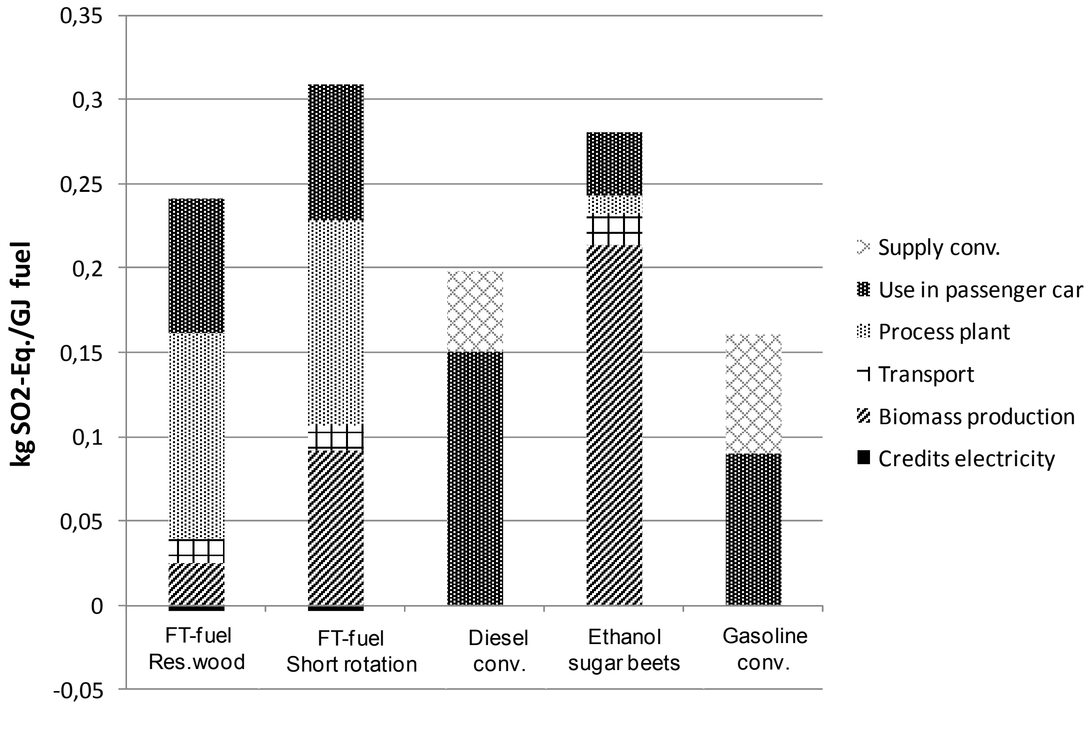

FIGURE 10: Results for the CML 2001 impact category *acidification*

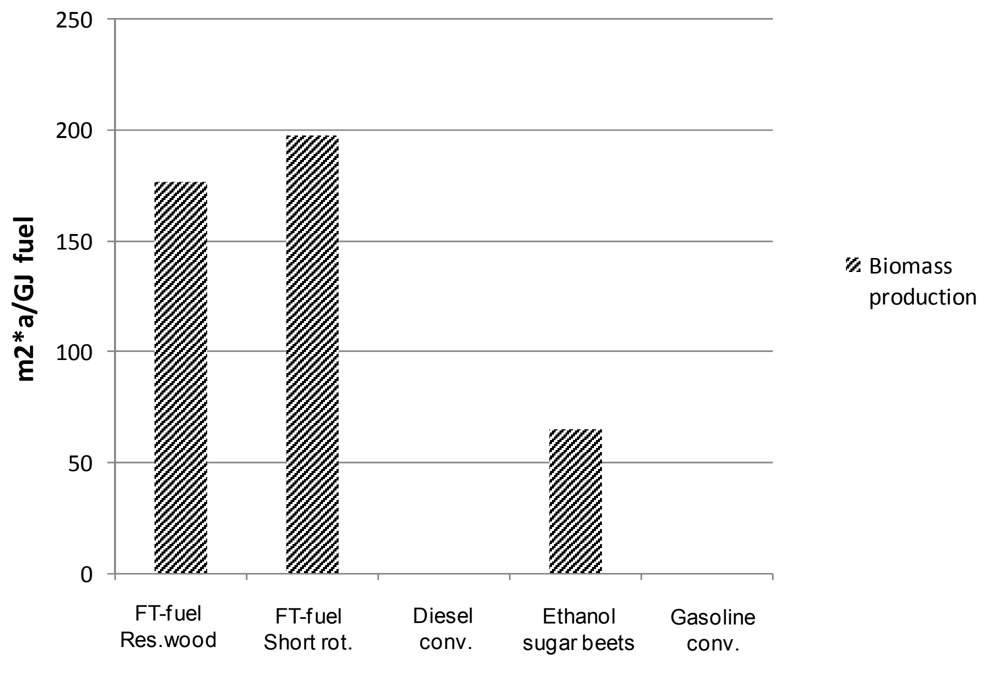

FIGURE 11: Results for the CML 2001 impact category *land use competition*

Ecological evaluation of the process chains using the Eco-indictor 99 method

In this section the environmental impacts of the presented process chains are determined using the impact assessment method EI 99. This method quantifies the damages for human health (HH), ecosystem quality (EQ) and resources (R). In FIGURE 12 the results for the three biomass utilization paths and the corresponding fossil references are shown as EI 99 points/GJ fuel. For the biogenic fuels land use which results in a damage for ecosystem quality shows the highest contribution to the overall environmental impact. FT fuel from short rotation wood as well as ethanol from sugar beets show higher overall environmental impacts compared to the corresponding fossil references mainly due to arable land occupation while FT fuel from residual wood exhibits the lowest overall environmental impact. The impact category *land use* affects the damage category *ecosystem quality* while for the damage category *human health* the impact category *respiratory effects* shows the main contribution. Besides the direct emissions of particulates (e.g. PM10, PM2.5) respiratory effects are caused by secondary particles formed via precursors such as NO_X as well as SO_2 emissions. For the damage category *resources* the impact category *fossil fuel extraction* shows the main contribution, especially for conventional fuels. In terms of land use EI 99 is taking into account the land occupation type together with the size of the occupied area and duration as well as the land transformation type. For our analyses we assume that no change in land use type occurs and therefore the effects of land transformation can be neglected. The damage to the ecosystems caused by land use is quantified in a loss of biodiversity. For sugar beets as well as short rotation plantations the land use type *agricultural crop land* is assumed while for residual forest wood the land use type *forest land* is assumed. In FIGURE 13 the contributions of particular process steps to selected impact categories are shown. For the impact category *land use* biomass provision is decisive while for the impact category *fossil resources* the supply of conventional fuels shows the main contribution. Respiratory effects are mainly caused by emissions of the process plants and fuel use in passenger cars. According to Rödl (2008) short rotation plantations have - unlike agricultural crop lands - a positive effect on biodiversity. Therefore we additionally assign the land use type *forest land* to short rotation plantations. The result of this analysis is shown in FIGURE 14. The change in land use type of short rotation wood affects the overall result remarkably: FT-fuel from short rotation wood shows lower overall environmental impacts compared to Ethanol from sugar beets as well as conventional fuels.

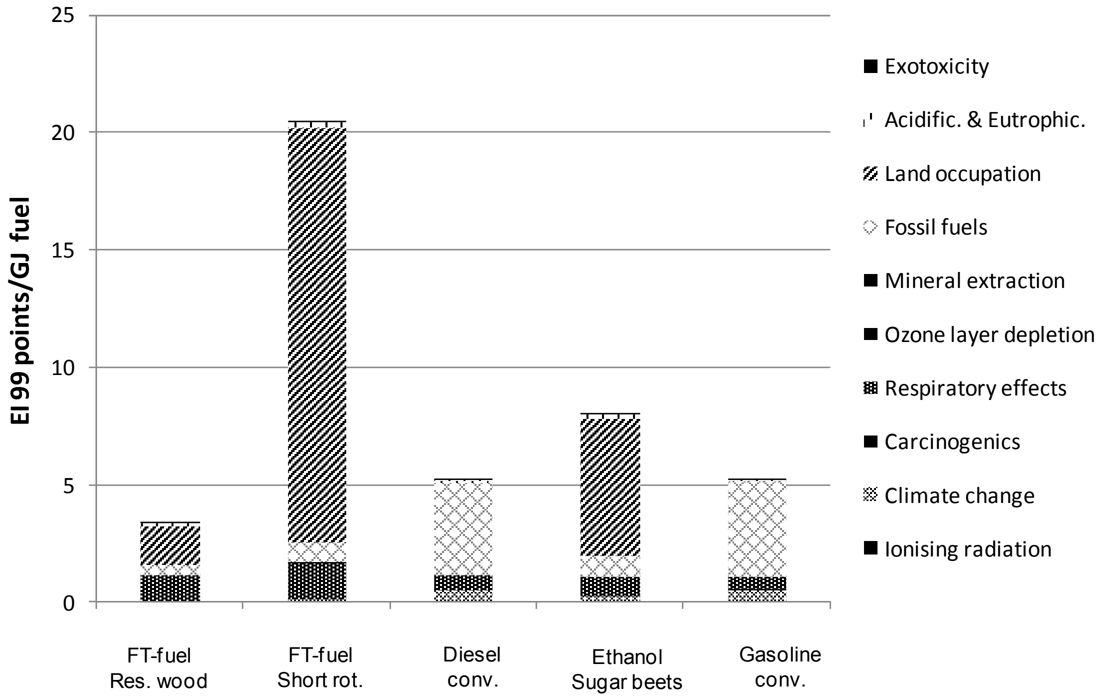

FIGURE 12: Overall environmental impact according to the EI 99 method (1)

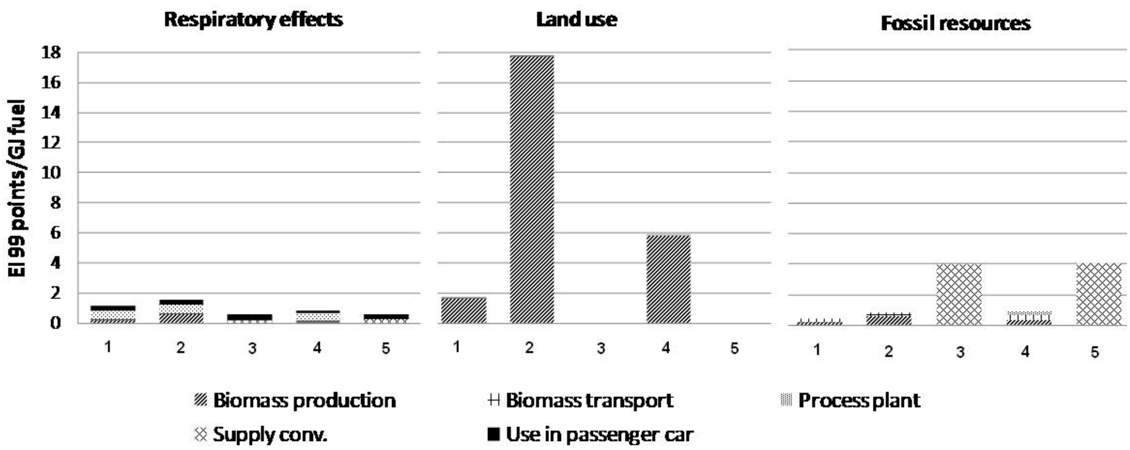

FIGURE 13: Contributions of particular process steps to selected impact categories according to the EI 99 method (1 = FT fuel res. wood, 2 = FT fuel short rot., 3 = Diesel conv., 4 = Ethanol sugar beets, 5 = Gasoline conv.)

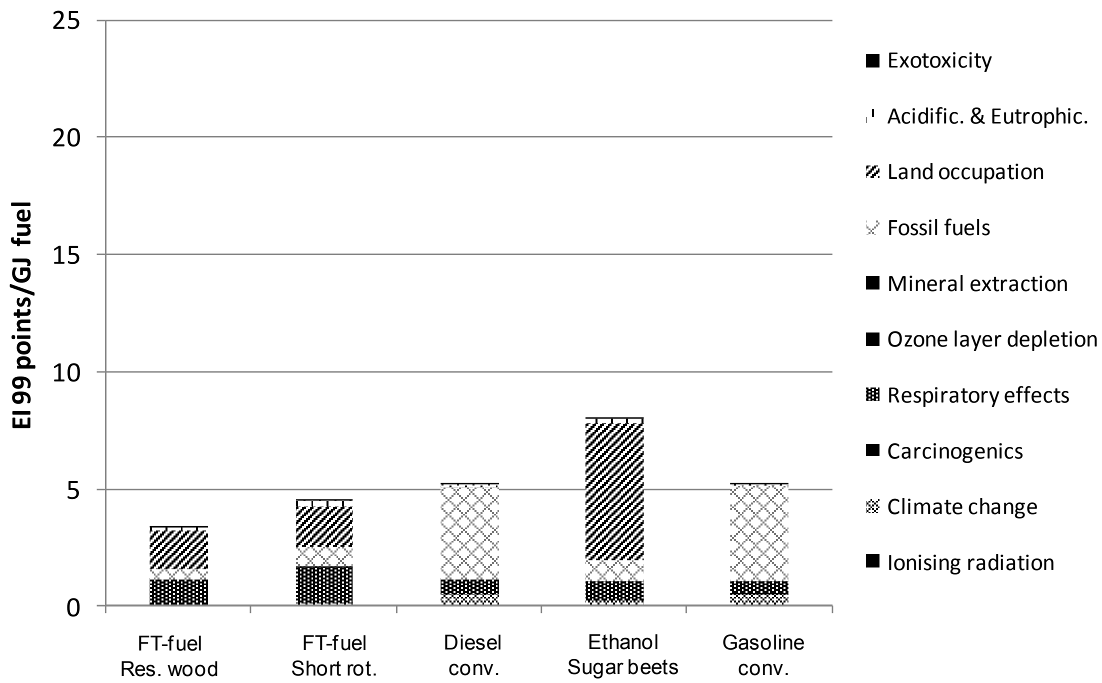

FIGURE 14: Overall environmental impact according to the EI 99 method (2)

CONCLUSIONS

The ecological assessment of process chains is supposed to contribute to the sustainability assessment of biomass utilization paths. As a basis for the modeling of product systems consistent information on mass and energy flows of the considered utilization paths is needed in order to perform comparative life cycle assessment. Especially for processes which are still on a pilot plant scale such as the production of FT fuel from wood detailed information is scarce and a uniform data source for the considered processes is not yet available.

In this contribution three different biomass utilization paths, FT fuel from residual forest wood, FT fuel from short rotation wood and ethanol from sugar beets are investigated using two different approaches for life cycle impact assessment. The application of these two approaches provides differing results.

According to the problem-oriented approach CML 2001 there are advantages for biofuels in comparison with the fossil reference products regarding the impact category *climate change* but disadvantages concerning the categories *acidification* and *land use competition*. As the CML 2001 impact category *land use competition* does not include the type of occupied land, it allows only a conclusion on the occupied area and not on the quality of this occupation. The consideration of different CML 2001 impact categories for an overall environmental assessment is possible but necessitates additional normalization and weighting of impact categories and is therefore not considered in this contribution.

A different approach is followed by the damage-oriented approach Eco-indicator 99. This method quantifies damages instead of environmental problems. Additionally, for this method normalized and weighted damage factors are applied and therefore a single value for an overall evaluation is obtained. This method shows a high dependence of the results on the impact category *land use.* Further relevant impact categories are *respiratory effects* and *fossil fuel extraction* while the impact categories climate change as well as acidification and eutrophication are less important. The overall environmental effect according to EI 99 turns out worse for bioethanol from sugar beets as well as FT fuel from short rotation wood in comparison to the fossil references. This is mainly due to the occupation of arable land during biomass cultivation. Only for FT-fuel from residual wood advantages are identified. For the analysis of agricultural or forest process chains the impact category *land use* is highly relevant and a change in the assumed land use type can change the overall result significantly. This was shown by the change in the assumed land use type of short rotation plantations. As for this impact category neither according to CML 2001 nor according EI 99 the necessary reliable characterization models are available the results need to be discussed and further analyzed.

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DEVELOPMENT OF A FLASH PYROLISIS PROCESS IN A THREE-STAGES FLUIDIZED BED REACTOR

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Abstract: A three-stages flash pyrolysis system is being developed at UDT to produce bio-oil (biodiesel). The pilot-scale reactor of 50 to 100 kg/h capacity is formed by the central pyrolysis reactor which is interconnected with two other fluidized bed reactors.

The flash pyrolysis takes place in a fluidized bed of silica sand which is continuously recycled from the pyrolysis reactor into a lower combustor reactor where the fluidizing gas for the pyrolysis reactor (pyrolysis gas) is heated by burning part of the char generated in the pyrolysis stage. The hot gases generated in the char combustion reactor also heats the external wall of the pyrolysis reactor as well as the gas cleaning section of it. The sand overflowing from the lower reactor is pneumatically, transported into the upper fluidized bed reactor, in which the sand is reheated by burning part of the pyrolysis gases generated. The preheated sand is then fed continuously into the central pyrolysis reactor.

The vapours generated in the pyrolysis reactor are cleaned in three stages then are rapidly quenched in a venturi-type system.

INTRODUCTION

The production of bio-oil from biomass by pyrolysis is being developed in several places around the world using different technologies such as conventional fluid beds, circulating fluid beds, transport reactors, ablative systems, rotary cones, screw reactors, etc. Although in all of these and other proposed systems it is possible to obtain bio-oil, it appears that fluidized systems has the potential to become a competitive approach with a relatively straightforward scaling-up.

Taking this consideration, the UDT at the University of Concepción is developing a three-stages fluidized bed system for flash pyrolysis that it is expected could have several advantages over the existing fluidized bed systems, such as a large capacity, flexible operation and complete automatic control.

The continuous interlocked system makes uses of three different mechanisms to transfer heat into the pyrolysis reactor: by circulating preheated coarse silica sand; by pre-heating the fluidizing gas (pyrolysis gas, PG) and by heat transferred through the walls of the pyrolysis reactor.

REACTOR CONCEPT

The fluidized bed system is composed of three interlocked reactors: the central pyrolysis reactor –which is the hearth of the system – a lower reactor where the fixed carbon (char) is burned to preheat the fluidizing gas for the pyrolysis reactor and also to heat externally the pyrolysis reactor and its gas cleaning system, and an upper fluidized bed reactor in which the sand is preheated by burning part of the PG generated. The vapours generated in the pyrolysis reactor are rapidly quenched in a venturi-type cooling system. In Figure 1 it is shown a conceptual design of the most relevant equipments of the system.

The bed of the flash pyrolysis reactor is fluidized with PG preheated in a heat exchanger located inside the lower fluidized reactor. The dry biomass is pneumatically injected into the bed of the pyrolysis reactor also by means of preheated PG. The fine feed (less than 3 mm) has a mean reaction time in the pyrolysis reactor of less than 3 sec, which requires fluidizing velocities in excess of 0.8 m/s.

The vapors generated in the flash pyrolysis reactor, carrying elutriated carbon particles and fine particles of silica sand, are cleaned in three stages: by inertial impactors, in a cyclone and in a metallic submicronic filter. The cleaned pyrolysis vapors emerging from the cleaning system are rapidly cooled down in a venturi-type quencher system. The bio-oil is then separated from the GP. The GP is stored and part of it is used in the process.

The flash pyrolysis reactor is fed continuously by gravity with preheated sand (650/750ºC) heated in the upper fluidized bed reactor. A solid control valve (SCV) permits to control the flow of the sand into the pyrolysis reactor and avoid short circuits of vapours. The silica sand overflowing from the pyrolysis reactor, mixed with the char generated in the pyrolysis, discharge continuously through a SCV into the lower peripherical fluidized bed reactor in which the char is burned at 800/850ºC by blowing air into the fluidized bed.

The sand overflowing from the lower char combustion reactor discharges through a cooling section and an in-line screen to remove the ashes and then through a SCV into an air-operated venturi ejector that transports pneumatically the sand into a cyclone where the sand is separated and recirculated back into the upper preheating fluidized bed reactor through an SCV.

The upper reactor preheats the silica sand by burning PG with air which is preheated in a heat exchanger attached to the freeboard section. Off gases are cleaned in a cyclone and the fine material collected are separated from the gases and discarded.

SYSTEM PARAMETERS

The pilot unit being built is 15 cm in diameter (pyrolysis reactor) with an estimated maximum capacity of 100 kg/hr of dry feed and an expected yield of about 1800 lt/day of bio-oil.

The main design parameters of the flash pyrolysis pilot plant are:

- Flash pyrolysis reactor

- Diameter	:	15 cm.
- Height	:	162 cm.
- Height of fluidized bed (in operation)	:	55 cm.
- Feed rate (maximum)	:	100 kg/hr (2400 kg/day)
- Gas velocity	:	80 -200 cm/sec @T
- Gas cleaning system	:	Impact – cyclone – filter
- Temperature of operation	:	400 – 700ºC

- Char combustion reactor

- Diameter	:	30 cm.
- Height	:	185 cm.
- Height of fluidized bed (in operation)	:	88 cm.
- Feed rate (silica sand)	:	100-250 kg/hr (recirculated)
- Gas velocity	:	60 -80 cm/sec @T
- Temperature of operation	:	800 – 850ºC

- Silica sand preheater reactor

- Diameter	:	25 cm.
- Height	:	238 cm.
- Height of fluidized bed (in operation)	:	98 cm.
- Feed rate (silica sand)	:	100 – 250 kg/hr. (recirculated)
- Gas velocity	:	60 - 80 cm/sec @T
- Temperature of operation	:	650 – 750ºC

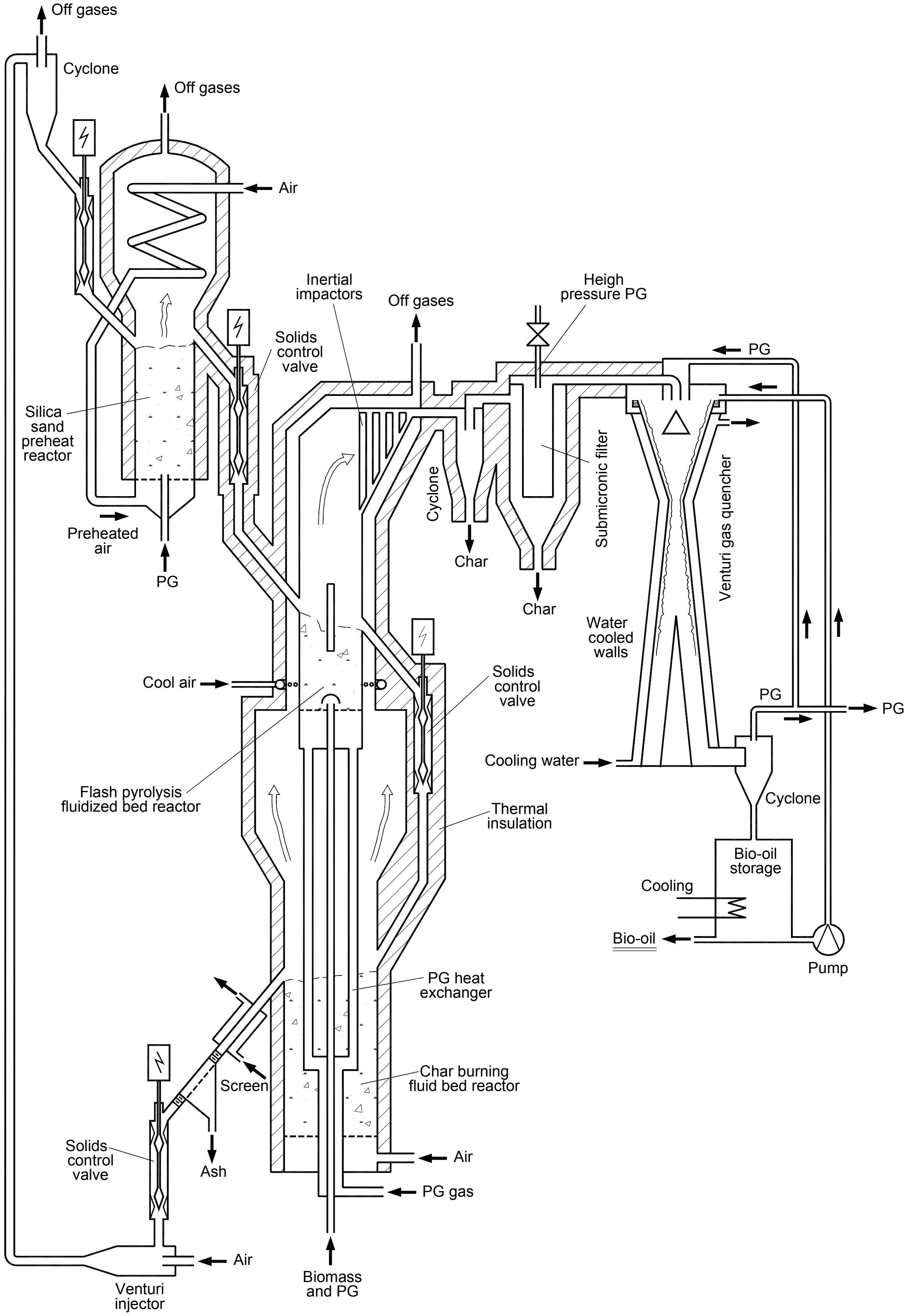

Figure 1. Three-stages fast pyrolysis system

MASS AND THERMAL BALANCE OF THE SYSTEM

To evaluate the expected performance of the pilot system, data from the technical literature was used to simulate its behavior. In Fig. 2 is shown a schematic diagram used to simulate the heat and mass balance.

The physico-chemical properties of the feed, bio-oil, carbon and PG used to perform the mass and energy balances are given in Tables 1 to 4. Some simplifications have been made in this preliminary balance, such as that some of the recycled flows were not considered in the balance (i.e. the PG used for injecting the feed), as well as the heat input through the pyrolysis reactors walls.

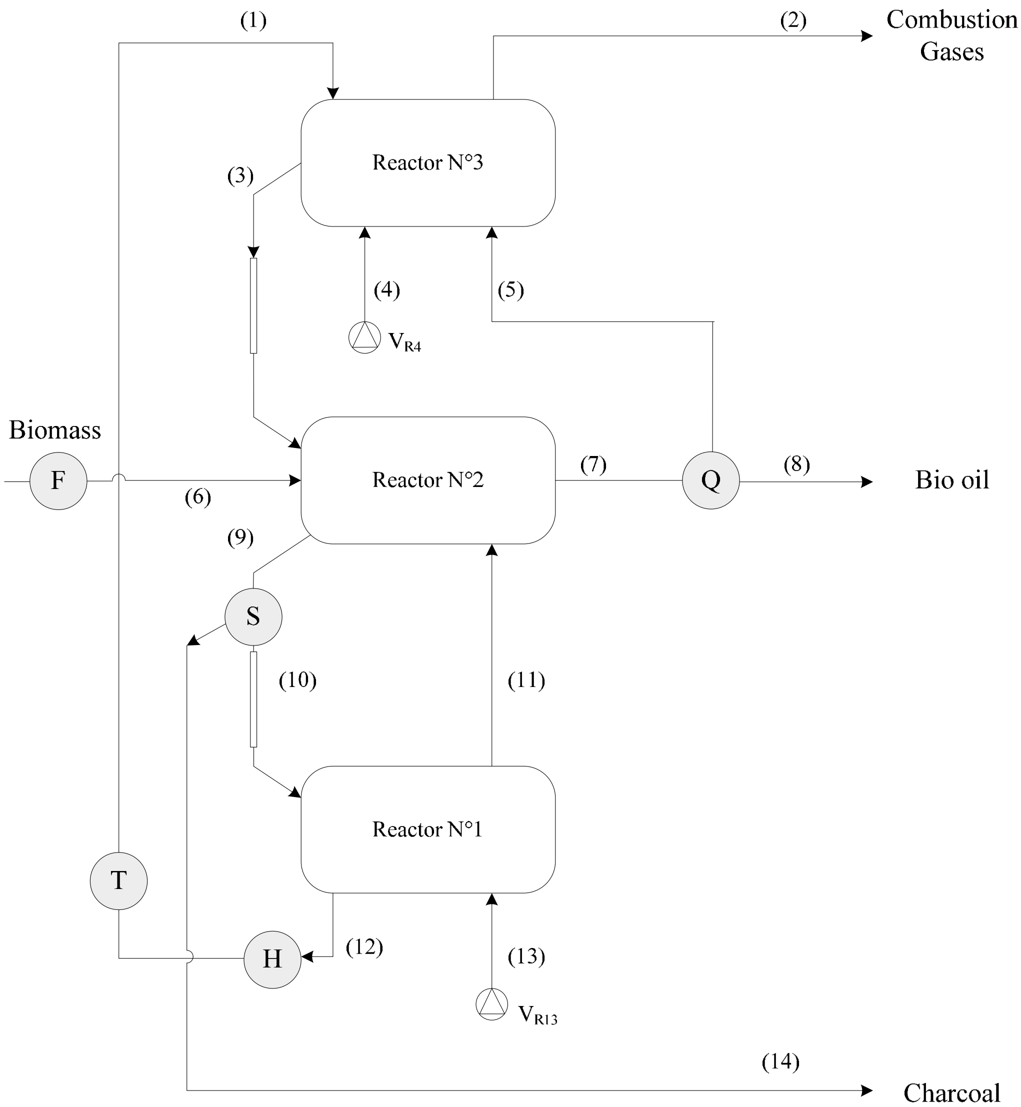

Figure 2. Schematic diagram used for mass and heat balance.

Table 1. Expected distribution of products generated in the system (Pyrolysis reactor operating at 450ºC). (wt-% of total products)

Bio-oil	66.0
Pyrolysis gas	11.3
Carbon (charcoal)	21.6

Table 2. Typical composition of hot pyrolysis vapours leaving the reactor.

gas	CO	CO_2	H	CH_4	Others
vol-%	45.0	43.1	3.3	6.6	2.1

The heat of combustion of these vapours is 1577 kcal/kg.

Table 3. Typical composition of pyrolysis gas after condensation of volatiles (wt-% referred to the feed)

gas	CO	CO_2	H	CH_4	Others
vol-%	2.09	21.33	0.15	0.30	0.23

The heat of combustion of these gases is aprox. 2000 kcal/cu.m.

Table 4. Typical elemental composition of carbon generated at 450ºC (2)

Element	C	H	N	O	S	Ash
Wt-%	75.6	3.3	0.2	18.4	0.0	2.3

The preliminary mass and energy balance indicated that the three-stages pilot reactor requires to be fed with over 23 kg/hr (dry basis) of biomass to be operated autothermally, generating 15.2 kg/h of bio-oil. Due to some of the simplifications done, the minimum feed rate could be reduced by 15 to 20%. A more detailed mass and energy dynamic model is being built, considering all flows of the system, which will give a more accurate prediction of the reactor's performance.

CONTROL OF THE SYSTEM

The control of such a complex system requires an elaborated strategy if all variables are taken into consideration, therefore, in order to simplify the control, a distributed system can be considered. Under these conditions, the main variables that define the optimum conditions for the pyrolysis (temperature and average reaction time of solid feed), can be fixed. Two others variables can be also fixed based on their optimum operational conditions: the combustion temperature of the char in the lower fluidized bed reactor and the temperature of the preheated silica sand, fixed as a fraction of the total heat requirements for a given feed rate to the pyrolysis reactor.

Under these conditions, the pyrolysis reactor can be controlled by the heat input transferred through the walls; the biomass feed rate, the temperature and volumetric flow rate of the PG for fluidization, the mass flow rate of the preheated silica sand and the cool air injected into the gases that heat externally the pyrolysis reactor.

Alternatively, to control the temperature inside the pyrolysis reactor, the temperature of the preheated silica sand can also be included, although this could affect the yield of bio-oil due to either a larger fraction of PG formed or PG formed above temperatures of 700ºC.

LOGISTICS FOR BIOMASS-TO-LIQUIDS PLANTS

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Abstract: Various concepts to substitute fossil fuels with renewable resources have been developed. So-called 1st generation bio fuels (including bio diesel and bio ethanol) compete with grains for food production for agricultural land. As such competition is often considered objectionable, other concepts, called 2nd generation bio fuels, have been developed and promoted. These are based on the conversion of lignocellulose, e.g. timber or straw. While timber and straw have been used for heat production for millennia already, fuel production would require advanced concepts, such as gasification with subsequent Fischer-Tropsch or methanol synthesis. These provide feasible methods to process biomass into hydrocarbon fuels. The low energy density of most kinds of biomass makes it difficult to operate a plant of sufficient size to realize economies of scale significantly. Therefore, a techno-economic optimization of the logistics of Biomass-to-Liquids Plants (BtL) has to take into consideration plant sizes and transportation concepts simultaneously. Transportation costs for biomass and dendromass are influenced by the means of transportation, the wood-species or bale of straw and the kind of route chosen. Additionally, the cost of the whole gasification supply chain is determined by the number of pyrolysis plants. While a large number of small pyrolysis plants results in loss of economies of scale, the repeated production of identical or similar pyrolysis units should result in progress on the learning curve. If sizes are sufficiently small, mass production cost savings may overcompensate the less favorable influence of the low plant size.

INTRODUCTION

In recent decades, a variety of processes has been developed to replace fossil resources with renewable ones. Some of these, as sugar, fat or starch have been in industrial use for more than a century [Nordhoff et al. (2007)]. For several thousand years, by contrast, biomass has been used to make food for humans and feed for animals. In nearly all of these millennia, food has been scarce in most regions of the world.

In post-war America and Western Europe, however, the industrialization of agriculture, as well as a modest rise of population, has eliminated most of the risk of food shortages in the perception of the public. Instead, politically guaranteed prices for agricultural produce have resulted in significant surpluses, the disposal of which was a matter of intense political discussion in the 1990s [Bockey (2006)]. Partly as a consequence of this, it was deemed advantageous to use these surpluses to replace fossil fuels in industrial or energy applications.

From an economic point of view, the presence of agricultural surpluses is a price phenomenon. The price of a good determines the point on the supply curve that producers will choose. In case of agriculture, this means that a higher price for produce will result in more land to be used once the current agricultural areas have entirely been put to use. This may mean that forests are cleared to make way for more agriculture. In addition, more fertilizer will probably be applied to unproductive soils, resulting in additional undesirable ecological consequences.

CO_2 emissions are another important ecological aspect to be considered. Bio fuels are usually considered a valid approach to decrease emissions of fossil CO_2 [Wegener, Lücke (2008)].

If an investment into processes using biomass is being considered, an evaluation should be made whether other processes compete for the same kind of biomass- or, as mentioned before, for the same soils. Economic logic clarifies that if two industries compete for a raw material, the more profitable industry will prevail, if no suitable alternative is found. This has to be kept in mind when judging concepts like bio diesel or bio ethanol, which are now introduced.

The use of rape seed oil-derived bio diesel in combustion engines is one of the most common bio fuel concepts in Europe [Bockey (2006)]. FAME (Fatty Acid Methyl Ester) is referred to as a first-generation bio fuel, as the plant oil undergoes only minor chemical treatment in comparison to gasification processes, which, among others, are called second generation bio fuels. While rape seed oil is very similar to hydrocarbons used for combustion engines already, some upgrading is necessary to meet diesel fuel standards. As large areas of agricultural land were left unused in the years following the significant surpluses resulting from the Common Agricultural Policy (CAP), rape was grown to an increasing extend, reaching 1.4 million ha in 2006 [Bockey (2006)]. This development was helped by state subsidies and tax breaks to promote the use of bio diesel. In terms of mass yield, the rape oil yield is approximately 40% of the total harvested plants' weight. As rape-seed oil can be converted to bio diesel with a ratio of 1.1 liters of rape oil per liter of bio diesel, a harvest of 1 ton of rape plants will result in 364 kg of rape seed oil. The remaining 636 kg are not entirely wasted, as rape grist can be used as animal feed. The bio diesel concept has repeatedly been criticized for compromising food supply by competing for arable land.

Another bio fuel concept is the production of bio ethanol. Ethanol (C_2H_5OH), more commonly known as “alcohol”, can be used as a fuel for combustion engines as well. On a world scale, bio ethanol is even more widespread than bio diesel. Most notably Brazil and the United States of America (USA) have significant capacities to produce ethanol from sugar cane or corn respectively. From an ecological perspective, bio ethanol is often considered ambiguous in several publications. While the use of sugar cane in tropical regions such as Brazil is thought to be favorable, the increased production of corn in temperate regions has repeatedly been criticized due to the comparably low energy efficiency of the process. Ethanol, which was considered as a fuel alternative to gasoline from the beginning of automobile developments, can be produced from both fossil and renewable sources, whichever is cheaper.

BIOMASS-TO-LIQUIDS

Both FAME and ethanol concepts suffer from a severe disadvantage. Rape, corn and sugar cane are grown on the same soils as agricultural crops for food and feed production. “1st generation biofuels” such as these have come to be considered less attractive since the increases in food prices in 2008, which were in part attributed to growing demand for biofuels. Therefore, an economic conversion of biomass to bio fuels is threatened by moral considerations as well as significant price risks. In order to reduce the risk of potential effects on human nutrition caused by the use of bio fuels, competition for agricultural land has to be kept in check. Accordingly, research to use only those kinds of biomass for fuel production that cannot be consumed for nutrition purposes, might be preferred over the use of crops or plant oils. So called “second generation biofuels” are produced using a different concept. Similar to existing processes using natural gas or coal, biomass is used to produce liquid hydrocarbons via intermediate stages, including reforming, oxidation, liquefaction and gasification. Of these, the gasification route is the main topic of this study.

The gasification process is a concept to convert liquid or solid substances into a gaseous form. The first major application was the production of “town gas” in the early 1800s. If carbonaceous fuels are gasified, the resulting gas usually contains mainly carbon mono- (CO) and dioxide (CO_2) as well as hydrogen and water. As water and CO_2 can be removed from the gas mixture, gasification is a feasible process to produce “synthesis gas”, a term used for mixtures of hydrogen and carbon monoxide, as either both or at least hydrogen are necessary to conduct some large-scale industrial synthesis reactions. These include ammonia, Fischer-Tropsch (FT) and methanol (MeOH) syntheses. The two gases can be produced from any carbonaceous feedstock, including hard coal and lignite, natural gas, biomass, wastes and refinery residues. Other than for synthesis purposes, H_2 & CO can also be burned for power generation. This is especially favorable for coal power plants, as this enables the use of integrated gasification combined cycle power plants (IGCC), which have a higher (thermal) efficiency than non-gasification coal power plants.

In order to produce substitutes for crude oil imports, however, hydrocarbon synthesis processes are called for. One of the processes for this end is the Fischer-Tropsch Synthesis.

Fischer-Tropsch synthesis is a process known for almost a century. While experimenting with town gas at the Kaiser-Wilhelm Institute in Mülheim/Ruhr in the early 1920s, Franz Fischer and Hans Tropsch discovered that synthesis gas reacts to hydrocarbon chains over selected metal catalysts. CO is thought to cling to the catalyst surface, replacing the oxygen, which reacts to water, with two hydrogen atoms. As long as the CH_2-species remains bound to the catalyst, further CO-molecules can be added, resulting in hydrocarbon chain growth. Temperature and pressure levels affect the product distribution, which is why FT-synthesis is subdivided into high temperature (HTFT) and low temperature (LTFT) synthesis reactions. As the hydrocarbon chain growth is subject to probability aspects, the result is often approximated using statistical models. If diesel production is attempted, a possible way to maximize production of the desired product components is to encourage the growth of long chains (i.e. waxes), which are then treated in more selective cracking reactors to produce diesel fuels. Alternatively, shorter chains will be more suitable for gasoline production. As the resulting chains are mostly linear, however, octane-upgrading is necessary. Consequently, Fischer Tropsch reactors can help adapt to oil scarcities [Steynberg (2004)].

In order to use biomass as a feedstock, a feasible concept for biomass gasification is necessary. Compared to the gasification of natural gas or coal, biomass gasification should ideally only release CO_2 that has previously been absorbed by the plant in question - with the same amount being absorbed by new plants. Therefore, ideal biomass concepts have a closed carbon cycle. And while annual biomass production is far from infinite, biomass is renewable and therefore not subject to depletion as long as the fertility of the land can be sustained.

"Biomass-to-Liquids" (BtL) has been developed by companies and research institutions such as Choren Industries or the Forschungszentrum Karlsruhe, with medium-sized research reactors and early plant concepts already in operation.

Developing a valid and economically feasible concept for biomass gasification is a complex task. In addition to possible price risks on the output and especially on the input side, each concept has to deal with a number of technical difficulties. Ashes, especially from straw gasification, have been found to be much more corrosive than those known from coal gasification processes. Therefore, handling and removal of ashes, as well as the inner structure of the reactors need to be prepared to withstand the corrosive effect. In most cases, biomass gasification results in both the desired gaseous products and unwanted tars, which tend to condense during the quench. These tars must either be gasified or removed from the synthesis gas stream.

BIOMASS LOGISTICS

Even more importantly, transportation of low-density biomass is an economic challenge, as the ideal size of BtL plants is subject to a tricky contradiction. Economies of scale imply that an extension of capacity leads to less than proportional rises in construction costs. Therefore, larger plants have lower unit costs as long as economies of scale can be realized. Mathematical expressions to cover this phenomenon include the cost-capacity-factor, which can be written as follows:

$$\left(\frac{Capacity_{new}}{Capacity_{old}}\right)^x = \frac{Costs_{new}}{Costs_{old}}$$

The exponent x is the decisive figure in this expression. For most industries, it ranges between 0,6 and 0,7 [Peters et al. (2003)]; the latter being used for Fischer-Tropsch equipment in some literature sources [Steynberg (2004)]. Accordingly, plant sizes should be chosen as large as possible.

On the other hand, large plants do require large input feeds and therefore, large areas would need to be used to supply a BTL plant with sufficient biomass. Transportation of biomass, which usually has a low energy density, would increase the input feedstock price significantly. In existing process concepts, this challenge has been met in different ways.

The Carbo V® process, commercialized by the German company Choren Industries, is often considered the most advanced BtL process to date. While several details of the process are subject to non-disclosure, Choren information materials help develop a basic understanding of the concept. Carbo V® includes three stages of gasification to maximize cold gas efficiency. The first stage is a "low temperature" process, in which the biomass feed is partially oxidized. In the following "high temperature" gasification, tar contained in the gaseous product is oxidized, while the third stage makes use of the high temperatures involved to endothermically gasify char. As pointed out by [Fertl et al. (2008)], the last stage is especially important to secure a high efficiency and therefore economic viability of the process as a whole.

Using Fischer-Tropsch technology supplied by Choren shareholder Royal Dutch Shell, the synthesis gas is then converted into diesel fuel, often referred to as “Sundiesel”®.

A drawback of the Carbo V® process is that it does so far not include a biomass pre-treatment. This is naturally an important obstacle for possible scale-up, as the input biomass would have to be transported over large distances. As mentioned before, transportation of biomass may lead to prohibitive input feedstock costs.

The other popular concept is the “Bioliq”® process, developed by the Forschungszentrum Karlsruhe, was designed to enable gasification plants sufficiently large to make use of economies of scale [Henrich et al. (2007)]. Biomass transportation is inefficient due to low energy density and the amount of biomass growing in a specified region. This limits the amount of biomass residue available for gasification. In order to increase the area for biomass supply, a 2-stage concept is promoted. Fast pyrolysis, a thermo-chemical process that transforms biomass into hydrocarbon slurry, is proposed to reduce logistics costs for the large distances necessary to supply sufficient biomass. This is meant to increase the energy density of the input feedstock and therefore reduce overall transportation costs. In the Bioliq® process, dry biomass is converted into hydrocarbon slurry, which is then brought to a central gasification plant. The slurry’s energy density is more than 10 times the original biomass value, enabling a more efficient transportation [Leible et al. (2007)].

Whether it is profitable to produce hydrocarbon fuels from biomass therefore depends on the price of biomass relative to crude oil, transportation costs for either biomass or the intermediate slurry and the investment necessary to construct the pyrolysis sites. If these construction costs were sufficiently low, a large number of pyrolysis plants could be set up. While this would probably help control transportation costs, savings would eventually be offset by the costs associated with plant construction. In an analysis of several settings [Kerdoncuff (2008)], it is shown that at an annual capacity of 100.000 t of fuel, a decentralized plant setting is competitive for straw gasification only. As residual wood usually contains roughly 50% water, decentralized drying would become necessary. The costs associated with a large number of relatively small dryers were found to be prohibitive, as the investment required would be too high.

In the overall production cost estimation, Fischer-Tropsch fuel made from residual straw in a centralized location is estimated to result in costs of 152.6 million €, while the scenarios with 2 and 10 pyrolysis plants cost 155.21 and 154.87 million € respectively. As the numbers are relatively close, the underlying sub-figures gain importance. As expected, when compared to the 10 pyrolysis plant-scenario, the centralized solution has lower investment-related costs (81.97 million € vs. 87.87 million €) but higher costs for transportation (29.77 million € vs. 22.56 million €). Due to the closeness of these figures, it can be found worthwhile to check the assumptions made to calculate these figures and attempt some further optimization of the logistics concept. In both sources [Kerdoncuff (2008), Leible et al. (2007)], a learning curve was used to estimate the costs for the pyrolysis reactors. Learning curve calculations can be performed using the following formula:

$S_n = S_1 \bullet X^d$,

Where

S_n Investment for the nth site

S_1 Investment for the first site

X learning percentage

d $\frac{\ln(n)}{\ln(2)}$

As the learning curve suggests a certain reduction of construction costs every time the cumulative number of manufactured products or plants doubles, it has an especially amplified importance at the beginning of a product life cycle. As, however, both authors make calculations for one specific (and relatively small) area only, cost reductions are relatively modest. The costs for the first unit are estimated to be 6,38 million € [Kerdoncuff (2008)]. Using a learning percentage of 0.9, the result for the tenth unit is 4.49 million €. This means an average of 5.1 million €. If, by contrast, 5 projects of similar sizes to the Baden-Württemberg example were realized, the same approach would yield 3.52 million € for the 50th unit and almost 20 % less on average.

Mass production of these units might relatively quickly reduce the average costs and help offset the undesirable effect of lacking economies of scale.

These considerations are relevant, as common refineries have a capacity of roughly 10 m metric tons of liquid product a year. This is quite exactly 100 times bigger than the gasification plant envisioned in the scenario mentioned [Kerdoncuff (2008)]. The existence of refineries of this size proves the possibility of scale-up into those areas. With a 100-fold increase of size, economies of scale matter significantly. If an exponent of 0.7 is assumed, cost for a plant 100 times the size of another will only be 25 times higher than those of the smaller plant. Even if a more pessimistic exponent of 0.87 is assumed, cost will only rise to 55 times the ones of the small plant. It is apparent that the significant share of costs caused by the central gasification, synthesis and product upgrading facility will be much more favorable on a large scale. Decentralized concepts gain importance when distances are large. While the pyrolysis step appears competitive only for straw in the reference example [Kerdoncuff (2008)], it would be much more valuable for greater plants. On the other hand, as Germany's annual production of residual organic matter totals only approximately 70 million tons [Leible et al. (2007)], which would just be sufficient to fuel on single Fischer-Tropsch plant comparable to contemporary refineries, such a scale may be considered unrealistic for Germany. Nevertheless, greater facilities, maybe even co-using biomass and another fuel such as lignite, should remain in the focus of research.

If plants of this scale should become realistic, biomass logistics would need to be optimized beyond the warehouse-location problem discussed in one of the sources [Kerdoncuff (2008)], as cost structures would hardly be available on such a scale. An approach that enables users to quickly determine sound locations for pyrolysis slurry production is needed in order to quickly propose a preliminary distribution of a number of pyrolysis plants.

APPLICATION OF THE K-MEANS ALGORITHM FOR PYROLYSIS PLANT LOCATION PLANNING

To achieve this, the K-Means Algorithm is applied in a linear optimization model. K-Means refers to a number of "K" centers that are to be placed in the middle of a number of data points. In the first step of the algorithm, the data points are assigned to the center that is closest to their position by Euclidian distance. In a second step, the centers are then moved to a point that minimizes the sum of the Euclidian distances from the data points to the respective center. Afterwards, another iteration of the same steps is performed. As some data points may now be closer to other centers, the minimization of distances may move the centers to different positions, possibly resulting in further changes of assignment. Once two consecutive iterations of the algorithm deliver identical assignments and center positions, no further iterations are necessary. The algorithm is a heuristic, as it usually yields helpful, but not always optimal results. This is partly due to the algorithm inability to recognize local optima [Schreiber (1991)].

An application of the algorithm has been programmed. In the standard K-Means algorithm, the sum of distances from the assigned data points has to be minimized for each center:

$$\text{Min} \sum \sqrt{(xi - x)^2 + (yi - y)^2}$$

Subject to
$x_i = l_i$
$y_i = m_i$,
$i = \{1,\ldots,k\}$

x_i and y_i therefore refer to Euclidean coordinates (l;m) of the k data points. These coordinates also serve as constraints and therefore enable the use of optimization tools such as the Microsoft Excel Solver™. In the model described in this study, optimization steps for the k centers were carried out consecutively, as this was possible with significantly less computing time.

In the case of biomass gasification, it was found feasible to place the central gasification and synthesis site at the center of an Euclidean coordinate system (0;0). This helped make several calculations and considerations significantly simpler.

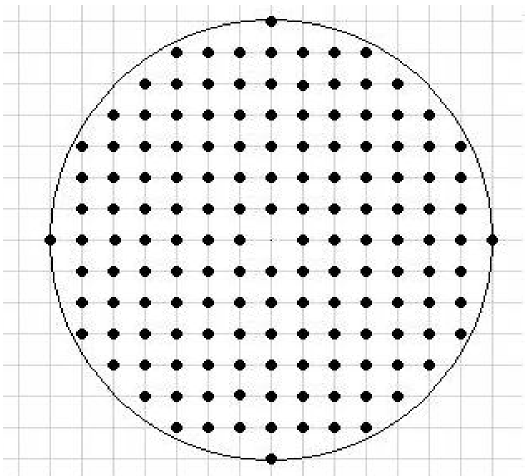

FIGURE 1: The simplified area of biomass production with the gasification plant in the center

It is assumed that the biomass needed for the gasification plant was distributed evenly around the central site. A circular area is considered to supply the biomass needed. In the model, the northernmost source of biomass is given the coordinates (0;7) in the coordinate system. Sources of biomass were assumed to exist at every corner of a grid with a distance of 1 Euclidean unit between two adjacent sources. Accordingly, the circle as a whole would include 148 such sources, as the gasification facility itself was not assumed to supply any biomass. While these assumptions obviously appear very artificial, they merely serve as an example to check the validity of the programmed model. As both the coordinates of all sources and the weighting factor for each source can be altered, the model can easily be adapted to real-world problems once it is considered relevant.

Consequently, a 148 x 16 matrix was set up to calculate distances from each of the 148 Sources to all 16 pyrolysis plants. For each source of biomass, i.e. each line of the matrix, the minimum distance was determined and applied to assign sources to the closest pyrolysis plants. In order to avoid changes of assignments during the subsequent optimization of the pyrolysis plants' locations, the assignments are fixed before the optimization starts.

Distances between source and pyrolysis plant are obviously an important aspect when calculating transportation costs. However, other factors need to be considered as well. The costs covered in the model also include wages for the drivers and rents for the vehicles. Different kinds of vehicles were used for biomass and slurry transportation. Analysing data from a diploma thesis [Bornemann (2009)], a tractor was considered realistic to transport biomass, while a truck was assumed to be feasible for the slurry transportation. For some preliminary results, the following calculations were performed.

Transportation costs are subdivided into costs proportional to the duration (vehicle rent and wages) and fuel costs. This is considered necessary, as higher values for "k", the number of pyrolysis plants, would result in lower biomass transportation costs but more expenses for the slurry transportation. A variable called "n_{tours}" was introduced, which deserves some explanation. It was assumed that biomass can be stored at the point of origin until one truckload can be brought to the closest pyrolysis site. While this assumption hardly appears worth mentioning, it simplifies the problem significantly. It helps avoid planning tours to enhance the truck utilization, as each truck is utilized to its full capacity (at least on the trip to the pyrolysis site). Consequentially, the number of trips necessary to move all the biomass from the points of origin to the pyrolysis plant is calculated as follows:

$$Number\ of\ truck\ tours = \frac{Annual\ biomass\ production\ at\ one\ site}{Amount\ of\ biomass\ transported\ per\ truck\ load} * number\ of\ sites$$

The resulting number of truck tours is then used to calculate the costs of biomass transportation. Once that figure has been determined, the costs of slurry transportation are calculated. Due to the higher density of the slurry, less slurry has to be transported. According to [Leible et al. (2007)], 14.6 metric tons of slurry can be transported by one truck, compared to only 8.1 metric tons of biomass. As one kg of biomass is reduced to 0.654 kg of slurry, 2.756 truckloads of biomass are necessary to produce one truckload of slurry.

The resulting sum of transportation costs can then be minimized for a given number of pyrolysis plants using linear optimization.

$$\min [(C_{fuel} + C_{duration}) * n_{tours}]_{Biomass} + [(C_{fuel} + C_{duration}) * n_{tours}]_{Slurry}$$

(This formula was used as the objective function in the optimization step of the K-Means algorithm instead of merely minimizing distances)

The following examples are presented in diagrams that show the distribution of the pyrolysis sites only. As in figure 1, the east-west and north-south diameters are 140 km each. A set of interesting results was encountered, when the number of pyrolysis plants was chosen to be 16 (2^4, as distinctive points of the learning curve were investigated). If these location diagrams, which show the distribution of the pyrolysis sites in a Cartesian coordinate system (see figure 2, left-hand side), are combined with the circles as in figure 1, the resulting diagram (see figure 2, right-hand side) represents a birds-eye view of the area surrounding the gasification site.

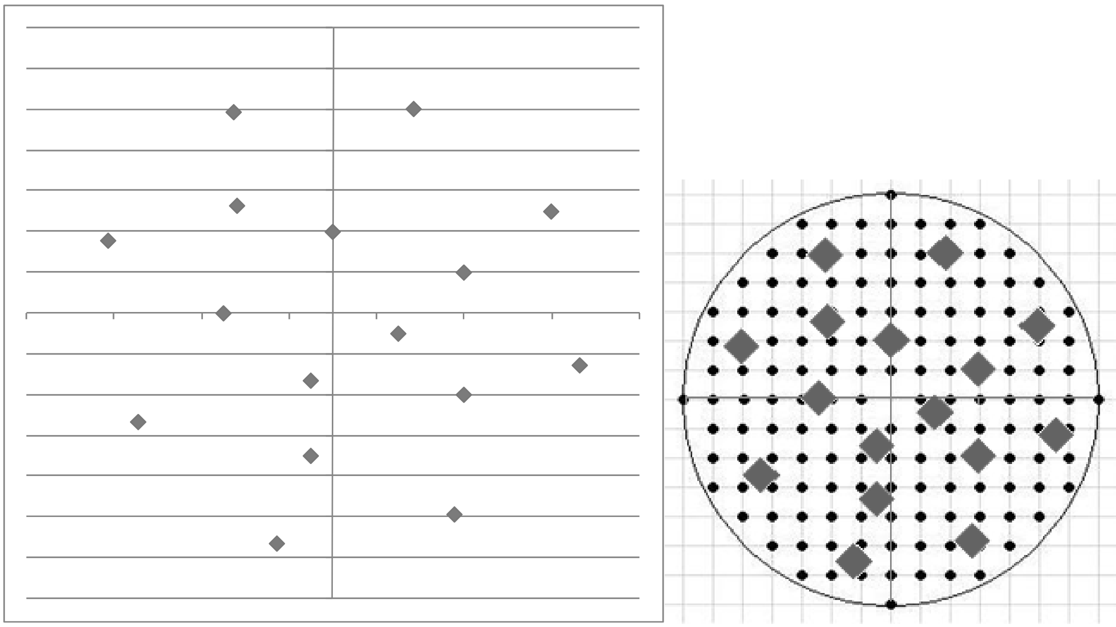

FIGURE 2: Applying the resulting diagrams to the problem description; left: Cartesian coordinate system from spreadsheet, right: simplified birds-eye view of the area surrounding the gasification site

The color red was chosen to contrast the pyrolysis plants from the biomass sources.

Example 1: "O"-Setting

As most heuristics results depend on the quality of the default setting, it was attempted to begin with a rather simple task. Using the starting points as shown on the left-hand side of figure 3, the algorithm was checked for validity of results.

Due to the appearance of the diagram, this setting was labeled “O”-setting. When applying the K-Means algorithm to minimize distances between sources and their assigned pyrolysis plants, the distribution on the right-hand side of figure 2 results. While similar forms (i.e. a circle of 12 pyrolysis plants with four plants in between) often emerged when using the K-Means algorithm, this solution is not the global optimum. In fact, the sum of costs was found to be roughly the same for both scenarios. The objective function, which calculated the costs for one truckload of biomass to be transported from every source to the pyrolysis plants and the subsequent slurry transportation to the central gasification site, increased from 72,097.61 € to 72,355.02 € using K-Means.

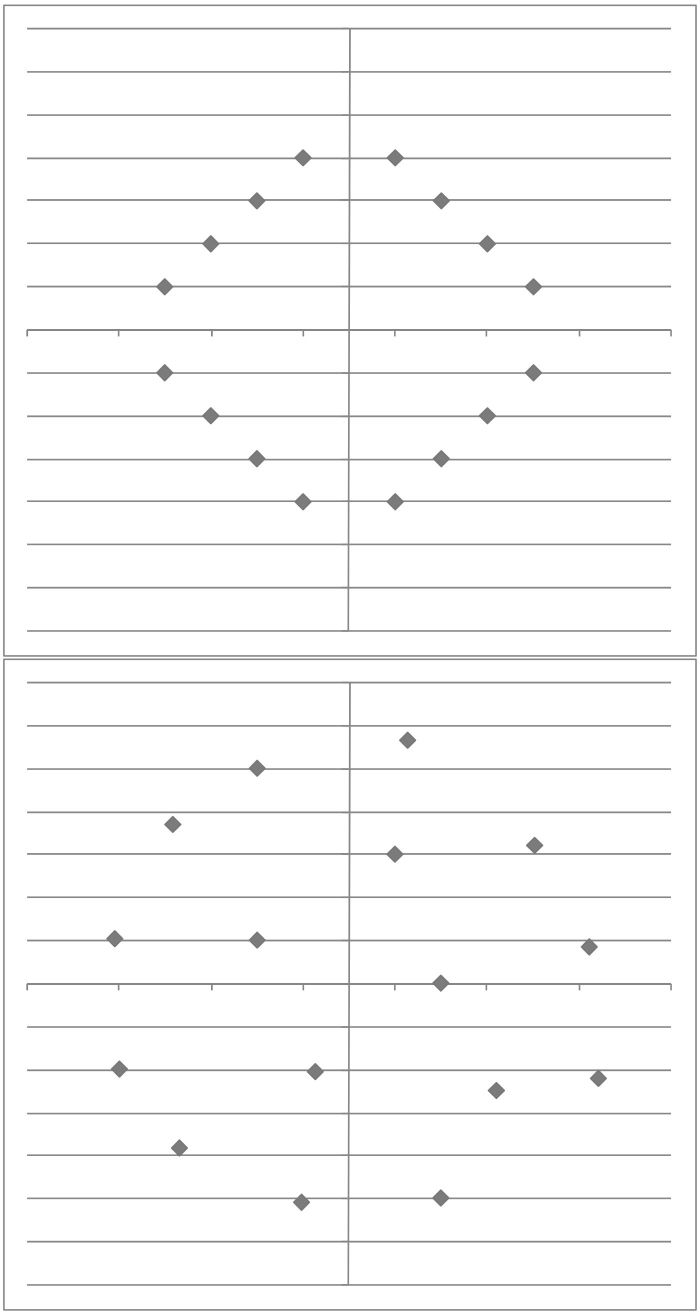

FIGURE 3: “O”-Setting K-Means

In spite of being more expensive, and therefore less optimal than the “O”-setting itself, such a development is by no means unusual, as costs are not the objective function of K-Means at all. Even if costs are included, as shown in figure 4, total costs increase to 72,178.29 €. As optimization is performed consecutively for all pyrolysis sites, global optima may obviously be missed.

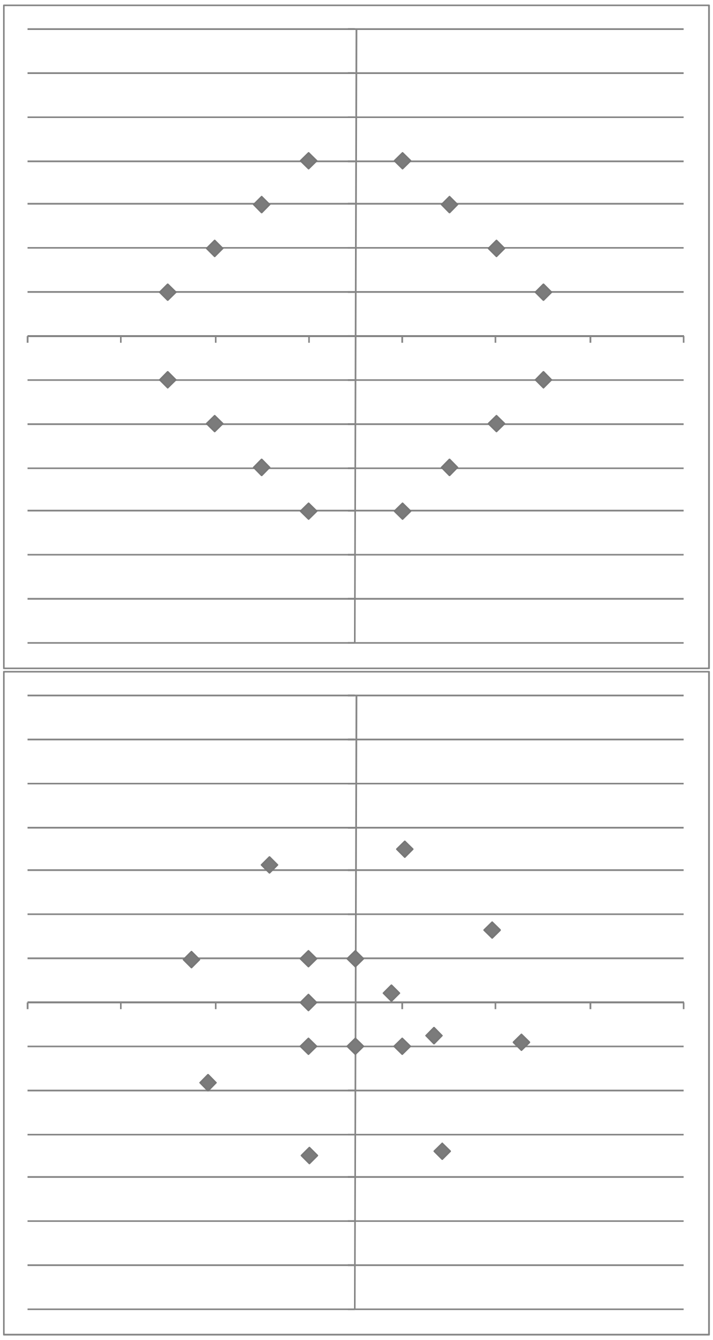

FIGURE 4: “O”-Setting Cost-K-Means

Example 2: "X"-setting

As the "O"-setting was assumed to be relatively close to the optimal solution, another setting was investigated that was slightly less challenging to beat. The "X"-setting as shown in figure 5 and 6 has an initial objective function value of 73,147.42 €. As this is higher than the algorithms solution in the "O"-setting, it is interesting to find out whether either algorithm would achieve a total cost reduction in this case. Moving the pyrolysis plants as visible on the right-hand sides of figures 5, K-Means reduced costs to 72,355.02 €.

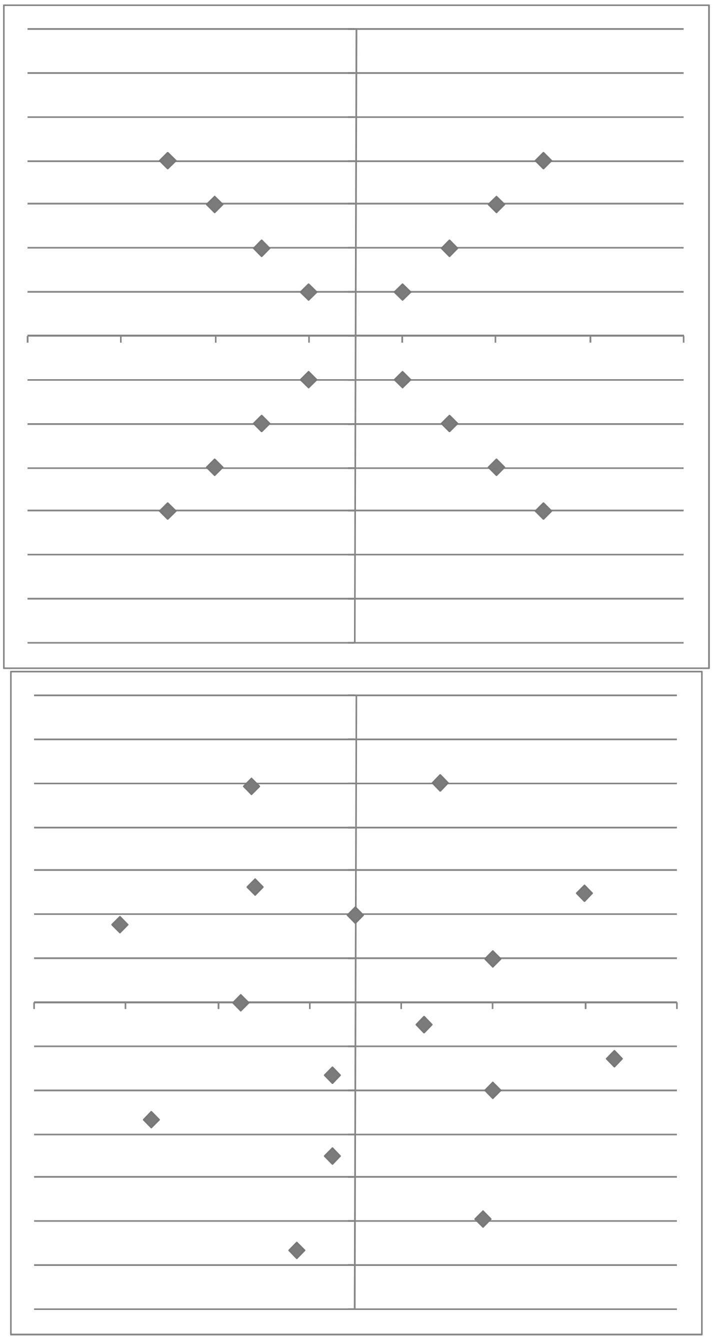

FIGURE 5: "X"-Setting K-Means

The second algorithm, labeled "Cost K-Means" in figure 6, even managed a reduction to 72,178.29 €. It is interesting to see, that although the original settings were quite different, the algorithms solution appear relatively similar.

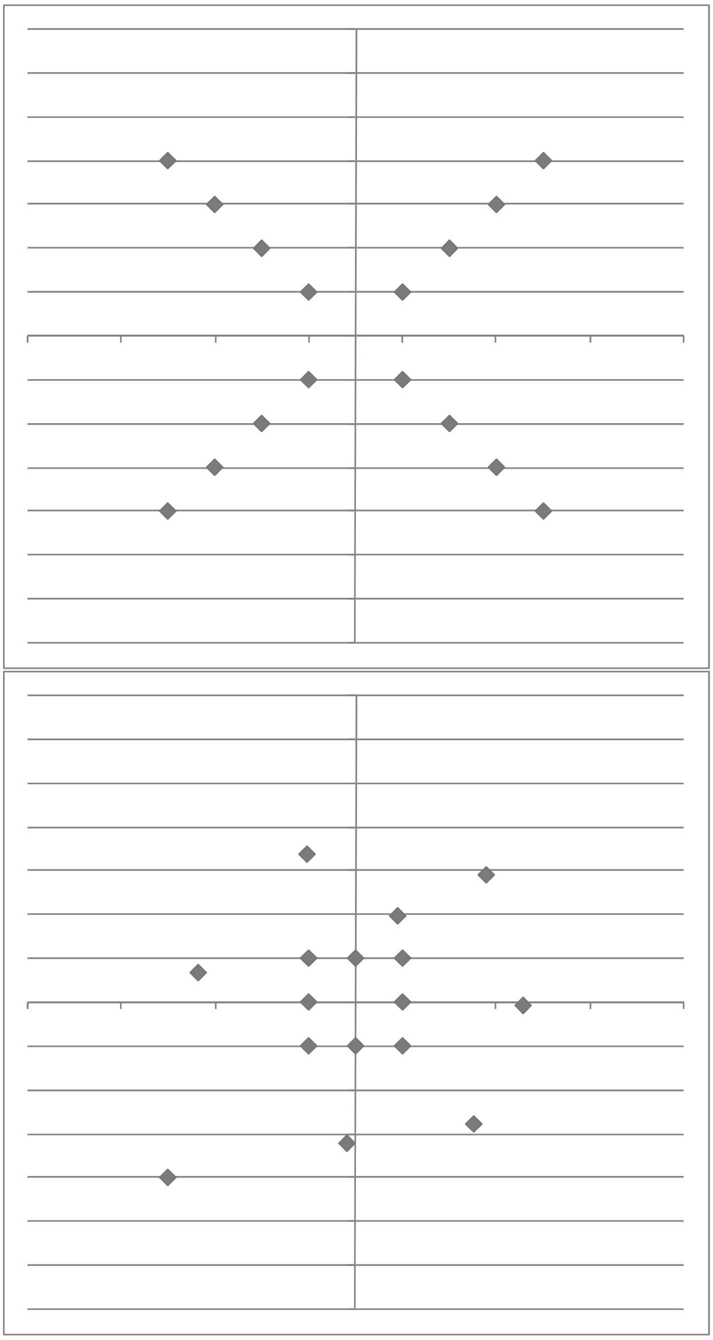

FIGURE 6: "X"-Setting Cost-K-Means

Example 3: “Smart Human” Setting

The third setting is the one with the best objective function value (71,689.54 €) encountered while testing the algorithm. When using the K-Means algorithm to optimize the setting (figure 7), the resulting distribution reminds of the result found in the “O”-setting (figure 3). The resemblance to an ideal circle borne by the twelve outside points is even more apparent than before, and the objective function value is lower (72,068.12 €).

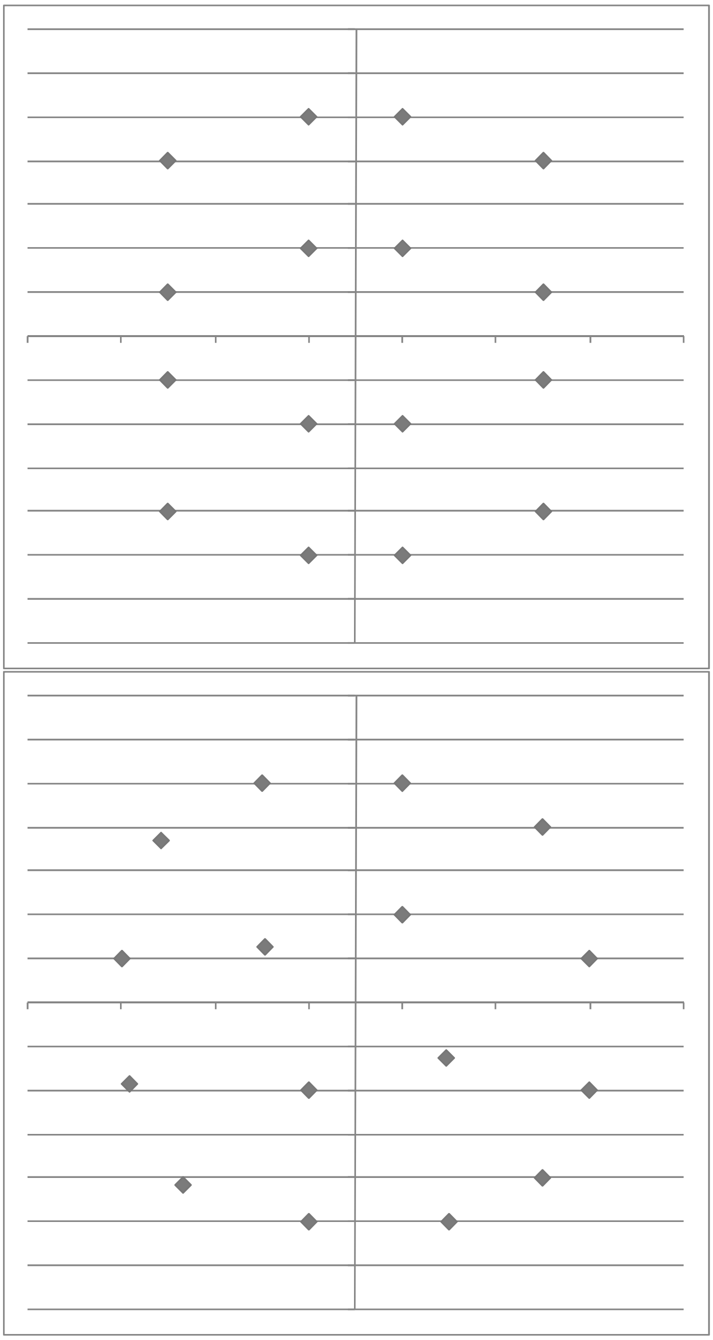

FIGURE 7: “Smart Human” K-Means

When the "Cost K-Means" algorithm is applied on the "Smart Human" setting (figure 8), no changes occur at all. While this may be considered superior to the performance of K-Means, no improvement was achieved either.

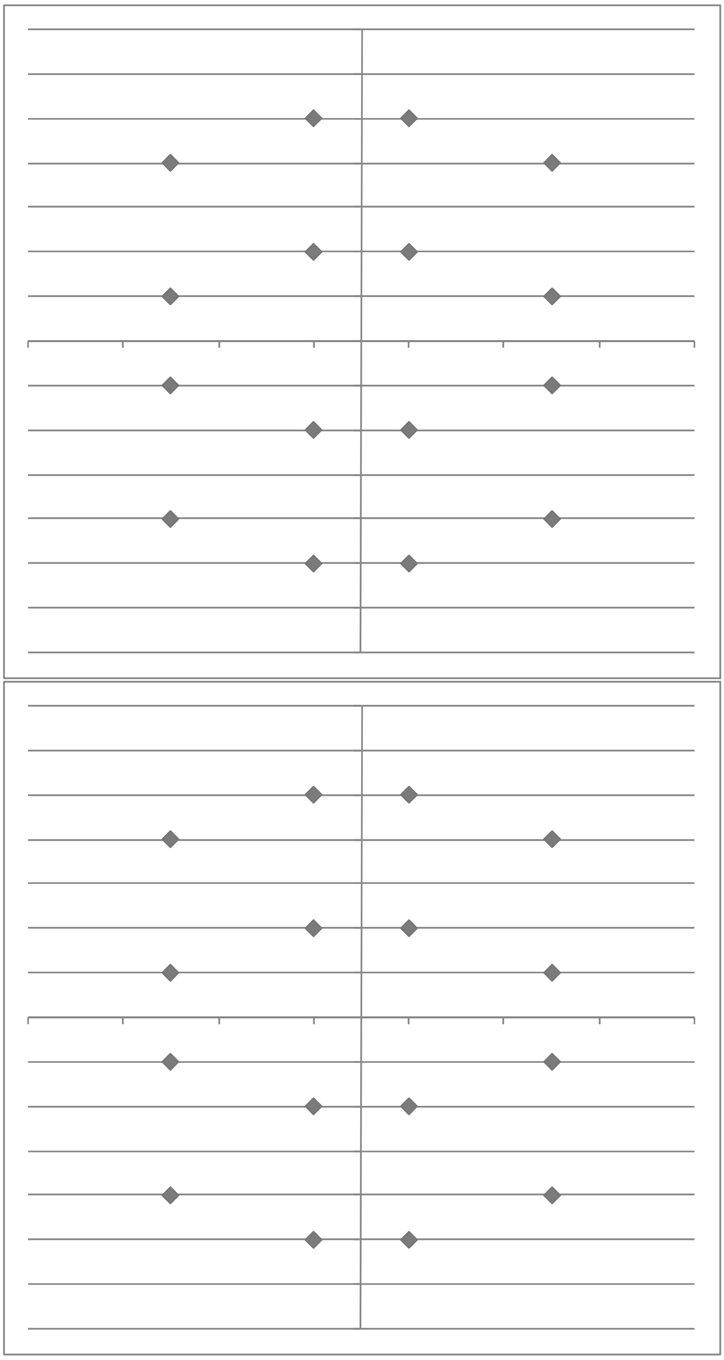

FIGURE 8: "Smart Human" Cost-K-Means

CONCLUSION AND OUTLOOK

Biomass-to-liquids offers the possibility to substitute some crude oil based products with those made from biomass. One of the main obstacles is the lack of profitability due to the lack of logistic efficiency in existing concepts. As economies of scale are of utmost importance for the concept to approach economic feasibility, gasification plants need to be large and accordingly, areas providing biomass have to be far-reaching. In order to avoid costs resulting from transporting low-density biomass, further progress on the learning curve of pyrolysis reactors is necessary to provide low-cost biomass slurry for gasification in a central facility.

The greater the area necessary to supply sufficient amounts of biomass to fully utilize large gasification plants, the greater is the importance of feasible logistics concepts. The K-Means algorithm can be used to find locations for pyrolysis reactors that are relatively close to an optimum, if a suitable distribution is used to initiate the algorithm. The locations found by the algorithm can then be used to make estimations of logistics costs, which are necessary to make preliminary cost estimations for the process as a whole.

If costs are included into the K-Means algorithm, the proposed locations for pyrolysis plants move closer to the center compared to simple K-Means that does not include slurry transportation.

A closer look at some early results has not yet proven the ability of the algorithm to improve given settings towards optimality. The subsequent optimization of individual locations has sometimes yielded results with higher costs than previous solutions.

However, further development and applications to real problems may help shape the algorithm into a helpful tool for preliminary plant location planning.

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SCENARIO ANALYSES OF LOGISTICAL CONCEPTS FOR 2ND GENERATION BIOFUELS

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Abstract: To reduce CO_2 emissions within the transportation sector and the dependency on scarce oil resources the production of second generation synthetic fuels is widely discussed. The production of such fuels via the Gasification - Fischer-Tropsch Synthesis pathway can be carried out in a five step process consisting of *Biomass Preparation*, *Gasification*, *Gas cleaning and Conditioning*, *Synthesis* and *Product Conditioning*. The low energy density of the biomass supply makes the transport over long distances problematic, both from an economic and from an ecological point of view. Hence regional concepts are considered to be a viable option to establish such process chains in practice. We investigate from a logistical point of view possible plant concepts for a target region, the German state of Baden-Württemberg. We formulate a facility location model, implement this in the algebraic modelling system GAMS and apply it to analyze different scenarios. In these scenarios we deal with the consequences of varying biomass feedstocks (wood residues and residual straw) and logistical configurations. A central integrated production concept is considered as well as a decentralised concept in which the biomass preparation is carried out in several smaller locations which are spatially separated from the further processing steps. Though the specific investments of such a decentralised concept are higher in comparison to a central concept, transport costs decrease and a transport over larger distances becomes more attractive due to a higher energy density of the biomass that has to be transported. We compare the results for different feedstock scenarios to determine their influence on the results.

INTRODUCTION

Research and development for sustainable biomass utilization concepts are enforced as crude oil resources decline and the pressure to reduce greenhouse gas emissions increases. As a consequence, numerous biomass utilization chains at different stages of process development are currently under discussion. The so called 2nd generation biofuels are one promising option. They have advantages as they reach higher fuel yields in comparison to 1st generation biofuels, and they do not compete with the food chain. An assessment of such concepts at an early stage of the process development can help to support the development of cost-effective and environmentally sound industrial scale production processes.

Within biomass valorisation concepts the configuration of the logistics system plays a key role. Biomass accrues spatially distributed and has a low energy density. This makes transports of large biomass amounts over long distances, which are necessary to achieve reasonable plant sizes for the utilisation plant, unattractive from an economic as well as from an ecological point of view.

With our study we want to determine the influences of different logistical concepts on economic and ecological key parameters for different feedstocks of one promising and currently broadly discussed 2nd generation biofuel process chain, the production of synthetic biofuels via preparation, gasification and Fischer-Tropsch synthesis, the so called Biomass-to-liquid (BtL) fuel production. We apply a two-staged capacitated facility location model to analyze the economic and ecological implications of different logistical configurations. For this analysis we use data of a detailed techno-economic and ecological assessment of a BtL process chain plant with a capacity of approx. 1 Mio. t of wood residues and residual straw with 15 % moisture.

The paper is structured as follows: First we give a brief overview of our methodological approach by describing the considered process chain and considered logistical scenarios as well as the analysis steps. In the third section we describe our planning model and refer to the used data. The fourth shows the results of exemplary model runs, analyzing the influence of the different scenarios. Finally we draw conclusions of our study.

METHODOLOGICAL APPROACH

Reference process chain

As a starting point for our analyses we use a reference configuration of the following BtL fuel production concept: The biomass is dried and milled in order to achieve optimal conditions for the subsequent fast pyrolysis. The produced intermediate ("slurry") is gasified in an entrained-flow reactor under high pressure ($2.5 \cdot 10^6$ Pa) and high temperature (1,500 °C). Thus, a tar-free synthesis gas is produced. In order to fulfill the requirements of the FT synthesis, the gas is cleaned from its pollutants by using conventional low-temperature gas cleaning techniques, i.e. cyclone, bag filter and a wet scrubber. To reach optimal synthesis conditions a H_2/CO molar ratio of 2:1 is required. Therefore a CO conversion step is installed. After the FT synthesis in a fixed bed reactor with cobalt as catalyst, the synthesis products are separated by distillation into wax, diesel and gasoline. The gained waxes are converted with a hydrocracker into diesel and gasoline, leading to an increased biofuel production. The described reference configuration is depicted in FIGURE 1.

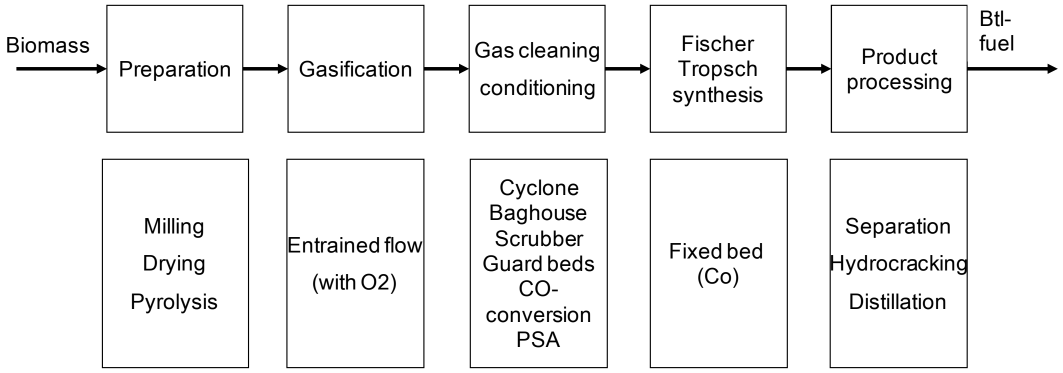


FIGURE 1: Reference process chain

As raw materials we compare the utilization of 1.7 Mio t of wood residues (water content 50 %), and 1.0 Mio t of straw (water content: 15 %).

Considered scenarios of logistics configurations

Designing a BtL process chain also demands for the consideration of the logistical system. Currently, two major logistical concepts for a BtL concept are under investigation in two pilot plants which are built in Germany. The concept of CHOREN Industries GmbH, cf., e.g., Kiener (2008), follows a central integrated concept, in which the biomass is collected and transported directly to one central integrated plant in which all processing steps described in the previous section take place. The CHOREN concept is based on the feedstock wood.

The Forschungszentrum Karlsruhe GmbH (FZK) follows a concept of "decentralized preparation units", in which a decoupling of the process chain is carried out. The biomass is transported to a number of smaller decentralized units in which it is prepared and conditioned to produce an intermediate "slurry", also called "bio-syncrude", with a ten times higher volumetric energy density. This intermediate is transported to the integrated process plant where the further steps of gasification, gas-cleaning and conditioning, synthesis and product processing take place. The number of preparation plants and their sizes can principally be varied. For a further description of the FZK concept cf., e.g., Henrich et al. (2009). The concept is based on straw as feedstock.

As the necessary preparation steps for the feedstock, i.e. the chopping, milling and drying differ for different types of biomass, the suitability of the one or the other logistical concept is influenced by the feedstock choice. Residual straw has e.g. a different chemical composition and a significant lower water content in comparison to residual wood. In general, the decentralized solutions demand for more preparation units of smaller sizes. This results in negative effects of economies of scale on the one hand side. On the other hand side a larger number of preparation units may have positive impacts due to learning effects.

Therefore we investigate in this study the following four scenarios (cf. TABLE 1): for the two feedstocks of wood residues and residual straw, in each case two logistical concepts, a central integrated plant and a central synthesis plant with ten decentralized preparation units are considered.

TABLE 1: Considered scenarios

Scenario	Biomass feedstock	Logistical configuration
Scenario I	Wood residues	Central integrated plant
Scenario II	Wood residues	Central synthesis, 10 decentralized preparation units
Scenario III	Residual straw	Central integrated plant
Scenario IV	Residual straw	Central synthesis, 10 decentralized preparation units

Problem characterization

For the assessment of the scenarios of the two logistical concepts and different feedstocks we interpret the elaboration of the scenarios as a capacitated warehouse location model with two stages, biomass provision to the preparation unit and slurry transport to the synthesis unit (cf. FIGURE 1).

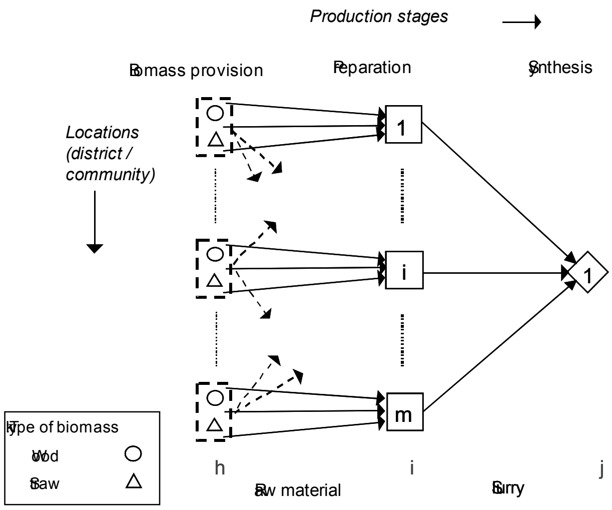


FIGURE 1: Structure of the planning problem

The indices in this network representation denote:

$h \in H$, $H = \{1,...,l\}$ set of biomass suppliers (districts, communities)

$i \in I$, $I = \{1,...,m\}$ set of possible locations of the preparation units

$j \in J$, $J = \{1,...,n\}$ set of possible locations for the synthesis unit

$k \in K$, $K = \{1,...,p\}$ set of biomass feedstocks

Within the network, the following material flows occur: biomass of type k is transported from supplier h to the preparation unit i where it is converted to slurry. The slurry is transported from preparation unit i to the synthesis plant j where it is finally converted to synfuel.

To elaborate and assess the scenarios, for each scenario a planning problem is solved. This problem consists of the optimal choice of the locations for the preparation units and the synthesis plant, so that the decision relevant costs, originating from the biomass supply and transport, fixed and variable production costs at the preparation and the synthesis stage, as well as for transport between the preparation and the synthesis stages, are minimal. The case of a central integrated plant is a special case of the above mentioned problem, in which preparation and synthesis are in one location and no transportation costs accrue between them. To investigate the scenarios described in the previous paragraph, a two-staged capacitated warehouse location model is formulated, implemented and applied to the scenarios.

A FACILITY LOCATION PLANNING MODEL TO ANALYZE LOGISTICAL CONFIGURATIONS OF A BTL PRODUCTION CHAIN

For the mathematical formulation of the warehouse location problem the symbols which are declared in the following TABLE 2 are used.

TABLE 2: Symbols

	Indices	
Prep	Preparation	-
Sy	Synthesis	-
B	Biomass	-
S	Slurry	-
F	Fuel	-
	Parameter	
p_{hk}	Price for biomass of type *k* of supplier *h*	€ / (t wet)
$c_{hik}^{b,LKW}$	Transport costs for biomass of type *k* from collection point in location *h* to preparation unit *i*	€ / (t wet)
$c_{ij}^{s,LKW}$	Transport costs for slurry from preparation unit at location *i* to synthesis unit *j*	€ / (t slurry)
f_i^{Prep}	Fixed costs for a preparation unit at location *i*	€ / a
f_j^{Sy}	Fixed costs for synthesis unit at location *j*	€ / a
$c_{ik}^{var,Prep}$	Variable costs of the preparation of one tonne biomass (wet) of type *k* at location *i*	€ / (t wet)
$c_j^{\mathrm{var},Sy}$	Variable costs of the processing of one tonne slurry in the synthesis unit at location *j*	€ / (t slurry)
$y^{Sy,total}$	Total amount of slurry that has to be processed in the synthesis unit	t Slurry / a
$\overline{x}_{hk}$	Maximum amount of biomass of type *k* available in location *h*	t Raw material / a
β_{ik}	$\beta_{ik} = \frac{Pyro_{out,ik}}{Pyro_{in,ik}}$: Production coefficient preparation unit	t Slurry / (t wet)
α_{hk}	Water content factor	-

M^{Prep}	Number of preparation units	-
M^{Sy}	Number of synthesis units, here: $M^{Sy}=1$	-
	Variables	
x^{b}_{hik}	Amount of biomass of type *k* transported from location *h* to the preparation unit at location *i*	t wet / a
x^{s}_{ij}	Amount of slurry transported from preparation unit *i* to synthesis unit *j*	t Slurry / a
y^{Prep}_{ik}	Amount of slurry produced from biomass of type *k* in the preparation unit at location *i*	t Slurry / a
y^{Prep}_{i}	Total amount of slurry produced at location *i*	t Slurry / a
y^{Sy}_{j}	Amount of slurry that has to be processed at synthesis unit at location *j* (with lower and upper bounds $\underline{y}^{Py}_{k}$, $\overline{y}^{Py}_{k}$, $\underline{y}^{Sy}$, $\overline{y}^{Sy}$)	t Slurry (processed)/ a
z^{Prep}_{i}	Binary decision variable for a preparation unit at location *i*	-
z^{Sy}_{j}	Binary decision variable for a synthesis unit at location *j*	-

With these symbols the warehouse location problem can be formulated as:

Objective function:

Min $[\sum_{h\in H}\sum_{i\in I}\sum_{k\in K} p_{hk}\cdot x^{bm}_{hik}$	Biomass supply costs	(1)
$+\sum_{h\in H}\sum_{i\in I}\sum_{k\in K} c^{bm,truck}_{hik}\cdot x^{bm}_{hik}$	Short distance transport costs biomass (truck) supplier to preparation	(2)
$+\sum_{i\in I} f^{prep}_{i}\cdot z^{prep}_{i}$	Fixed costs of biomass preparation units	(3)
$+\sum_{h\in H}\sum_{i\in I}\sum_{k\in K} c^{var,prep}_{ik}\cdot x^{bm}_{hik}$	Operation costs of biomass preparation units	(4)
$+\sum_{i\in I}\sum_{j\in J} c^{slur,truck}_{ij}\cdot x^{slur}_{ij}\ ]$	Long distance transport costs for slurry (truck), preparation to synthesis	(5)

Subject to:

$\sum_{i \in I} x_{hik}^{bm} \leq \overline{x}_{hk}$	$\forall h,k$	Limited availability of biomass of type k	(6)
$y_{ik}^{prep} = \sum_{h \in H} \alpha_{hk} \cdot x_{hik}^{bm} \cdot \beta_k$	$\forall i,k$	Production of slurry from biomass k at location i	(7)
$y_i^{prep} = \sum_{k \in K} y_{ik}^{prep}$	$\forall i$	Total mass of slurry produced at location i	(8)
$y_{ik}^{prep} \geq \underline{y}_k^{prep} \cdot z_i^{prep}$	$\forall i,k$	Lower capacity limit in the preparation unit	(9)
$y_{ik}^{prep} \leq \overline{y}_k^{prep} \cdot z_i^{prep}$	$\forall i,k$	Upper capacity limit in the preparation unit	(10)
$y_i^{prep} = \sum_{j \in J} x_{ij}^{slur}$	$\forall i$	Mass balance preparation	(11)
$\sum_{i \in I} z_i^{prep} \leq M^{prep}$		Limitation of the number of preparation units	(12)
$y_j^{sy} = \sum_{i \in I} x_{ij}^{slur}$	$\forall j$	Mass of slurry used in synthesis unit j	(13)
$y_j^{sy} \geq \underline{y}_j^{sy} \cdot z_j^{sy}$	$\forall j$	Lower capacity limit of the synthesis unit	(14)
$y_j^{sy} \leq \overline{y}_j^{sy} \cdot z_j^{sy}$	$\forall j$	Upper capacity limit of the synthesis unit	(15)
$\sum_{j \in J} y_j^{sy} = y^{sy,total}$		Mass balance synthesis	(16)
$\sum_{j \in J} z_j^{sy} \leq M^{sy}$		Limitation of the number of synthesis units	(17)
$x_{hik}^{bm}, x_{ij}^{slur}, y_i^{prep}, y_i^{sy} \geq 0$	$\forall h,i,j,k$	Non-negativity of the decision variables	(18)
$z_i^{prep}, z_j^{sy} \in \{0,1\}$	$\forall i,j$	Definition of the binary variables	(19)

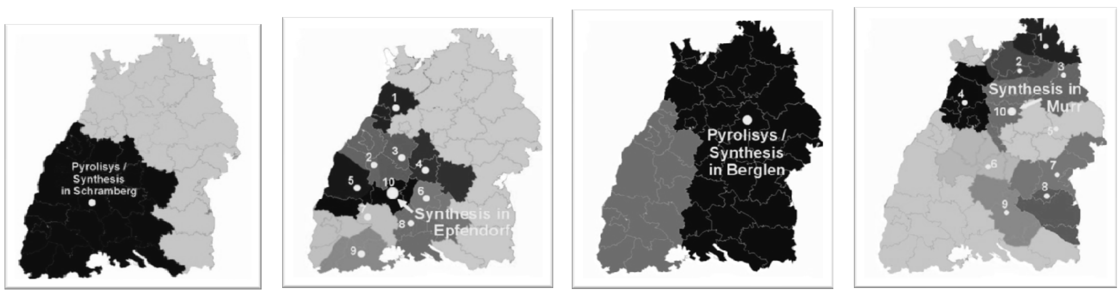
The model is implemented in the General Algebraic Modelling System (GAMS) and solved using the CPLEX solver.

EXEMPLARY APPLICATION RESULTS

As input data we use the amount of accruing biomass for residual wood and residual straw determined by Leible (cf. Leible et al. (2005)). For the biomass prices also data from Leible (cf. Leible et al. (2005), Leible et al. (2007)) is used. For fixed and variable production, as well as for transportation costs we use a cost estimate by Kerdoncuff et al. (2007), Kerdoncuff (2008). In total 87 communities in Baden-Württemberg are considered as possible sources of biomass and possible locations for the preparation and synthesis units. The distances for the calculation of the transportation costs are derived from a 87x87 matrix calculated using data from Mappy SA (2006).

The developed model is applied in the four specified scenarios, differing in feedstock and logistical configuration. Scenario I and Scenario II deal with wood in a central and decentral configuration, whereas Scenario III and Scenario IV cover the according scenarios for the feedstock residual straw.

FIGURE 2 displays the computed configurations. It can be seen clearly, that in the case of wood residues the wood rich south-western part of Baden-Württemberg is selected as source for the BtL plants in Scenarios I and II. For residual straw in Scenarios III and IV the sources lie mainly in the eastern part where more agriculture is situated. With only small differences between the central integrated and the decentralized scenarios the area used for the biomass supply is the same within the two scenarios of each feedstock. It can also be stated, that the location for the central integrated plant in the central scenarios does not differ significantly from the synthesis plant in the decentralized scenarios.



Scenario I Central Concept	Scenario II Decentral Concept	Scenario III Central Concept	Scenario IV Decentral Concept
Wood Residues		Residual Straw	

Legend: Light grey: area does not provide biomass for BtL production
Dark grey / colored: area provides biomass to the integrated plant / prepartion plant

FIGURE 2: Logistical configurations obtained from the location planning

The results regarding the objective function value, i.e. the decision relevant costs, and the results concerning the transportation load are given in TABLE 3. Residual straw is advantageous from an economic point of view. This is due to the advantages of straw in the used cost estimates. The higher costs for wood residues per annum originate mainly from a needed additional preparation and drying. In the case of wood residues, the decision relevant costs increase by 20 Million € in the decentralized scenario. This is also due to the needed preparation and drying. In the decentralized scenario the negative impacts through the down-scaling of the preparation and drying, are not compensated by a reduction of transport costs.

In this regard, the results of residual straw differ. Due to the lower water content of the feedstock, no additional drying is needed and therefore a decrease in the transportation load leads to a small decrease of the decision relevant costs and therefore overcompensates the negative impacts of the scale-down of the preparation unit. Thus, in the case of residual straw the decentralized scenario is slightly favorable. Significant differences in the scenarios can be observed concerning the transport load. For wood, the transport load is cut by more than 40 % by a shift to a decentralized configuration. The effects concerning residual straw are considerably smaller but do also exist. The decrease in this case is approx. 15 %. Concerning the transport load, the most favorable scenario is the decentralized scenario with wood residues.

TABLE 3: Objective function value and transportation load in the scenarios

Scenario	**Objective function value [10^6 €]**	**Transportation load [t·km]**
Scenario I (wood residues, central)	165	$11.4 \cdot 10^7$
Scenario II (wood residues, decentral)	185	$6.6 \cdot 10^7$
Scenario III (residual straw, central)	157	$9.4 \cdot 10^7$
Scenario IV (residual straw, decentral)	156	$8 \cdot 10^7$

CONCLUSIONS

Biomass to liquid fuel production is an emerging technology. This technology has the advantage, that an industrial realization is possible without direct interference with the food chain. Nevertheless, the technology is still under development and has yet to prove its economic and ecological competitiveness. One crucial factor in the elaboration of BtL concepts is the supply of the necessary amounts of biomass at reasonable costs. Therefore the choice of feedstock and the logistical configuration of the process chain play an important role in the development of such technologies.

This contribution analyzes the influence of the choice of logistical configuration and biomass feedstock on the results of an economic assessment of a BtL concept for the German state of Baden-Württemberg. Based on earlier studies, a two-staged capacitated warehouse location model is used to analyze scenarios of a central integrated plant and a central synthesis plant with ten decentralized preparation units for the feedstocks of wood residues and residual straw.

The results show that a decentralized concept with residual straw as feedstock has slightly lower decision relevant costs in comparison to a central integrated concept of residual straw and significant advantages in comparison to the same scenarios for wood residues. In the scenarios with central integrated plants the decision relevant costs are aprox. 5% lower, in the scenarios with decentralized preparation units the difference is with approx. 15% even bigger. A decentralized concept with wood residues as feedstocks has the minimum transport load in the compared scenarios. This indicates environmental advantages concerning a reduction of greenhouse gas emissions from transport.

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The industrial or energetic use of woody or herbal biomass can provide solutions to the ecologic and economic problems of the growing worldwide demand for energy and fuel.

A two-year research exchange named Biociclo between the Universidad de Concepción (Chile) and the Universität Karlsruhe (TH) (Germany) aimed at establishing contracts for supporting joint research in this field. This book contains the contributions for the final workshop of this exchange funded by the German BMBF and the Chilean CONICYT.

It reflects the internationality and interdisciplinarity of the workshop's participants and the scope of the contributed papers about Biomass Utilization Paths in Chile, Pyrolysis and Life-Cycle Assessment of Biomass and Logistic Concepts of Biomass Utilization Concepts. We are glad to offer a documentation, which may foster the exchange of scientific approaches and their practical application.

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