1 Introduction

Scarce fossil energy resources, resulting in steeply rising prices, have fuelled the development of alternative concepts to supply energy and other fossil-derived products such as organic chemicals in several periods in the 20th century. The economic importance of liquid hydrocarbons has been a driver of technical innovation during periods with high prices of crude oil. While other fossil resources, such as coal or natural gas, have been the preferred choice as substitutes for crude oil in the earlier disruptions of crude oil supply, developments in the final quarter of the 20th century have led to a shift in attention towards renewables (Bundesregierung 2010, p. 3; BMU 2011, p. 3). Concerns about climate change, which is generally assumed to be triggered by a rising level of greenhouse gases in the atmosphere, have promoted the reducing greenhouse gas emissions resulting from the conversion of fossil energy carriers to water and carbon dioxide (IPCC 2007, p. 30). Numerous renewable sources of energy have been developed and promoted in recent decades (BMU 2011, p. 5). Processes to produce power from wind, solar radiation, geothermal energy and biomass are among the most visible developments to reduce fossil fuel consumption for power generation. While this approach is feasible to tackle the considerable portion of anthropogenic CO_2 emissions resulting from coal combustion in power plants, its effect on transportation is, as of now, limited. Until concepts independent of hydrocarbon fuels, like e-mobility, can be used to cover mobility needs, the production of liquid hydrocarbon fuels therefore remains a necessity.

If it is assumed that the supply of oil will be insufficient to cover the rising world demand or even peak at some point in the near future, oil prices are likely to rise and require the pursuit of alternatives for crude oil's areas of application (Erdmann/Zweifel 2007, p. 207). Biomass, the most versatile renewable energy, can be part of the solution to this problem. In addition to using biomass for power production via direct combustion or combustion of biogas produced by fermentation, biomass can also be used for the production of liquid transportation fuels (Kaltschmitt 2001, p. 4). Converting sugars to bioethanol, or plant oils to biodiesel, is already pursued on a large scale in many industrialized and some transition economies around the globe. Among the initial reasons to promote the use of crops from agriculture for fuel production in the technologies' earlier stages was the reoccurring situation of large agricultural surpluses in industrialized countries. By developing new paths of usage for agricultural products, these surpluses were reduced. In the European agricultural reform of 1992, 15 % of the agricultural land was legally required not to be used for food production. The only plants that could be planted and harvested on these unused lands, were renewable resources such as rape, sunflowers or miscanthus. The share of decommissioned land was reduced to 10 % in the so-called "agenda 2000", before it was lifted in 2008, as rising demand for both food and bioenergy were found to have eliminated the need for artificial supply reductions (Schönleber 2009, p. 5ff). This shows that the potential for further increases in the production of energy crops on agricultural land is limited. In addition, the ability to produce crude oil substitutes from agricultural products linked the markets for food and energy, increasing the likelihood of rising crude oil prices to affect the prices for food

(Nordhoff, et al. 2007, p. 553; Cassman/Liska 2007, p. 18). If the prices for agricultural goods in industrialized areas like the European Union increase beyond the level sustained by subsidies, the European market for agricultural goods is likely to demand more such goods from the world markets. The potential ensuing price increases for food have been subject of intense political discussion since early 2008 (WISU 2008a, WISU 2008b).

As the (BioKraftQuG 2009) requires biofuels to be make a significant contribution to substituting fossil energy carriers in the future, mineral oil companies must identify biomass sources other than agricultural areas and use them with the greatest possible efficiency. While not as easily yielding substances for immediate use as agricultural crops do, some forms of biomass can be gasified and used for the synthesis of liquid hydrocarbons using processes for the production of so-called 2nd generation biofuels, such as Fischer-Tropsch or methanol synthesis. Such kinds of biomass include residuals from both agriculture and forestry. As the whole plant can be gasified and converted to liquid hydrocarbons, the yield per hectare is usually considered to be significantly higher than for 1st generation biofuels such as bioethanol or biodiesel.

While plants for the conversion of residual biomass (or waste) to hydrocarbon fuels have already been constructed in pilot scales, a widespread application of the technology has not yet taken place (Gottschau 2006, p. 26ff). Although biomass gasification for the production of the required synthesis gas is more complex, i.e. expensive, than gasification of coal or the reforming of natural gas, several processes exist that are technically feasible to accomplish the conversion in sufficient quantities. The core hindrance for the construction of Biomass-to-Liquid (BtL) plants appears to be economic, instead of technical, in nature. Comparable coal or natural gas conversion facilities are constructed in the vicinity of coal mines or natural gas fields. Accordingly, the costs for transporting the input materials to the conversion facility are relatively low and economies of scale can be applied to improve specific production costs.

Biomass, by contrast, has to be collected over large areas, which may be owned and tilled by numerous farmers or foresters. Transportation distances, and therefore costs, grow in more than linear terms relative to capacity (Wright/Brown 2007a, p. 194f). The higher a plant's capacity, the higher its specific biomass transportation costs (e.g. in €/ton of products). Capacities in the scale of contemporary oil refineries therefore appear infeasible for Biomass-to-liquid plants due to prohibitive biomass transportation costs. In addition, the high water content of biomass makes transportation less efficient, as well as making it necessary to dry the biomass at some point before the actual conversion can take place. Therefore, if biomass is to be economically converted to hydrocarbon fuels, an optimal plant size has to be determined to make as much use of economies of scale as possible while averting unreasonable biomass transportation costs (Wright/Brown 2007a, p. 192).

Several concepts have been developed to ease this antagonism between economies of scale and rising transportation costs either by improving the specific transportation costs or the specific investment necessary for the installation of BtL plants. For a potential realization of such a plant, is it important to know which concepts appear to be the most promising with regard to improving competitiveness. The comparison of any two concepts with different cost structures can quickly become misleading in this context. Concepts with low investment requirements are more favorable at relatively low capacities, while concepts with improved logistics concepts gain attractiveness when capacities are large. Therefore, the separation of relatively valuable chemicals may not be advantageous for low plants, but become more attractive if capacities are sufficiently large. Consequently, comparisons at a given, fixed plant capacity without consideration of potential product upgrading alternatives may favor some concepts over others.

It is the aim of this thesis to develop a decision support model that takes these differences into account appropriately. The development of both economies of scale and transportation costs can be modeled on an upgrading process basis using nonlinear functions, as these mirror the actual correlation with rising plant capacities relatively accurately. Such a model can then be used to determine optimal plant capacities for each concept individually. The comparison of the relative advantage of the concepts can then be performed by comparing a representative performance indicator, such as the level of product prices required to earn a minimum return on investment.

While linear functions are sometimes used to approximate these developments in a limited range of capacities, deviations from the actual development become significant if a large range of potential plant capacities is investigated. Linearized functions are therefore less accurate in mapping the effects of rising BtL plant capacities, as deviations may significantly alter the determined optimal plant size. Additionally, approximating the relatively large number of process-individual cost-capacity exponents would result in a considerable effort. Therefore, the nonlinear character of both economies of scale and biomass transportation costs is ideally represented by the corresponding nonlinear functions (Wright/Brown 2007a, p. 195). This approach is intended to determine whether common assumptions regarding feasible BtL plant capacities can be verified and to inquire which product distribution is optimal in a given situation.

While there are numerous proposals that appear fit to improve the competitiveness of second generation biofuels, assessing their impact by individual case studies is an arduous task. It is advisable to investigate the likelihood of actual improvements before detailed investigations are attempted. This thesis aims to represent the most significant influencing factors in an optimization model. By means of mathematical optimization and parameter variation, a large number of plant setups and proposed improvements can be analyzed with relatively little effort. If the model is found to be satisfyingly accurate, it can help to identify the most promising concepts. Based on these relative findings, more detailed investigations can then follow to verify the model’s results.

In order to help develop an understanding of the current energy supply situation, the second chapter is intended to give an overview over both existing processes and potential competing concepts. Therefore, some background information about the German energy supply and the expanding share of renewables is given before the processes required for the production of 2nd generation biofuels are described in detail.

As favorable economic indicators are both necessary to attract sufficient capital for the realization of plant concepts and to guarantee an economically sustainable allocation of resources, the third chapter gives an overview over available methods to determine the economic advantage of investment projects.

In the fourth chapter, the mathematical concept of optimization is described. Several optimization approaches are introduced with a focus on the nonlinear optimization algorithms needed to solve the underlying problem.

In chapter 5, the model for the determination of optimal process setups and plant sizes is set up. The objective function with its nonlinear components is introduced as well as the linear constraints that represent mass balances, technical restrictions and similar limiting factors.

Chapter 6 shows the results if this model is applied to some common process setups for the production of 2nd generation biofuels. Exclusive fuel production is contrasted with fuels and chemicals co-production as well as from the production of SNG.

In chapter 7, the model is expanded to account for improvements of the plant and logistics concept proposed in literature. These include pretreatment of biomass, combined traffic concepts, BtL plant construction adjacent to refineries and coal and biomass co-gasification.

In the last chapter, a summary of results is given and conclusions are drawn. A special emphasis is given to the discussion of the modeling results in the context of their significance for the potential realization of BtL plants in the future.

2 Use of Renewable Energies in Germany

Since the industrial revolution, fossil fuels have increasingly been extracted from coal mines, gas fields and oil rigs in Germany to increase the amount of energy available for the generation of heat, power and transportation fuels. The relative ease with which such extractions could be achieved led to a market dominance of fossil fuels over other sources of energy. The oil crises of the 1970s and other price developments have spread the assumption that fossil fuels, especially oil and gas, will not be sufficient to ensure economic energy supply in the future. Accordingly, the adaptation of industry and transportation to the worsening supply-demand relationship of crude oil and natural gas is a major challenge for Germany and other industrialized countries. In order to dampen the expected effects of rising mineral oil prices on transportation and the chemical industry, a number of processes to replace crude oil using renewable energy sources have been developed and implemented. In the following chapter, the status quo of energy supply in Germany will be outlined with special attention on the use of renewables.

2.1 Energy Supply in Germany

As of 2010, Germany's primary energy supply of 14,057 petajoule (PJ) relied on five major sources, namely coal, mineral oil, natural gas, nuclear power and renewables (see Figure 2-1). The advantages of the processes using these resources, both of fossil and renewable nature, are the benchmark against which new processes for the supply of energy have to be measured. Three of the main conditions for a sustainable energy supply are economic viability, security of supply and environmental impact (EnWG 2005).

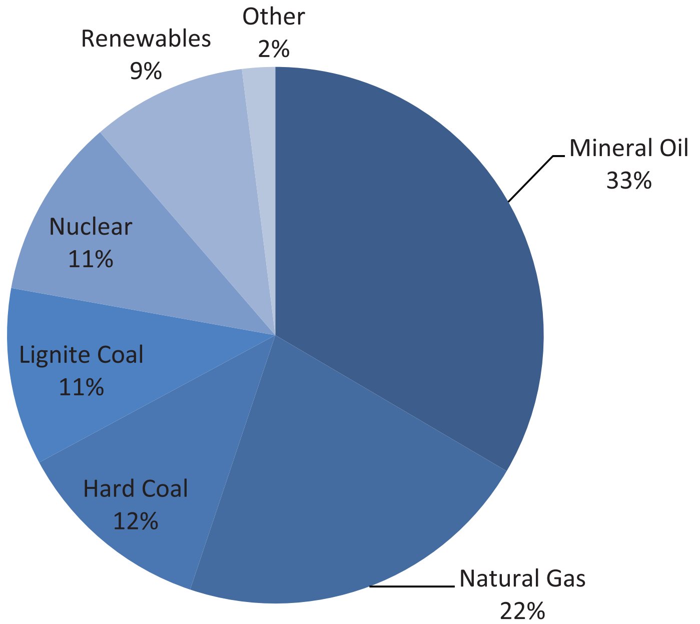

Figure 2-1: Primary energy supply in Germany in 2010 (AGEB 2011)

While economic viability refers to expected price and cost developments, domestic abundance or reliability of imported resources play a part in the maximization of supply security. An often-quoted measure in this field is the “reserves-to-production ratio”, which expresses how long economically extractable reserves are expected to last at current production rates and current prices. While this ratio is often quoted to predict the time-frame in which resources will be available for further energy generation, the resulting number of years has often grown, rather than shrunk, over time (Erdmann/Zweifel 2007, p. 126). This is due to the fact that economic extraction depends on the value of the produced resources, i.e. when resource prices rise, the amount of economically extractable resources grows. High prices also increase the incentive to search and discover new deposits of resources. In spite of these shortcomings, the reserves-to-production ratio usually gives an indication of the availability of energy resources.

In addition to such considerations, the prospects of resources in the energy mix have also come to increasingly depend on the perceived gravity of environmentally hazardous side-effects. As the importance of environmental considerations has had an increasing effect on decision-making in the energy business, the composition of the German energy mix has been undergoing a continuous change in the last 20 years (BMU 2011, p. 7). In order to give an overview of the current prospects of energy processes in Germany, the five most significant energy resources will be discussed with regard to their expected developments in terms of economic competitiveness, supply security and environmental impact.

2.1.1 Coal

Hard and lignite coal, Germany’s traditional domestic energy resources, supplied 22.8 % of primary energy supply in 2010. The exploitation of domestic surface mining pits has made Germany the greatest lignite coal producer in the world. The reserves-to-production ratio implies that a production at this level should be possible for at least another 200 years, with significantly more lignite available if the overall level of energy cost increased sufficiently to justify further exploitation (Erdmann/Zweifel 2007, p. 254). Due to economic transportation limitations, the production of electricity from lignite coal is restricted to areas close to the lignite surface mining pits (Wolk, et al. 2008a, p. 18). As reserves in the historically most significant area of exploitation, in central Germany, are nearing exhaustion, lignite coal production is increasingly focused on the more abundant fields in the Rhineland and the Lausitz (see Table 2-1).

In spite of the significant production and reserves, “cap-and-trade”[1] of CO_2 emissions is expected to significantly deteriorate lignite coals competitiveness if prices for CO_2 certificates were to rise.

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[1] Cap-and-trade refers to a legal limitation of CO_2 emissions that results in the trading of CO_2 emission certificates (Erdmann/Zweifel, 2007, p. 353)

Table 2-1: German lignite coal production (Pfaffenberger/Ströbele 2010, p. 97)

Million tons	1950	1960	1970	1980	1990	2000	2005	2008
Rhineland	64	81	93	118	102	92	97	96
Lausitz	36	84	134	162	168	55	59	58
Central Germany	101	142	127	96	81	16	19	19
Helmstedt	8	7	5	4	4	4	2	2
Hesse	3	4	4	3	1	0	0	0
Bavaria	2	4	5	5	0	0	0	0
Total German Production	213	322	369	388	357	168	178	175
Employees (in 1,000)	106	150	122	152	130	21	17	17

Where no lignite coal is immediately available, hard coal is used as it can be transported more efficiently due to its higher energy density. Domestic hard coal production, which used to take place in the Ruhr and Saar regions, has declined as depleting mines lead to rising production costs, rendering domestic hard coal increasingly scarce and expensive. To compensate for the declining amount of hard coal mined domestically, it is being imported to an increasing extent. Germany is considered part of the Atlantic coal market, which is being supplied from countries such as Columbia, South Africa, Russia, Poland, Venezuela and the United States of America (Pfaffenberger/Ströbele 2010, p. 100). While the reserves-to-production ratios of hard coal in these countries forecast that the current pace of extraction could be maintained for more than two hundred years, hard coal prices have shown an even greater fluctuation than those for mineral oil in recent years. In percentage terms, hard coal prices rose by 423.8 % from November 2005 to July 2008, as compared to 239.5 % for "Brent" crude oil (see Figure 2-2).

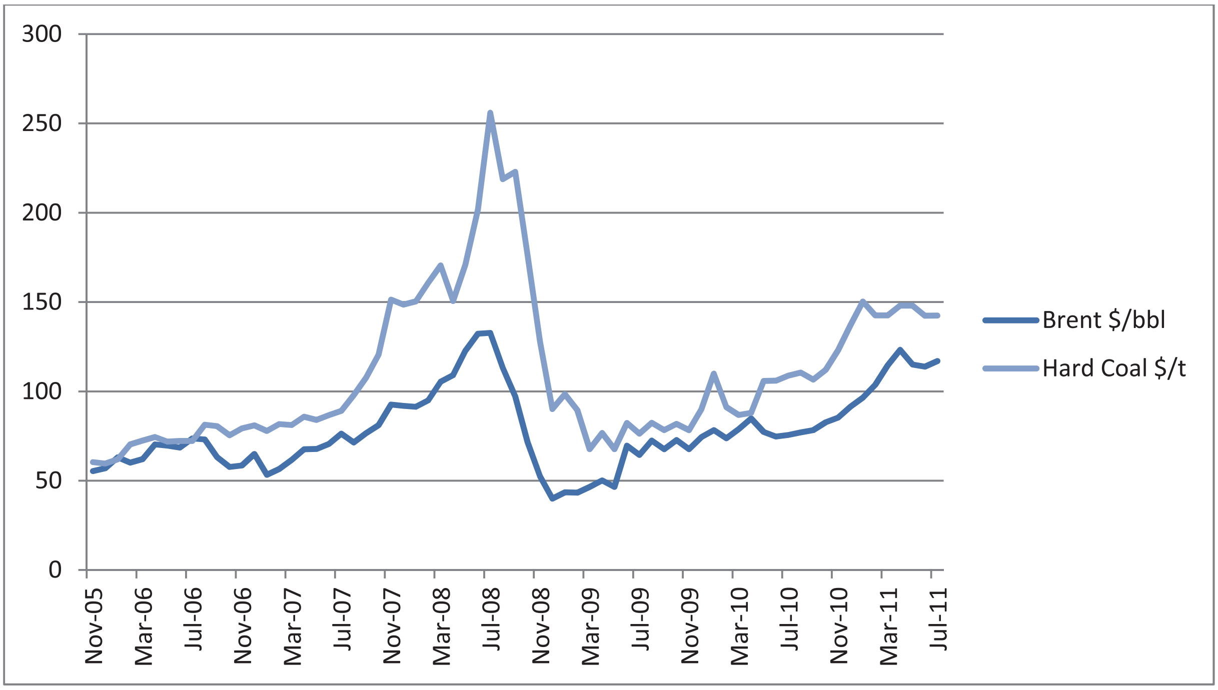

Figure 2-2: Development of hard coal and crude oil prices (BGR 2005-2011)

This is partly due to the fact that, as of 2007, only 16 % of world hard coal production have been traded internationally (Pfaffenberger/Ströbele 2010, p. 100). The increasing dependency on imported hard coal therefore results in significant price risks for power plants and other users of hard coal in Germany.

2.1.2 Mineral Oil

With exception of the high oil prices during political restrictions of production commonly referred to as “oil crises”, fossil fuels were known to be among the cheapest sources of energy and organic chemicals (Bosselman 2010, p. 252). The direct comparison between oil and coal reveals that during most of the last 50 years, a premium was paid for oil as compared to coal. It can be concluded that the main reason for this was the lack of processes to use coal in replacing oil in the field of mobile transportation. In fact, despite the similar chemical composition of the two resources, their application grew rather more than less distinct in the course of time. Apart from providing household heating, coal was limited to centralized power generation. By contrast, mineral oil became the primary source of automobile and aviation fuels.

Due to this dominant use of crude oil in the transportation sector, as well as the high proportion of mineral oil derivatives used for heating, more than one third (33.6 %) of Germany’s primary energy was supplied from mineral oil. As only 3 % of domestic demand is being covered by domestic oil production mainly in or close to the North Sea, Germany is dependent on imports mainly from other European countries and members of the OPEC (Malz, et al. 2008, p. 83). Therefore, the German industry is relatively exposed to price changes on the world market. While predicting the future development of oil prices has proven difficult due to speculative fluctuations, it is generally accepted that the exploitation of non-conventional oil deposits[2] is considerably more complex, i.e. expensive, than extracting crude oil from traditional onshore oil fields (Erdmann/Zweifel 2007, p. 178). As the demand for petroleum products continues to rise, while reserves (at constant prices) shrink, shortages leading to higher prices in the future appear likely. While the reserves-to-production ratio is usually estimated to be around 40 years, the “peak oil theory” predicts that the annual production of crude oil will reach a maximum in the near future and decline afterwards (Erdmann/Zweifel 2007, p. 176). Increasing scarcity and complexity of exploitation are therefore likely to result in a tendency towards rising prices (Erdmann/Zweifel 2007, p. 207).

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[2] Non conventional sources of oil include heavy crudes, oil sands, bitumen, tar and shale oil (Erdmann/Zweifel, 2007, p. 178)

2.1.3 Natural Gas

Similar price problems can be expected for natural gas, as European natural gas prices are pegged to the oil price. In so-called “take-or-pay”-treaties[3], an average of prices of heating oil is usually used as a basis for the calculation of natural gas prices (Erdmann/Zweifel 2007, p. 235).

Consumption of natural gas made up 21.8 % of primary energy supply in 2010. Utilization of natural gas has increased for several reasons. Among the available fossil fuels, natural gas has the lowest CO_2 emissions and is therefore expected to benefit from cap-and-trade regulations (van der Wal 2003, p. 13; Erdmann/Zweifel 2007, p. 240). The reserves-to-production ratio is estimated to be around 60 years, which is slightly more advantageous than the one for mineral oil (Wolk, et al. 2008b, p. 83). Natural gas power plants also have the advantage of being very flexible, a characteristic that becomes increasingly important due to the rising share of volatile renewable sources of energy (Erdmann/Zweifel 2007, p. 301). When the production of electricity from wind parks and photovoltaic cells fluctuates, the resulting change in total production must be compensated quickly. As neither nuclear nor coal-fired power plants can increase or decrease their electricity production as easily, natural gas-fired plants have become the means of choice to fill the gap. Another advantage of natural gas, even if sometimes questionable, is the well-developed infrastructure to import it from countries like Russia, Norway and the Netherlands (Mez 2003, p. 217).

2.1.4 Nuclear Energy

The most important non-fossil source of electricity in Germany was nuclear energy, which accounted for 10.9 % of primary energy supply in 2010. As uranium production in Saxony and Thuringia, which was significant in the second half of the 20th century, has been abandoned after German reunification, all nuclear fuel is being imported. As German politics plan to phase out nuclear power in the decade to come, nuclear power plants will have to be replaced by other sources of energy and, more specifically, of electric power (AtG 2011, p. 3). The main reason for this phasing-out is the risk of exposing the population to radiation in case of a nuclear accident or meltdown.

2.1.5 Renewables

The removal of nuclear energy from the energy mix and the worsening conditions for fossil fuels due to cap-and-trade of CO_2 emissions are expected to favor the expansion of renewable energies. These have expanded to 9.4 % of primary energy supply until 2010. These 9.4 % can be subdivided into biomass-derived energy (6.6 %), wind power (0.9 %), water power (0.5 %) and solar heat and power (0.4 %). Geothermal energy, while often

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[3] Take-or-pay treaties secure a payment for a high proportion of the ordered natural gas even if the gas is not actually withdrawn from the gas grid (Erdmann/Zweifel, 2007, p. 235)

considered a promising option for the future, did not yet contribute significant amounts of energy (approximately 1 PJ) (BMU 2011, p. 5)

Energy supply from renewables can be subdivided into electricity and heat supply. In 2010, renewables supplied 16.8 % of electricity in Germany, while the share of renewable heat sources, including wood heating, biogas and geothermal energy was 9.8 % of total heat demand (BMU 2011, p. 8). The expansion of renewables is partly due to German energy policy, which includes both direct subsidies and tax exempts (EEG 2009). Problems concerning both the economic competitiveness as well as technical reliability are part of the reason why the renewables' share of energy production has not yet grown further.

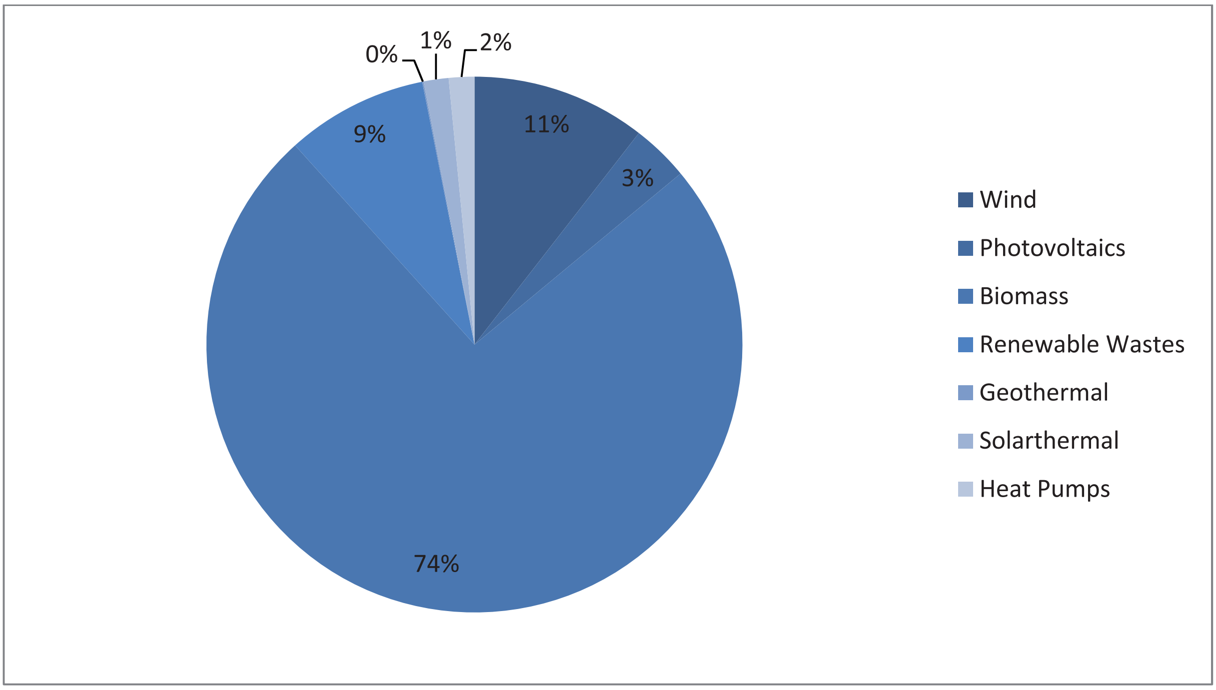

Figure 2-3: Renewable energy generation in Germany in 2010
(AGEB 2011)

Compared to other renewables such as solar power, geothermal energy or wind power, biomass-based processes have the potential to substitute mineral oil in more areas than merely electricity or heat due to their carbonaceous nature. Various processes exist to re-arrange the hydrocarbons of biomass to create fuels or products for the chemical industry, which have mostly been made of crude oil in the past (Kamm/Kamm 2006, p. 65). In 2010, the share of biogenous fuels on the German fuel market was 5.8 % (BMU 2011, p. 4). Consequently, as biomass is both the most versatile and, as of 2010, the most significant source of renewable energy (see Figure 2-3), it is worthwhile to investigate existing processes, problems and developments relating to the energetic use of biomass.

2.2 Established Biomass-Based Energy Processes

Generally speaking, biomass is defined to include all living organisms, including the phytomass (plants) and zoomass (animals) (Kaltschmitt 2001, p. 2). The term biomass also covers all remains and excrements that are produced by phyto- and zoomass. If a broader approach is being used, “biomass” may also be used for materials or substances that have been produced by conversion or material use, such as paper or black liquor. In order to use a certain type of biomass for energy generation, allocation chains must be established to secure a sufficiently large supply of the type of biomass as well as its subsequent conversion to the desired form of energy or fuel. In addition to the use, sale and allocation, the production and harvesting of biomass are not trivial either, as both legal requirements and the desired sustainability of biomass production need to be accounted for. In terms of composition as well as basic conditions of production, a distinction between two different kinds of biomass is being made. On the one hand, plants such as rape, potatoes or sugar beet produce oils, starch or sugars, while on the other hand, wood, straw and similar input materials contain significant amounts of lignin, hemicelluloses and cellulose (Kaltschmitt 2001, p. 2f). Some of the former have been in industrial use for more than a century (Nordhoff, et al. 2007, p. 551). The latter group is being targeted as input materials for future processes for several reasons. Among these reasons is the limited amount of forests and farmland available to produce biomass. Due to the large number of processes that require biomass, an evaluation should be made whether other processes compete for the same kind of biomass (or the same soils to grow it) before an investment is being considered. The most significant processes in terms of the amount of biomass used are wood heating, biogas, biodiesel and bioethanol. These either compete for the same raw materials or agricultural soil or they offer alternative biogenous sources for some of the products of the Fischer-Tropsch-based BtL concept to be discussed in subsequent chapters.

2.2.1 Wood as an Energy Resource

Before the exploitation of fossil fuels, wood was the primary energy resource of mankind (Nersesian 2010, p. 3). While excessive use of wood for both combustion and the construction of houses, ships and various other structures led to deforestation of many areas of the world, modern forestry aims for a sustainable approach. Sustainable forestry primarily means that the amount of wood withdrawn from a forest does not exceed the amount that is added through plant growth in a given period of time (Erdmann/Zweifel 2007, p. 141).

In addition to energy conversion purposes, wood serves as input material for a number of industrial processes. High-quality wood is suitable as input for the most demanding applications of the furniture industry. Due to the relative scarcity of such high-quality wood, prices are constantly higher than for other applications. Wood is also used for construction, paper and a variety of other industrial processes. If wood is found to be of inferior quality and therefore considered unsuitable for any industrial application, it is referred to as "residual wood". As there used to be hardly any competing fields of application for this material, it has often been considered an ideal input for thermo-chemical processes such as combustion or gasification. The amount of residual wood available from woods and industry processes in Germany has been estimated to be 22.4 million tons of dry organic matter in 2002 (Leible, et al. 2007). If all other wood was exclusively used for purposes that require high-quality wood and no agricultural land was used for so-called rapid-turnover plantations, only this amount would be available for the production of energy.

The lower heating value of dried wood of various kinds is around 18.5 Megajoule (MJ) per kilogram (kg) (Englert 2001, p. 77). While the most important fuels for household heating nowadays are heating oil and natural gas, the market for renewables in the heating market has increased from 45,591 thermal gigawatt-hours (GWh_{th}) in 1997 to 137,800 GWh_{th} in 2009 (BMU 2011, p. 24). This is contrary to the development during most of the 20th century, when both wood and coal had lost most of their market share due to relatively cheap alternatives and to the pollution resulting from their use at home (Varadarajan 2008, p. 216). In spite of significant improvements in terms of filters and combustion processes, the composition of emissions from biomass combustion is still one of the major disadvantages of biomass-based heating. These emissions contain substances generally considered hazardous to human health, especially significant amounts of particulate matter (Nussbaumer 2001, p. 534).

Nevertheless, increasing prices for heating oil and natural gas, advances in process engineering and subsidies have caused wood's market share to rise again (EEG 2009). Solid biogenous fuels, most prominently consisting of wood, provided about 67.8 % of renewable heat supply in Germany in 2009, which equates to 77,970 GWh_{th}. Furthermore, long-distance and local heating as well as electricity are being produced in various sizes of block heat and power plants. Excluding renewable wastes and liquid biogenous fuels, biomass-fuelled power plants produced more than 33.5 Terawatt-hours (TWh) of electricity in 2010 (BMU 2011, p. 5).

2.2.2 Biogas

The production and combustion of biogas for the generation of heat and power has found widespread application in recent years (FNR 2010a, p. 4). Biogas is produced with a biological process called anaerobic digestion, based upon the use of bacteria. The bacteria are able to process a variety of renewable input materials, such as bio waste and food residues as well as agricultural products like intertillages, corn or clover grass. The conversion process to biogas consists of three steps, namely hydrolysis, acetogenesis and methanogenesis. In the hydrolysis, the substrate particles are being split up by hydrolytic bacteria’s enzymes to transform proteins to amino acids, fats into fatty acids and carbohydrates into sugars. During the acetogenesis, acetic acid is formed from propanoic, butanoic and valeric acids, which are being produced from the products of the hydrolysis. From the acetic acid, methane is then created in the methanogenesis (Scholwin, et al. 2001, p. 853ff).

In addition to methane, the output gases contain carbon dioxide, water and relatively small amounts of nitrogen, oxygen, hydrogen, ammonia, and hydrogen sulfide. To meet environmental and technical standards, the output gas must undergo de-sulfurization and water has to be removed. Prior to use in subsequent processes, the pressure of the gas must be increased if it is to be used for the production of both electricity and heat by combustion (Scholwin, et al. 2001, p. 900).

While conversion efficiencies of state-of-the-art biogas facilities are among the highest of all renewable fuel production processes, the rapid built-up of biogas capacities in Germany was triggered by subsidies for electricity from biomass (FNR 2010a, p. 10). As shown in Table 2-2 biogas plants in Germany can expect a price from electricity suppliers which is several times higher than those paid on the market. The regulated prices consist of up to several items that have to be paid for every kilowatt-hour that is supplied to the natural gas grid. The first and second are a basic allowance and a bonus for using renewables instead of waste. Both depend on the size of the biogas plant in question.

Table 2-2: Bonuses for biogas plants (FNR 2010a, p. 10; EEG 2009)

Capacity	Basic allowance [ct/kWh]	Bonus for Renewables [ct/kWh]	Bonus for manure
$x \leq 150$ kW$_{el}$	11.44	6.86	3.92
$150 < x \leq 500$ kW$_{el}$	9.00	6.86	0.98
$500 < x \leq 5{,}000$ kW$_{el}$	8.09	3.92	0
$5{,}000 < x \leq 20{,}000$ kW$_{el}$	7.63	0	0

Other allowances include bonuses for joint supply of both heat and electricity, for "newer technologies" and for emission reduction (FNR 2010a, p. 10).

Instead of feeding biogas to combustion, the methane can also be purged from CO_2 and other unwanted by-products to yield highly concentrated so-called biomethane (Mueller-Langer, et al. 2008, p. 9). Processes like pressure swing adsorption (PSA) or a variety of established gas cleaning processes can be used for this end. The purified biomethane can then be fed into the natural gas grid at subsidized prices if it is used for combustion at another location (EEG 2009). Several sites in Germany are either under operation or construction to facilitate this method of substituting fossil natural gas.

Biogas facilities have so far mostly been built on a modest scale. As their input materials are commonly available in rural areas, while their production capacity is usually in the range of small villages or towns, biogas plants are especially suitable to supply settlements in sparsely inhabited areas. By the year 2010, an estimated 5,800 of these small scale plants with a capacity of 2,300 MW have been erected in Germany (FNR 2010a, p. 4).

Biogas facilities offer a number of advantages, including a high yield per hectar and a fossil-carbon dioxide (CO_2)-neutral supply of electricity and heat or synthetic natural gas. Another positive side-effect is that the manure which is used in biogas plants retains its fertilizer value while its unwanted smell characteristics disappear in the biogas facility (Amon/Döhler 2010, p. 153). In the context of the expansion of renewables, biogas has the potential to play an important role due to its controllable output level. In contrast to fluctuating sources of renewables such as wind or photovoltaic power, biogas plants can therefore be used to supply electricity in controllable amounts in a desired time frame. Continuous plant utilization on a high level is advantageous to maximize the plant's revenues (Jäger/Schwab 2010,

p. 167). On the downside, biogas plants are associated with disadvantages such as an increased tendency towards monocultures in agriculture (Ruppert, et al. 2008, p. 79).

2.2.3 Biodiesel

The ambiguous use of the word "oil" for both mineral and vegetable oils can probably be attributed to their similarity of appearance, even if they are different in chemical structure. The difference in chemical structure results from the fact that mineral oil has been formed from dead organic matter in the course of millions of years while vegetable oil is produced from living plants every year anew. After undergoing upgrading processes, both can be converted to substances suitable for use in internal combustion engines (ICE). While mineral oil usually contains significant amounts of hydrocarbons in the diesel range already, the plant seed oil molecules can be broken up by chemical reactions to yield fatty acid methyl esters, whose combustion properties are similar to those of diesel fuel. Among the most commonly applied plant oils for biodiesel production are oils from palms, sunflowers or rape (Schmitz, et al. 2009, p. 9). Biodiesel, which is the predominant biofuel in Germany, is produced from rape seed oil via a chemical reaction with methanol called transesterification (Schmitz, et al. 2009, p. 12). In the transesterification process, the rape seed oil is split into the desired rape seed methyl ester (RME) and three molecules of glycerin, which may to some extent be used in other industries. Another by-product of the extraction of oil from rape, the non-seed portion of the rape plant, is used as livestock feed. From an energy efficiency perspective, the production of RME results in a net energy gain of 38 GJ per hectare at a cost of 24 € per GJ (Schmitz, et al. 2009, p. 20). As this implies that the production of biodiesel yields more energy than its production requires, it can be considered advantageous to substitute fossil fuels with biodiesel. A reduction of around 38 % of fossil CO_2 emissions is quoted as compared to fossil diesel (FNR 2010b, p. 10f). With a production 3,264,000 tons of biodiesel in 2007, it is the most important biofuel in Germany. Deterioration in state subsidies have however led to a decrease of biodiesel production in recent years, with only 2,517,000 tons sold in 2009 (FNR 2010b, p. 4). Instead of biodiesel, some plant oils can also be used as diesel substitutes without further chemical conversion. While biodiesel is however still demanded due to quota regulations that require biodiesel to be blended into fossil diesel for sale to customers, demand for unconverted plant oils has declined, from more than one million tons in 2006 to about 100,000 tons in 2009 (FNR 2010b, p. 3).

In addition to the prevalent production from rape seed oil in Germany, different plant oils have established themselves in countries like Malaysia and India. In Malaysia, palm oil is being produced in increasing quantities to be exported to industrialized countries (Searchinger, et al. 2009, p. 527f). The installation of palm plantations is being criticized due to the extensive land use change, as tropical forest is assumed to be replaced with palm plantations, leading to a potentially disadvantageous CO_2 balance overall (Fargione, et al. 2008, p. 1235ff).

An alternative source of biodiesel is the jatropha plant. As jatropha plants can be grown in relatively arid regions and on eroded soils, the effects of land use change are thought to be