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***Masterarbeit* Nr. 3468**

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Lebenszyklusanalyse (LCA) der Herstellung synthetischen Flugturbinentreibstoffes aus Biomasse, Strom und CO_2

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Aufgabenstellung

Masterarbeit Nr. 3468

für Herrn cand. M.Sc. ENT *Georg Hartfuß*

Matr.-Nr. 2972327

Lebenszyklusanalyse (LCA) der Herstellung synthetischen Flugturbinentreibstoffes aus Biomasse, Strom und CO_2

Life Cycle Assessment (LCA) of the Production of Synthetic Jet Fuel from Biomass, Power and CO_2

1. Problembeschreibung

Am Institut für Technische Thermodynamik des DLR werden techno-ökonomische Studien zur Herstellung synthetischer Treibstoffe durchgeführt. Diese Betrachtungen müssen für eine ganzheitliche Bewertung auch aus sozio-ökologischer Sicht bewertet werden. Lebenszyklusanalysen für konventionelle sowie auf biogener Rohstoffbasis basierender Verfahren zur Herstellung synthetischer Treibstoffe sind in der Literatur bereits vorhanden. Lebenszyklusanalysen zu innovativen Verfahren wie die Kombination von Strom und Biomasse zur Herstellung wurden jedoch noch nicht durchgeführt.

2. Zielsetzung

Übergeordnetes Ziel der Arbeit ist die Berechnung des Umweltbelastungspotentials von synthetischen Treibstoffen mit besonderem Fokus auf die THG-Emissionsbilanz. Als Fallstudien sollen das Power&Biomass-to-Liquid-Verfahren und das Power-to-Liquid-Verfahren untersucht werden. Dabei sollen unterschiedliche Rohstoffszenarien betrachtet werden und ein Vergleich mit konventionellen und rein biogenen Verfahren durchgeführt werden.

3. Durchzuführende Arbeiten

1. Methodik der Lebenszyklusanalyse
   a. Auswahl der für synthetische Treibstoffe am besten geeigneten LCA-Methodik
2. Einarbeitung der LCA-Methodik in das DLR-in-house Tool TEPET*

3. Definition von Szenarien der Erzeugung synthetischer Treibstoffe
    a. Welche biogenen Rohstoffe stehen zur Verfügung?
    b. Welche erneuerbaren Stromquellen sind denkbar?
4. Durchführung der Lebenszyklusanalyse für das Power-to-Liquid-Verfahren
5. Durchführung der Lebenszyklusanalyse für das Power&Biomass-to-Liquid-Verfahren
6. Vergleich des THG-Potentials mit konventionellen und biogenen Treibstoffen

• TEPET: Techno-economic Process Evaluation Tool
- Auf Grundlage der am DLR vorhandenen Fließbildsimulationen der genannten Prozesse

Die studentische Arbeit wird beim DLR Stuttgart, Institut für Technische Thermodynamik durchgeführt und dort von Herrn *Friedemann Albrecht* betreut. Die Betreuung am IFK erfolgt durch *Herrn apl. Prof. Dr.-Ing. Uwe Schnell.*

Das Merkblatt zur Durchführung und Anfertigung von studentischen Arbeiten am IFK ist zu beachten, ebenso die „Richtlinie für die Abwicklung von studentischen Arbeiten in den Studiengängen der Gemeinsamen Kommission Maschinenbau der Fakultäten 4 und 7" vom 22.06.2016. Über den Fortgang der Arbeit ist in regelmäßigen Abständen (alle 4 – 6 Wochen) am IFK zu berichten.

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Abstract

According to emissions reduction targets of the aviation sector, future use of alternative green jet fuel becomes necessary. Therefore different production processes for sustainable jet fuels are developed and optimized by the German Aerospace Center. Additionally cost analysis for the operation and construction of appropriate refineries were performed. However, the environmental impact of the green fuel production was not analysed. To determine the environmental impact of synthetic jet fuel, three production pathways are analysed, by using life cycle assessment (LCA) methods.

The expected carbon footprint ranges, for the green fuel production in Baden-Württemberg, are determined by analysing best and worst case scenarios. The result show, that green jet fuel could be produced by using residual straw and waste wood. Electricity using production pathways are only able to produce sustainable jet fuel, if renewable electricity is used. For the production for sustainable jet fuel, utilization of grid electricity is not an option. Additionally, feedstock and production potentials for the alternative jet fuel production in Baden-Württemberg are investigated. The requirement of the utilization of electricity for synthetic fuel production is pointed out.

Zusammenfassung

Der Einsatz von alternativem Flugturbinentreibstoff wird zukünftig notwendig werden, um die Emissionseinsparziele der Luftfahrtindustrie zu erreichen. Das Deutsche Zentrum für Luft- und Raumfahrt (DLR) hat daher Herstellungsverfahren für nachhaltiges Kerosin entwickelt und optimiert. Weiterhin sind Kostenanalysen, welche den Betrieb und Bau der entsprechenden Raffinerien untersuchen, durchgeführt worden. Jedoch ist der Umwelteinfluss der alternativen Kerosinherstellung noch nicht untersucht worden. Es werden deshalb drei entsprechende Herstellungsverfahren mit Methoden der Lebenszyklusanalyse untersucht.

Der zu erwartende Bereich für den Kohlendioxidfußabdruck wird durch die Untersuchung von best- und worst-case bestimmt. Die Ergebnisse zeigen, dass es möglich wäre Biokerosin aus Reststroh und Waldrestholz herzustellen. In Herstellungsverfahren, welche elektrischen Strom benötigen, ist die Verwendung von erneuerbaren Strom aus Wind- oder Sonnenenergie erforderlich. Der Einsatz von Netzstrom zur Produktion von nachhaltigem Kerosin ist nicht zulässig. Zusätzlich werden die Potentiale für die Herstellung von nachhaltigem Kerosin für Baden-Württemberg untersucht. Die Notwendigkeit strombasierte Herstellungsmethoden zu verwenden wird herausgearbeitet.

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Abbreviations

C	carbon
FC	fuel consumption
GBEP	Global bioenery parnterchip
H	hydrogen
IATA	International Air Transport Association
LCA	lifecycle assesment
LCI	life cycle inventory
LHV	lower heating value
LU	lifestock unit
LW	loading weight
N	nitrogen
O	oxygen
Q	heat
S	sulfur
TEPET	techno-economic process evaluation tool
$\Delta_R H_{298K}$	enthalpy of reaction
ρ	density

Indices

deion	deionized
dry	dry
empty	empty
Lorry	Lorry
max	max
raw	raw
syncrude	syncrude
water	water

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Motivation

Aviation is responsible for 2% of global anthropological carbon dioxide emissions (IATA, 2009). An annual expansion in the aviation sector by 5% is expected for the next decades (Thess, 2016). Without improvements total carbon dioxide emissions would likely increases by 63% in the next 10 years. To stop this development the International Air Transport Association (IATA) set targets for a carbon neutral growth of the aviation sector. The IATA targets are following.

from 2020	carbon neutral growth
from 2009 until 2020	1.5% annual improvement of fuel efficiency
until 2050	carbon dioxide emission reduction of 50% compared to the 2005 level

Furthermore a roadmap with detailed measurements to achieve these three targets was derived by the IATA in 2009. Improvements on air planes, operation and infrastructure are included, which should reduce carbon dioxide emissions by 30% (comp. Figure 1).

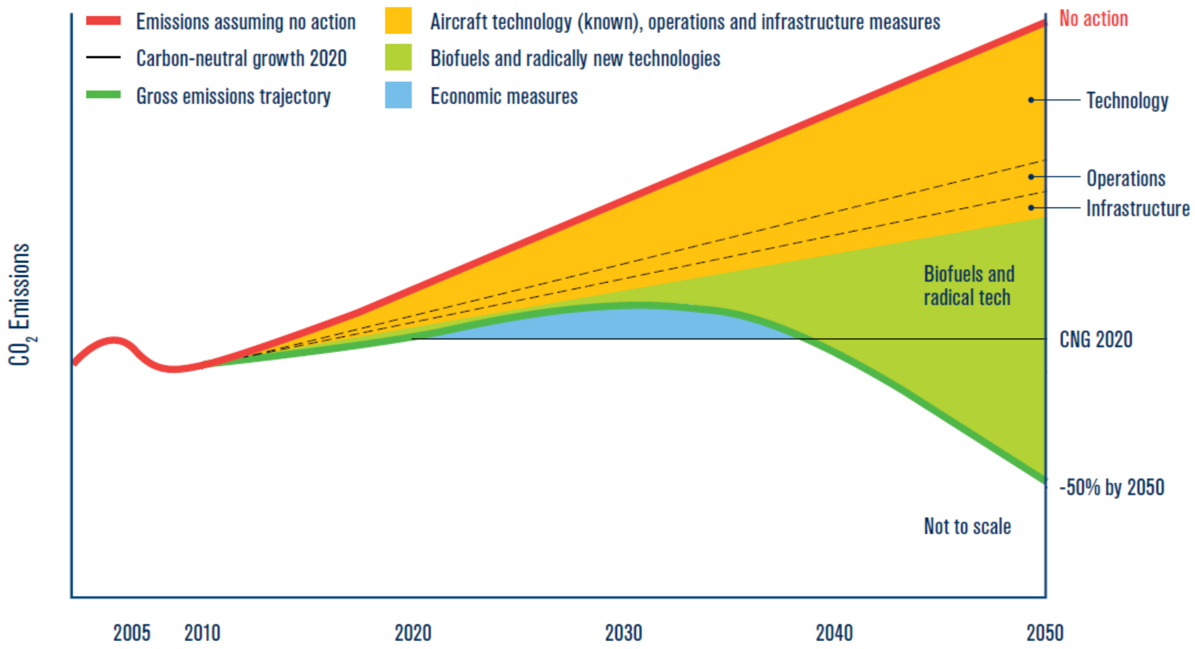

Figure 1: Schematic carbon dioxide emission reduction roadmap (IATA_I, 2013)

However, most of the carbon dioxide emissions reduction has to be done by using alternative jet fuels with low carbon footprints or new air plane technologies. The future large scale implementation of new drive technologies for air planes is at least questionable. It is expected that aviation will at least depend on the availability of liquid jet fuels for turbines until 2050 (EU, 2011). A global supply with 10% sustainably fuels is planned by the IATA in 2017 (IATA, 2009). Studies for the Federal Republic of Germany estimate an annual use of 39 PJ bio jet fuels in 2020 (BMWi_II, 2014), which correspondent to a consumption of approximately 880.000 tons alternative jet fuel (LHV = 44.0 MJ/kg). Today however bio kerosene is only used in small or pilot scale (UFZ, 2012). Just five long-term contracts for the production of alterative jet fuel, which are reported price-competitive, are signed between airlines and fuel suppliers worldwide in 2015. All in all these five contracts represents an annual volume of 497 kilotons kerosene beginning in 2019 (IATA_II, 2016). Only 27 kilotons are ordered for 2017 (IATA_II, 2016). By comparing the ordered amount of green kerosene and kerosene demand world wide of approximately 200 million tons (Lang & Elhaj, 2014) is must be concluded, that the IATA target for 2017 will be failed. The implementation of refineries for synthetic fuel production is consequently a task for the next years, if the IATA targets should be fulfilled in the future.

The German Aerospace Center already developed simulation models for future green fuel refineries and evaluated them economically with the in-house tool TEPET (Techno-Economic Process Evaluation Tool). The analyzed refineries and processes will be discussed later (comp. chapter 1). Questions about production costs and efficiencies of sustainable fuel refineries are already answered, but now the ecological impact of these fuels must be evaluated to check if the produced kerosene is suitable to match the IATA targets.

Every synthetic fuel must fulfil the same restrictions as usual kerosene for large scale commercialisation without additional investments for new or modified turbines. Properties of kerosene are determined and controlled by standardisation ASTM D7566. According to this standard Fischer-Tropsch fuels were approved, as first synthetic fuel, by the American Society for Testing and Materials (ASTM) for use in 50:50 blending's with conventional jet fuel in 2009 (Lang & Elhaj, 2014). Other approved pathways are hydroprocessed esters and fatty acids (HEFA) and sugar to hydrocarbons in 2011 and 2014, respectively (IATA_III, 2015).

Serval studies and guidelines with different intentions about LCA of synthetic fuels were published since 2009. Most of them use methods of the international standards ISO 14040:2006 and ISO 14044:2006. Hints for system borders and calculation methods of LCA are given in both standards.

The biofuel sustainability ordinance (Biokraftstoffnachhaltigkeitsverordnung), which defines inputs and emission reduction targets for sustainable fuels of at least 35%, was adopted in Germany in 2009 (Biokraft-NachV, 2009). General carbon footprints for biomass based fuel production of the first generation like ethanol or plant oils are included in this ordinance. More advanced production methods, which utilize biomass and electricity, are not mentioned.

A framework for potential sustainable feedstocks and calculation methods of carbon footprints for alternative jet fuels was published by the U.S. Air Force Research Laboratory (AFRL) in 2009. However, independence of oil imports from foreign countries was the main focus (AFRL, 2009). Consequently only the production scenarios for the United States were discussed. Furthermore, no explicit results for carbon footprints were given, but future implementation target and calculation methods defined.

A comparing study for serval pathways of conventional and alternative BtL jet fuels was performed by MIT professor Russel W. Stratton in 2010. Stratton did top-down analysis by defining low, baseline and high emission causing production scenarios and calculated the appropriate carbon footprints. By using top-down methods average values for process efficiencies or biomass yields were applied (Stratton, 2010). Exact evaluations of single plants or pathways didn’t take place in Stratton’s work. But this study is a valuable source to show carbon saving potential of future alternative jet fuels. Especially the evaluation of different biomass and land use change scenarios all over the world is a mentionable result of Stratton’s research (Stratton, 2010). According to Stratton’s findings, for example destruction of peatland or rainforest causes so many air pollution, that the produced jet fuel would be ecologically 9.6 times worse than conventional kerosene (Stratton, 2010).

By analysing the sunfire project in Dresden, Germany, the life cycle engineering department of the university Stuttgart performed a LCA for a PtL pilot plant in 2015 (sunfire, 2015). The importance of renewable electricity sources for a sustainable and carbon saving fuel production was pointed out. Furthermore, the environmental impact of refinery construction was determined and emphasised as negligible (sunfire, 2015). In the sunfire project the energy intensive technology direct air capture as carbon dioxide source is applied (sunfire, 2015), but the advantages of other carbon dioxide source like exhaust gas from power or industrial plants was also mentioned and analysed (sunfire, 2015).

Overall many studies and guidelines for the evaluation of alternative fuels are available, but they are mostly discussing only BtL first generation fuels like plant oil or ethanol or PtL processes. Except the sunfire study, all base on literature data and top-down approach for the calculation of carbon footprints.

Potentials of biomass, electricity and carbon dioxide are only evaluated in general and not for a specific region or refinery by using literature data. In the literature, LCA of more advanced production pathways like PBtL can't be found.

Based on international guidelines like ISO 14040:2006 or ISO 14044:2006 and the research results of the German Aerospace Center carbon footprints of three alternative jet fuels shall be calculated. In comparison to other studies, a specific region for the biomass supply will be chosen and the potential of usable biomass for the fuel production evaluated.
Primary, a clear method for the evaluation of green fuel production potentials of a specific region and calculation of life cycle carbon dioxide emissions should be shown. Furthermore, different production pathways of sustainable jet fuels will be discussed and compared.

1 Pathways for sustainable synthetic jet fuel

The research group alternative fuel of the German Aerospace Center is among others analyzing three pathways for the jet fuel production from biomass, power and CO_2.

1. biomass to liquid (BtL)
2. power and biomass to liquid (PBtL)
3. power to liquid (PtL)

The understanding of the process is essential for every life cycle inventory and assessment. Hence a short overview of the three pathways is given.

1.1 Fischer-Tropsch-Synthesis

The key process of the three discussed pathways is the Fischer-Tropsch-Synthesis (FT-Synthesis). The chemists Franz Fischer and Hans Tropsch invented this process to convert solid coal in liquid fuels and wax in 1925 (Hoinkis, 2007). Educts for synthesis of hydrocarbons via FT-reaction are carbon monoxide and hydrogen (comp. Eq. 1).

$$CO + 2\,H_2 \rightarrow (\text{-}CH_2\text{-}) + H_2O \qquad \Delta_R H_{298K} = -152\ \text{kJ/mol} \qquad \text{Eq. 1}$$

Fuel production via FT-Synthesis included basically three steps. The first step is the synthetic gas (syngas) generation, followed by the FT-Synthesis and finally the refining and upgrading (comp. Figure 2).

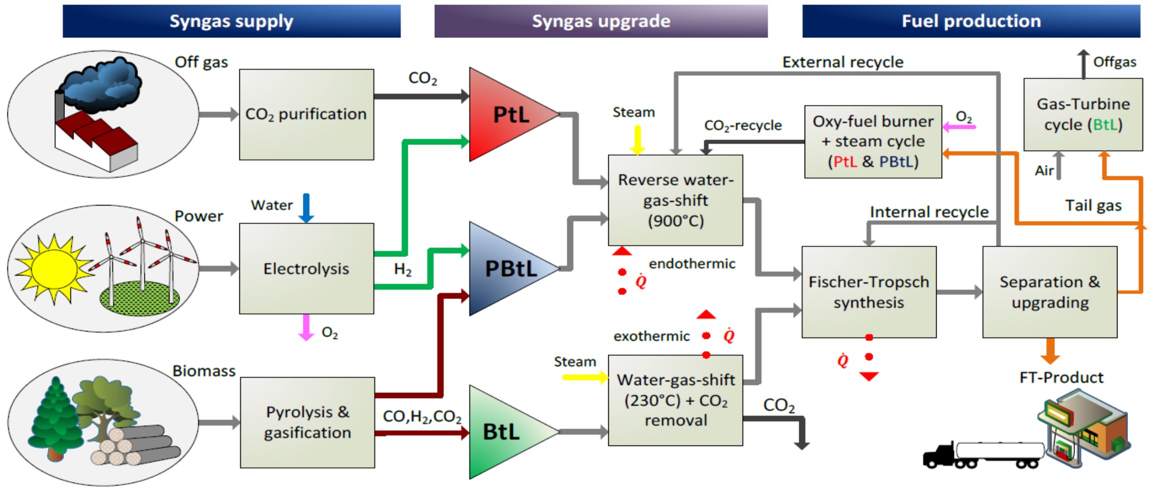

Figure 2: Block flow diagram and system boundary of BtL, PBtL and PtL concepts (Albrecht, König, Baucks, & Dietrich, 2016)

According to Eq. 1 syngas with hydrogen to carbon ratio of two is essential for an efficient synthetic fuel production. Every feedstock that contains hydrogen and carbon like natural gas, coal, municipal waste, biomass or a mixture of CO_2 and H_2 is suitable for syngas generation (König D. H., 2016). Coal and natural gas using FT-facilities are in commercial use since decades. For example runs the company SASOL coal-to-liquid plants in South Africa since 1955 and Royal Dutch Shell a gas-to-liquid plant in Qatar since 2000 (Leckel, 2009). However using coal and natural gas is not sustainable and the produced fuels don’t match the IATA targets for emission reduction (Stratton, 2010). Therefore only usage of biogenic feedstocks or sustainable CO_2 and H_2 will be analyzed in this thesis.

The product of every FT-synthesis is a mixture of different hydrocarbons. Depending on chain length are these hydrocarbons gaseous, liquid or solid waxes. In all three processes gas fraction utilized and applied to cover internal heating demands or to generate electricity. The remaining liquid and solid species are called syncrude. Syncrude is refined in gasoline, kerosene, diesel and waxes. The detailed composition of syncrude will be discussed later (comp. paragraph 2.2.2).

1.1.1 Biomass-to-Liquid (BtL) process

Pyrolysis and gasification of biomass delivers syngas for the BtL-process. Biomass is renewable and a widely available input. The harvesting and transportation of biomass is all over the world common knowledge (aireg, 2012). For the BtL process most kinds of organic material are suitable, but depending on the amount ash are modifications or use of special gasifiers required.

Another challenge is the chemical composition of the biomass itself. Biomass has a hydrogen to carbon ratio of approximately one. By using the water gas shift reactor the required hydrogen to carbon ratio of two is achieved and surplus carbon dioxide removed (König D. H., 2016). Only half of the supplied carbon could therefore be converted into hydrocarbons. The carbon conservation efficiency is consequently very low in the range of 20% to 30%.

1.1.2 Power and Biomass-to-Liquid (PBtL) process

The problem of low hydrogen supply via biomass could be solved by adding an electrolyzer to the BtL process. Additional hydrogen is then generated via electrolysis of water and a hydrogen to carbon ratio of two in syngas is realized. Hence, the carbon conversation efficiency is almost quadrupled from 24.9% to 97.7% (comp. Table 2). The electrolysis on the other side requires an external electricity supply, which causes additional costs and emissions.

1.1.3 Power-to-Liquide (PtL) process

For the PtL process, biomass is not needed. Carbon dioxide and hydrogen are inputs of PtL refineries. Carbon dioxide could be supplied by direct air capture or carbon capture from exhaust gas from industry. In this thesis only usage of exhaust gas will be investigated (comp. chapter 6), because direct air capture is a much more expensive and less efficient technology (sunfire, 2015).
During syngas generation carbon dioxide must be converted in carbon monoxide for the FT-synthesis (comp Eq. 1). One option is to use a reverse water gas shift reactor (comp. Eq. 2), which requires high temperatures and noble metal catalytic converters (Schnellbögl, 2016).

$$CO_2 + H_2 \rightarrow CO + H_2O \quad \Delta_R H_{298K} = 41.2\ \mathrm{kJ/mol} \qquad \text{Eq. 2}$$

Hydrogen for the reverse water gas shift reaction is generated via water electrolysis. Syngas hydrogen to carbon ratio of two and a carbon conservation efficiency of 98.0% are achieved (Albrecht, König, Baucks, & Dietrich, 2016). The possibility of improving the carbon footprint of industrial process and direct use of carbon dioxide offers large potential for PtL refineries. On the other side the electricity demand of a PtL process is even higher than for PBtL processes.

2 Applied LCA method

For a better comparison to other literature sources or projects of the German Aerospace Center, the LCA method has to follow international guidelines. The framework and principles for LCA's are defined in the ISO 14040:2006 and the ISO 14044:2006.

According to European Standard ISO 14044:2006 a LCA have to include four phases:

1. phase: goal and scope definition phase
2. phase: inventory analysis phase
3. phase: impact assessment phase
4. phase: interpretation phase

2.1 Goal and scope definition

LCA's could include different parameters and indicators. The global bioenergy partnership (GBEP) for example defined 24 indicators to evaluate bioenergy use, which are divided in three major topics environment, social and economy (comp. Table 1)

Table 1: GBEP indicators for the use bioenergy (GBEP, 2011)

environment	**social**	**economy**
Lifecycle GHG emissions	jobs in the bioenergy sector	productivity
soil quality	price and supply of a national food basket	net energy balance
harvest level of wood resources	change in income	gross value added
emissions of non-GHG air pollutants, including air toxics	allocation and tenure of the land for new bioenergy production	change in the consumption of fossil fuels and traditional use of biomass
water use	change in unpaid time spent by women and children collecting biomass	training and requalification of the workforce
water quality	bioenergy used to expand access to modern energy services	energy diversity
biological diversity in the landscape	change in mortality and burden of disease attributable to indoor smoke	infrastructure and logistics for distribution of bioenergy
land use and land use change related to bioenergy feedstock production	incidence of occupational injury, illness and fatalities	capacity and flexibility of use of bioenergy

These 24 indictors show the variety of different intentions for a LCA. Specialist from serval fields like medicine, geology, agriculture, finance and engineering are necessary for the evaluation of all indicators. Therefore a selection of the most important indicators has to be made.

According to IATA targets the primary target by using synthetic jet fuels is the reduction of carbon dioxide gas emissions in the aviation sector. Consequently, only the carbon footprint of sustainable jet fuel has to be analyzed. In the carbon footprint, production processes and feedstock supply are considered. As end of the LCA the refinery gate is defined. The transportation of jet fuel to the airport and use in air planes is not part of the evaluation. This type of system boundary is called cradle-to-gate approach. Following the biofuel sustainability ordinance, all results must be normalized to carbon dioxide emissions per megajoule on bases of the lower heating value (LHV) of bio kerosene (Biokraft-NachV, 2009). The lower heating value of kerosene is later determined (comp. 2.2.2).

As reference for the carbon emission saving potential of green jet fuel, conventional kerosene with an carbon footprint of 87.5 g_CO_2/MJ is applied (Stratton, 2010). According to the biofuel sustainability ordinance it must be checked, if the use of synthetic jet fuel saves at least 35% of carbon dioxide emissions or if the carbon footprint of the fuel production is higher than 56.875 g_CO_2/MJ.

Beside the carbon dioxide emission reduction, synthetic jet fuel must be available in large quantities to fulfill the IATA targets. Consequently, production potentials are not less important. For the evaluation of production potentials, a system border must be defined. In this thesis the federal state Baden-Württemberg is chosen as area of consideration. Only biomass and carbon dioxide sources in Baden-Württemberg are evaluated for the investigation of green fuel production potentials.

2.2 Life cycle inventory analysis (LCI)

During the life cycle inventory phase all major inputs and outputs of a process have to be investigated. As previously discuss input for the processes are biomass, oxygen, carbon dioxide, electricity and water for electrolysis and cooling.

2.2.1 Results of the process simulation

The German Aerospace Center developed simulation models of the BtL, PBtL and PtL process (Albrecht, König, Baucks, & Dietrich, 2016). Every process is thermally optimized by use of pinch-point analysis and parameter studies. AspenPlus® is used for the simulation and optimization. The results of the simulations are given in Table 2.

Table 2: Input and Output flows of the BtL, PBtL and PtL process (Albrecht, König, Baucks, & Dietrich, 2016)

Material flows [kt/a]	**BtL**	**PBtL**	**PtL (small/large)**
Biomass	-181.7	-181.7	-
Carbon dioxide	-	-	-74.8/ -282.5
Clean Water	-709.9	-900	-252.6/-953.9
Cooling Water	-10.548	-59.713	-12.417/-46.876
Waste Water	780.9	883.4	131.1/496.6
Liquid fuel	24.2	91.3	24.2/91.2
Energy flows [MW]			
Electricity	12.4	-164.6	-70.7/.267.1
Biomass	-98.3	-98.3	0
Steam (25 bar,230°C)	18.1	20.7	9/33.7
Steam (4bar, 150°C)	1.8	0	0
District heating	13.2	15	2.5/9.5
Fuel output	35.7	135.1	35.8/134.9
Efficiencies			
X-to-Liquid	36.3%	51.4%	50.6%
Overall plant	82.6%	65.5%	66.8%
Carbon conversation	24.9%	97.7%	98%

For the later investigation of production potentials of green kerosene, the output of every process syncrude must be further discussed.

2.2.2 Composition of Syncrude

Syncrude is a mixture of different hydrocarbon and just some parts of the syncrude could be used as kerosene. Other parts are gas, gasoline and diesel, which didn't match kerosene restrictions. The results of the AspenPlus® simulation supply the exact syncrude composition (comp. Figure 3).

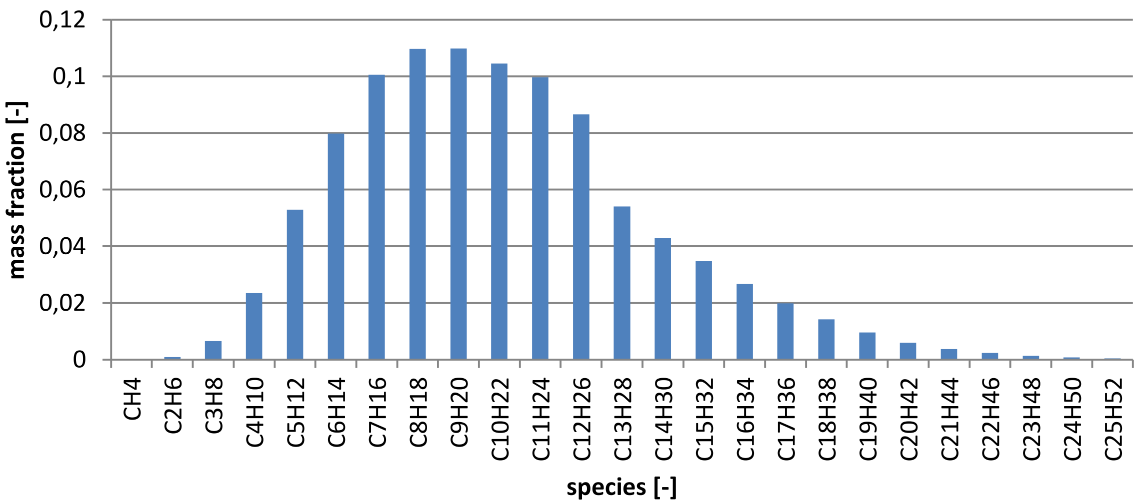

Figure 3: Composition of syncrude (König, Baucks, Dietrich, & Wörner, 2015)

The separation in the different components occurs during the final refining. Following fractions are considered as gas, gasoline, kerosene, diesel and wax (comp. Table 3).

Table 3: Chain length distribution representing the corresponding product fractions (König, Baucks, Dietrich, & Wörner, 2015)

Fraction	**Chain length**
Gas	$< C_5$
Gasoline	C_5 to C_8 + 25% of C_9
Kerosene	75% of C_9 + C_{10} + C_{11} + 50% C_{12} to C_{16}
Diesel	50% of C_{12} to C_{16} + C_{17} to C_{20}
Wax	$> C_{20}$

According to the chain length distribution 37.4% of syncrude are gasoline, 41.4% are kerosene and 17.4% are diesel. The detailed calculation is given in Appendix A.

Beside mass composition the lower heating value of bio kerosene must be determined, because carbon footprints of fuels have to refer to one megajoule according to the biofuel sustainability ordinance (Biokraft-NachV, 2009).
Mass compositions of syncrude and chain length distribution are used to determine the lower heating value of bio kerosene (comp. Table 4). The lower heating value is calculated by applying the Boie formula (comp. Eq. 3).

$$LHV = 34.8 \cdot C + 93.9 \cdot H - 10.8 \cdot O + 10.5 \cdot S + 6.3 \cdot N - 2.44 \cdot Moisture \qquad \text{Eq. 3}$$

Table 4: Lower heating value of bio kerosene

species	**mass fraction [%]**	**carbon mass fraction species [%]**	**hydrogen mass fraction species [%]**	**LHV species [MJ/kg]**	**mass fraction · LHV [MJ/kg]**
C_9H_{20}	19.97	84.38	15.63	44.03	8.79
$C_{10}H_{22}$	25.35	84.51	15.49	43.96	11.14
$C_{11}H_{24}$	24.15	84.62	15.38	43.89	10.60
$C_{12}H_{26}$	10.49	84.71	15.29	43.84	4.60
$C_{13}H_{28}$	6.55	84.78	15.22	43.79	2.87
$C_{14}H_{30}$	5.21	84.85	15.15	43.75	2.28
$C_{15}H_{32}$	4.21	84.91	15.09	43.72	1.84
$C_{16}H_{34}$	3.24	84.96	15.04	43.69	1.42
			$LHV_{bio\ kerosene}$ [MJ/kg]		**43.9**

3 Theoretic potential for biomass in Baden-Württemberg

After the investigation of all relevant inputs and outputs for the sustainable jet fuel production, available feedstock sources for biomass in Baden-Württemberg must be analyzed. In the next step the environmental impact of the biomass cultivation and transportation will be discussed.

3.1 Agriculture in Baden-Württemberg

Biomass is used in the BtL and PBtL process as carbon source. The theoretical potential of biomass is based on published statistic by the Federal Statistical Office.

In Baden-Württemberg an area of 1.623.500 ha is used for agriculture purpose and 1.370.000 ha are forest, that's 45.4% and 38.3% of the total land area, respectively (Destatis, 2016) . Compared to other federal states Baden-Württemberg, has an average level of agriculture area use, but the third highest forest concentration (comp. Table 5).

Table 5: Land use in the Federal States of Germany (Destatis, 2016)

Federal state	agricultural area [km²]	share of total area [%]	rank	forest area [km²]	share of total area [%]	rank
Baden-Württemberg	**16.235**	**45. 4**	**10**	**13.700**	**38.3**	**3**
Bavaria	33.063	46. 9	9	25.721	36.5	4
Berlin	38	4.3	16	164	18.4	13
Brandenburg	14.607	49. 3	7	10.534	35.5	5
Bremen	122	29.0	14	9	2.1	16
Hamburg	185	24.5	15	56	7.4	15
Hesse	8.845	41.9	12	8.488	40.2	2
Lower Saxony	28.459	59.8	4	10.532	22.1	11
Mecklenburg Western Pomerania	14.442	62.2	2	5.086	21.9	12
Northrhine-Westfalia	16.464	48.3	8	8.878	26.0	9
Rhineland Palatinate	8243	41.5	13	8.399	42.3	1
Saarland	1.100	42.8	11	874	34.0	6
Saxony	10.095	54.7	6	5.033	27.3	8
Saxony-Anhalt	12.547	61.3	3	5.069	24.8	10
Schleswig Holstein	11.009	69.7	1	1.672	10.6	14
Thuringia	8.880	54.8	5	5.300	32.7	7
Germany	184.332	51.6		109.515	30.6	

3.2 Available biomass in Baden-Württemberg

For the analyzation of the technical biomass potential only common crop plants and yields are used. To avoid displacements effects, biomass is not considered as resource for the fuel generation, if there are other utilization options like food or biogas production.

Short-rotational plantations like poplar or meadow are a promising option to increase the biomass yield in Baden-Württemberg, but right now they are not planted in large scale (Aust, 2012). In 2011 just 2.73 km² were used to grow this type of plants (Schütte, 2011). Short-rotational plantations offer today no considerable usable potential in Baden-Württemberg. With the mentioned restrictions only residuals could be used to produce synthetic jet fuels.

3.2.1 Excurse: Municipal Waste

Municipal waste in Germany has typically an organic mass fraction between 40% to 60% (Fricke, Niesar, & Turk, 2002) and approximately 1.5 million tons of organic wastes were collected at Baden-Württemberg in 2015 (Abfallbilanz, 2015). This organic waste could be considered as an interesting carbon feedstock. But while in many regions around the world organic waste is often just disposed on garbage dumpsite or burnt uncontrolled (WasteAtlas, 2013), the situation in Germany is totally different. Caused by the Closed Substance Cycle and Waste Management Act (Kreislaufwirtschaftsgesetz) all municipal waste has to be recycled as far as possible (KrWG, 2012). Consequently all organic waste is reused in Baden-Württemberg since 2006 (Abfallbilanz, 2015). Typical recycling pathways of organic waste are feedstock supply for biogas generation plants, waste-fired boilers or composting (Abfallbilanz, 2015).

To follow the restrictions of this thesis municipal waste is not expected to have great potential as feedstock for the synthetic fuel production. Otherwise displacements effects for existing waste treatment facilities and pathways could not be excluded.

3.2.2 Excurse: Root and fodder crops

In Baden-Württemberg root crops and fodder crops are grown on 249.4 km² and 1339.3 km², respectively, which corresponds to approximately 10% of the total cultivation area (Destatis_II, 2016). Root crops like potato or sugar beet have high specific yields. The typical yield range for potato is 33 to 50 t/(ha · a) and for sugar beet 58 t/(ha ·a) (Kaltschmitt M. , 2016). The grain to straw ratio however is small compared to other plants. The average grain to straw ratio of potato is 0.2 and 0.7 for sugar beet (DüV, 2013). An additional problem is the high straw moisture. Approximately 80% of the straw is water (DüV, 2013). Long time storage of moist straw is just as silage possible with use for biogas generation or animal feed.

Fodder corps like maize have also high specific yields of 48.5 t/(ha · a) in Baden-Württemberg (Destatis_II, 2016). The grain straw ratio of 1.0 indicates a high straw yield, but again is the moisture too high for storage. Maize straw has a water content of 65% to 70%. Silaging and use in biogas facilities or animal feed are the most common practice today (Kaltschmitt M. , 2016).

Overall the straw potential of root crops could therefore be neglected for the synthetic fuel production in Baden-Württemberg.

3.2.3 Cereal plants

Cereal plants are grown on the majority of the cultivation area in Baden-Württemberg. In 2007 5410.2 km² were cereal cultivation area that represents 64.8% of the total cultivation area. The main product grain is used for food production or as livestock feed. To avoid a conflict between food and synthetic fuel production, grain is not further considered as feedstock for the BtL or PBtL process even if this option is technical possible.

But never the less is the side product cereal straw available in large quantities. The Federal Statistical Office published land use and yields for the six main cereals wheat, rye, summer barley, winter barley, oat and triticale. With this data and typical grain-straw-ratios the straw production could be calculated (comp. Table 6). The yield is the average of the period 2010 to 2015. This is done to account for natural variability and the influence of crop rotations.

Table 6: Grain and Straw production in Baden-Württemberg (Destatis_II, 2016)

		Wheat	Rye	Winter Barley	Summer Barley	Oat	Triticale
cultivation area	[ha]	224636	9391	103911	83668	30074	19908
yield	[(t/ha)/a]	8.35	5.28	7.62	5.97	5.25	7.44
grain production	[t/a]	1,875,711	49,584	791,802	499,498	157,889	148,116
grain-straw-ratio	[-]	0.8	0.9	0.7	0.8	1.1	0.9
straw production	[t/a]	1,500,568	44,626	554,261	399,598	173,677	133,304
Total production		Grain: 3,522,600 tons per year			Straw: 2,806,034 tons per year		

Approximately 3.5 million tons of grain and 2.8 million tons of straw are produced in an average year in Baden-Württemberg. Most of the straw is chopped and ploughed in on the fields to receive the soil fertility (IFEU, 2008). The chemically bounded carbon of straw lignocellulos molecules is essential to form humus via biological processes. Humus is a mixture of several minerals and nutrients and necessary for plant grow (IFEU, 2008).

Another but less common option of straw utilization is the drying and pressing of straw bales. The straw bales are sold to livestock farmers who need the straw as bedding material or feed. After the use as bedding material, the used straw or manure is again ploughed in at the cultivation area to fertilize the soil (IFEU, 2008).

If straw is put to an energetic use like the biofuel production, this nutrient and carbon cycle is interrupted and the soil will become unusable for agricultural purpose. Therefore, not all straw can be used for biofuel or energy generation (IFEU, 2008).
Several studies had been made during the last years to evaluate the available straw potential (IFEU, 2008). The percentage of usable straw for energetic use varies from 10 to 60% of the total straw yield. Most studied focus on Germany as a whole. A more specific method was developed by Kappler in cooperation with the statistical office of the federal state Baden-Württemberg to evaluate the potential for residual straw in Baden-Württemberg (Kappler, 2008).

According to Kappler, a livestock unit needs every year 0.13 tons straw as feed and 0.55 or 2.2 tons straw as bedding material, depending on the animal species and type of stall. For pigs or cows, 0.55 tons per year are estimated as bedding material assuming that 75% stalls have a split floor and 2.2 tons for sheep's, which are kept in 100% bedded stalls (Kappler, 2008). Depending on the amount and kind of livestock is further the straw demand calculated. The results for Baden-Württemberg are given below in Table 7.

Table 7: straw demand for livestock keeping in Baden-Württemberg (Landwirtschaft, 2010)

animal species	pigs and cows	sheep's
livestock units	804,970 LU	24,865 LU
straw for feeding	104,646.1 tons	3,232.5 tons
straw bedding material	442,733.5 tons	54,703 tons
combined	547,379.6 tons	57,935.5 tons
	total	**605,315.1 tons**

The straw for livestock keeping is taken from the fields. Additional 40% straw remains on the field as basis for the humus production and soil fertility conservation. The scheme of the complete calculation method is shown in Figure 4.

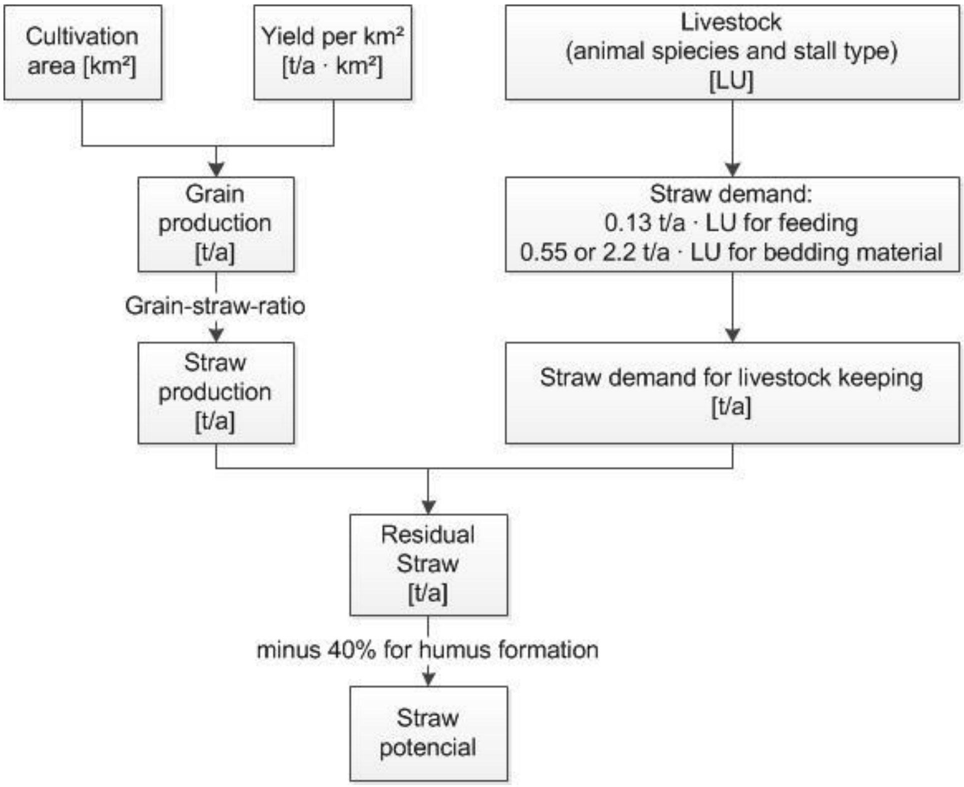

Figure 4: Kapplers method for the calculation of straw potentials (Kappler, 2008)

These method leads to the following results for the usable straw potential in Baden-Württemberg.

Table 8: Residual straw potential in Baden-Württemberg

total straw production	2,806,034 tons per year
straw demand for livestock keeping	- 605,315.1 tons per year
minus 40% for humus formation	- 880,287.6 tons per year
total residual straw potential	**1,320,431.3 tons per year**

Today are approximately 1.3 million tons straw usable in Baden-Württemberg without any impact to the soil fertility or livestock industry. 1.3 million tons are a considerable potential for large scale production of synthetic fuel. Actual this straw is not used for animal keeping or energetic use, but chopped and ploughed in. To keep the soil fertility, this is not necessary and a nutrient replacement by synthetic fertilizers would be possible. Consequently a further look at the properties and the environmental impact of cereal straw must be taken to evaluate the environmental impact and transportation effort.

3.2.4 Properties and environmental impact of straw

The following properties of straw in the course of a LCA are important to calculate the required straw or rather carbon input and the transportation effort.

- the density of straw bales for the transportation

The density of straw bales depends on the used straw press and straw moisture. The optimum in terms of loading capacity of the transportation vehicle is the use of square bales assumed. For every type of cereal straw moisture of 14% is assumed (DüV, 2013). Different studies are compared (comp. Table 9) for the assumption of an average straw bales density and a value of 150 kg/m³ have been taken.

Table 9: Density of straw bales

Literature	(Holzmann, 2012)	(Hering, 2015)	(Kaltschmitt M. , 2016)	(Krick, 2008)
Density [kg/m³]	180 - 200	130-160	150 -160	120 -220

- chemical composition/ elemental analysis

Straw is a natural product with variations in their chemical composition. For the chemical composition is the same average composition for all types of cereal straw (e.g. wheat or rye) applied (comp. Table 10).

Table 10: elemental analysis of straw (Qin, 2012)

Component	C_{dry}	H_{dry}	O_{dry}	N_{dry}	S_{dry}	Ash_{dry}	Moisture
Mass fraction [%]	45	5.9	41	0.6	0.15	7.35	14

3.2.5 Environmental impact of straw bales

The environmental impact of straw harvesting is caused by the energy demand for pressing and replacement of nutrient losses with synthetic fertilizers. According to the public biograce database, 144.48 MJ of diesel is necessary to press one ton of straw bales. Using the lower heating value of diesel in Germany (41.4 MJ/l) and equivalent carbon dioxide emissions (2.97 kg_CO_2/l) results an environmental impact of 10.35 kg_CO_2 per ton of straw (DIN_EN_16258, 2013).

The environmental impact of required fertilizer must be calculated based on the nutrient content of straw. Nutrients, which are removed from the field or not recycled as manure or digestate from biogas plants, must be replaced by synthetic fertilizers. According to previous calculations (comp. Table 8), 50% straw could be uses for the biofuel production. The appropriate amount of straw nutrients determined the fertilizer demand. The nutrient content and calculation of air pollution is given in Table 11.

Table 11: Nutrient content and environmental impact of straw (DüV, 2013; BioGrace, 2012; Kaltschmitt, 1997)

	Wheat	**Rye**	**Winter Barley**	**Summer Barley**	**Oat**	**Triticale**
Nutrient						
N [kg/t]	5	5	5	5	5	5
P_2O_5 [kg/t]	3	3	3	3	3	3
K_2O [kg/t]	14	20	17	17	17	17
CaO [kg/t]	0.45	0.45	0.45	0.45	0.45	0.45
Fertilizer use						
N [kg/t]	2.5	2.5	2.5	2.5	2.5	2.5
P_2O_5 [kg/t]	1.5	1.5	1.5	1.5	1.5	1.5
K_2O [kg/t]	7.0	10.0	8.5	8.5	8.5	8.5
CaO [kg/t]	0.225	0.225	0.225	0.225	0.225	0.225
environmental impact	N = 5.8806 kg_CO_2/kg	P_2O_5 = 1.0107 kg_CO_2/kg	K_2O = 0.5761 kg_CO_2/kg	CaO = 0.1296 kg_CO_2/kg		
fertilizer use [kg_CO_2/t]	20.28	22.0	21.14	21.14	21.14	21.14
with bale pressing [kg_CO_2/t]	30.63	32.36	31.49	31.49	31.49	31.49

Every ton of straw, which is used for the synthetic fuel production, causes between 30.63 and 32.36 kilogram of equivalent carbon dioxide emissions, for fertilizer use and bale pressing. The usage of straw is therefore not carbon dioxide neutral and must be taken to account in the LCA of synthetic fuel.

3.2.6 Waste wood

As said in the beginning of this chapter Baden-Württemberg is the federal state with the third highest percentage of forest area in Germany (comp. Table 5). From the 13.700 km² of forest area were 8.511.000 m³ wood harvested for construction and industrial purposes in 2015. Hence, this wood is not further considerable as feedstock for the fuel production.

Table 12: Wood harvest in Baden-Württemberg (Forst, 2015)

type of wood	**amount [m³]**
logs	5.941.000
industrial wood	1.077.000
other	1.494.000
total	8.511.000

Waste wood however is right now not utilized in large scale, caused by the poor homogenous quality and high ash mass fraction. Even for the production of wood pellets, waste wood is not suitable. The high ash components would influence the combustion and increase the emissions. (DEPI, 2016)

For the biofuel production, these problems could be solved by the use of special gasifiers for biomass like fluidized bed gasifier (Brellochs, Stenuell, Härdtlein, & Eltrop, 2014). With modified gasifiers, a large scale use of waste wood is technical feasible.

Waste wood is today a residual product of timber production. The moisture of fresh harvested waste wood is approximately 50% (LWF, 2012). This high moisture makes long term storage impossible, because wet wood is vulnerable for molds and rotting. Therefore is the wood collected and piled to dry. After 3 to 5 of drying month the waste wood got moisture of approximately 35% (Kappler, 2008) which is dry enough to avoid rotting (Kaltschmitt M. , 2016). The dried waste wood is shredded to wood chip, loaded and transported in roll-off containers.

The exact potential of waste wood is hard to calculate for Baden-Württemberg, because right now this type of wood is not statistical recorded. Today, waste wood remains in the forest and is not collected. Kaltschmitt however estimated a waste wood potential of 1.0 $t_{dry}/(ha \cdot a)$ without having an notable influences to the fertility or animals (Kaltschmitt M. , 2016). With this yield estimation, follows a potential of 1.37 Mio. tons dry waste wood every year in Baden-Württemberg could be expected, which is today not used. For the further life cycle evaluation the properties and environmental impact must be investigated.

3.2.7 Properties and environmental impact of waste wood chips

For the LCA of the biofuel production, the density and the chemical composition of waste wood chips are essential.

- density of waste wood chips

The density of the waste wood chips depends on the kind of wood and the moisture content. The density of hardwood chips is in general higher then softwood chips (Kappler, 2008), but for this thesis, one average value is used for all types of waste wood chips. Different studies are compared to find an appropriate average for the density of waste wood (comp. Table 13).

Table 13: Density of waste wood chips

Literature	(C.A.R.M.E.N, 2016)	(Kaltschmitt M. , 2016)	(Kappler, 2008)	(Leible, 2007)
density [kg/m3]	237 - 349	232 - 339	300	300

After the comparison of these studies an average density of 0.3 t/m³ is applied for further calculations.

- chemical composition/ elementar analysis

The slight difference in the chemical composition of different wood types is neglected in this thesis (Qin, 2012). The exact composition of waste wood is hard to determine, because waste wood is a mixture of serval tree components such like bark, log parts or branches. Additionally, natural variations can't be excluded. Therefore, an average chemical compositions is applied (comp. Table 14)

Table 14: elemental analysis of wood (Qin, 2012)

Component	C_{dry}	H_{dry}	O_{dry}	N_{dry}	S_{dry}	Ash_{dry}	Moisture
Mass fraction [%]	50	6	41	0.35	0.4	2.25	35

3.2.8 Environmental impact of waste wood chips

During the drying the waste wood remains in the forest and all leafs and needle fall from the tree. Most nutrients of trees are bound in leafs and needles (Kaltschmitt M. , 2016). A replacement of nutrients by fertilizers is therefore not necessary and only the chopping of wood chips causes an environmental impact.

Woodchoppers are run with diesel and according to the BioGrace database, 51.8 MJ of diesel is required to chop one ton of waste wood (BioGrace, 2012). 51.8 MJ diesel fuel is equal to 1.25 liters of diesel, which causes 3.68 kilogram of carbon dioxide emissions (DIN_EN_16258, 2013).

3.2.9 Adjustment of biomass to match the AspenPlus®-simulation

For the process simulation biomass was simplified by use of hemicellulose. Moisture and ash were not considered for the simulation. For the use of the simulation result the estimated straw and wood should at least match to energy and carbon input.

Hemicellulose molecules ($C_6H_9O_4$) have the following mass composition: 49.66% carbon, 6.21% hydrogen and 44.13% oxygen. A comparison of elemental analysis of hemicellulose, straw and waste wood is given in (comp. Table 15).
The lower heating value is calculated by using the Boie formula (comp. Eq. 3).

$$LHV = 34.8 \cdot C + 93.9 \cdot H - 10.8 \cdot O + 10.5 \cdot S + 6.3 \cdot N - 2.44 \cdot Moisture \qquad \text{Eq. 3}$$

Table 15: Elemental analysis for hemicellulose, straw and waste wood (Qin, 2012)

	hemicellulose	straw		waste wood	
		dry	wet	dry	wet
C_{dry} [%]	49.66	45	38.7	50	32.50
H_{dry} [%]	6.21	5.9	5.07	6	3.90
O_{dry} [%]	44.13	41	35.26	41	26.65
N_{dry} [%]	0	0.6	0.52	0.35	0.23
S_{dry} [%]	0	0.15	0.13	0.4	0.26
Ash_{dry} [%]	0	7.35	6.32	2.25	1.46
Moisture [%]	0	0	14	0	35
LHV [MJ/kg]	18.341	16.826	14.128	18.670	11.282

The comparison shows that straw and waste wood are not matching the properties of hemicellulose. In case of dry waste wood, the amount of carbon and the lower heating value are almost the same compared to hemicellulose, but in case of dry straw the carbon amount and lower heating value deviate by 5% and 12%, respectively. Nevertheless, in both cases a drying of biomass is necessary to match carbon and energy input. Carbon mass ratio and heating demand for the drying must be further calculated (comp. Table 16).
Compared to straw utilization, use of waste wood for the biofuel production requires a much higher drying effort to match the carbon and energy input, which is caused by the two times higher moisture content of waste wood.
0.432 MJ and 2.223 MJ of thermal energy are necessary to dry one kilogram of delivered straw or waste wood, respectively. Fortunately, in BtL and PBtL refineries large amounts of low temperature heat is available (comp. Table 2). This low temperature heat is suitable for drying. For every single type of biomass supply and refinery, it must be checked, if enough heat demand for the biomass drying is available.

Table 16: Calculation of carbon mass balance and drying

	formula	hemicellulose	straw	waste wood
input carbon [kg]	-	1	1	1
input raw material [kg]	$m_{raw} = 1/C_{raw}$	2.014	2.584	3.077
energy input [MJ]	$Q = m_{raw} \cdot LHV_{raw}$	36.939	36.507	34.715
drying necessary [-]	-	no	yes	yes
required moisture reduction [kg]	$m_{water} = \Delta Q/(2.44\ MJ/kg_{water})$	0	0.177	0.911
energy demand for drying [MJ/kg$_{raw}$]	$Q_{dry} = m_{water} \cdot 2.44\ MJ/kg_{water}$	0	0.432	2.223

For a complete evaluation of biomass the transport from field or forest to biofuel refinery must be considered. The available transportation options and their carbon footprint have to be analyzed.

4 Transportation

4.1 Discussion of the possible transportation methods in Baden-Württemberg

Baden-Württemberg has a dense road and railway network (comp. Figure 5). In total, there are 21.429 km of roads (Jahresvergleich, 2016) and approximately 4.300 km of railway tracks (LUBW, 2016).

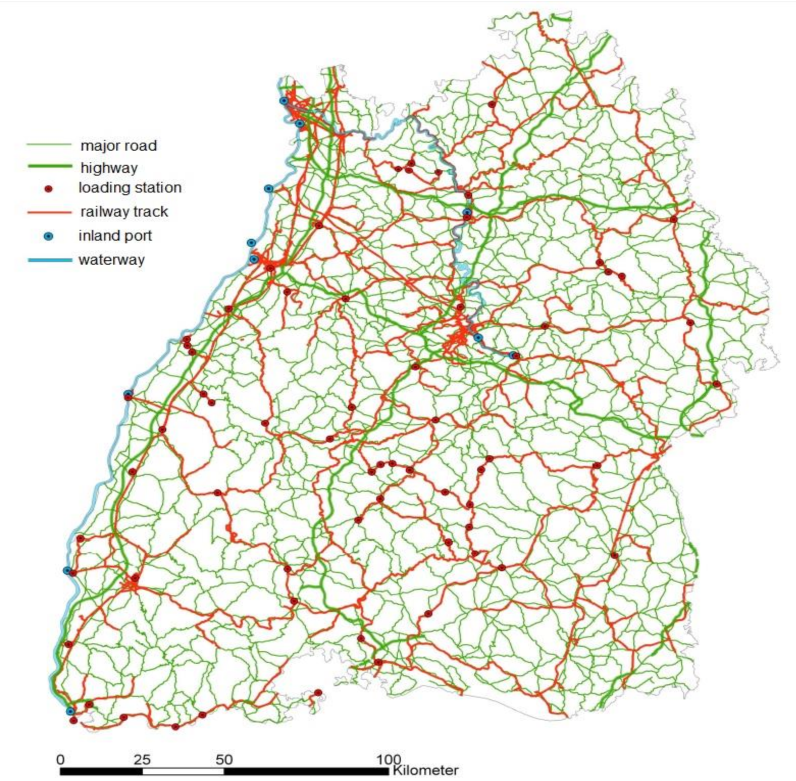

Figure 5: Transport routes in Baden-Württemberg (Kappler, 2008)

The transportations system via railways and streets is well developed, but caused by the geography, no large water transport or canal system exists. Only the rivers Rhine and Neckar are passable for tugboats (comp. Figure 5). For biomass transportation in Baden-Württemberg the waterways are not relevant and transportation by tugboats is therefore not further discussed in this thesis. However, the rivers Rhine and Necker could become an interesting transportation option, if biomass from other federal states or foreign countries shall be imported to Baden-Württemberg.

The transport by trains is an effective and cheap opportunity to move a large volume of goods, if goods are concentrated in one location close to a railway. Residual straw and waste wood however are harvested in small scales all around the country. Hence transportation by lorry or tractors to trains stations would become necessary and the advantages of trains become irrelevant.

Kappler calculated that a transport by train is just economically feasible, if the transport distance is higher than 250 km (comp. Figure 6). The longest distance in Baden-Württemberg is 324 km long (Lörrach, County to Heidenheim, County. Therefore it is concluded, that a supply chain based on train transportation will be not cheaper than a biomass transport with lorries.

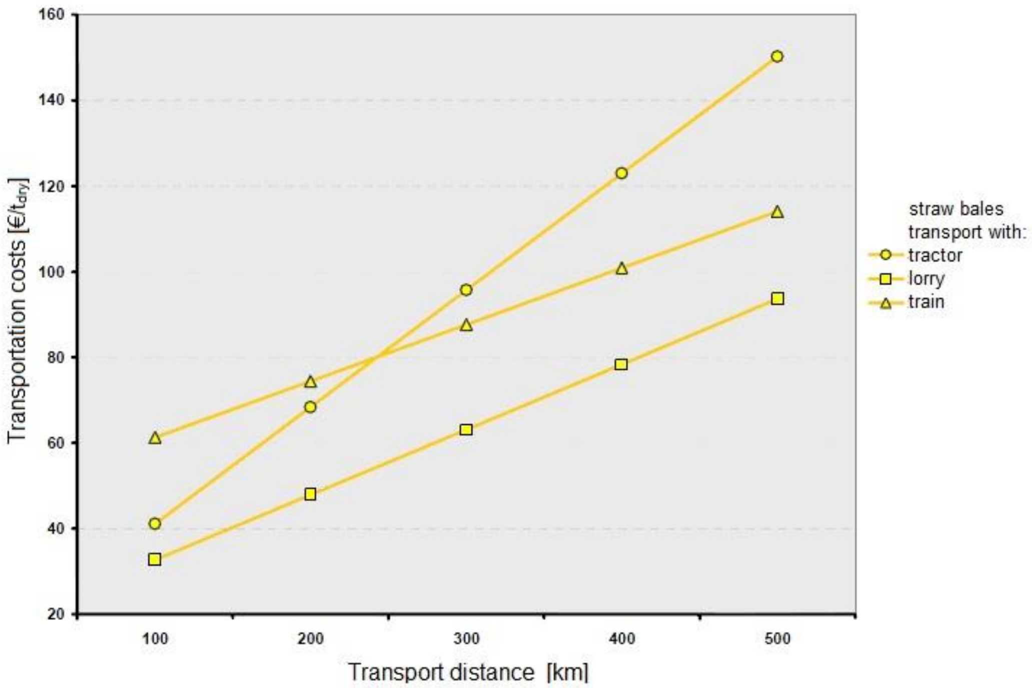

Figure 6: Transportation costs for straw bales with different methods (Kappler, 2008)

Tractors and lorries on the other hand are independed of railways, flexible and suitable for a transport of smaller quantities of goods. But tractors are to slow to go on high ways. Tractors are just necessary for the collecting of biomass and transport to streets, where lorries can pick up the straw bales or waste wood chips.

Consequently most of the transports will be done by lorries and a detailed look at the environmental impact of lorries must be taken, for a total evaluation of biomass utilization. The two other options will be not economically feasible to lorry transports and are not further discussed.

4.2 Environmental impact of transportation by lorries

The environmental impact of lorries could be divided in two phases. First the manufacturing and secondly the service phase. The emissions of the manufacturing are depending on the amount and kind of used materials for the lorry, while doing the service phase the emissions depends of mileage and load weight.

4.2.1 Environmental impact of the manufacturing phase

For each lorry, different kinds of material like steel, aluminum, copper and plastics are needed. Every material has a specific carbon footprint caused by mining, processing and transportation for the material production.

For the evaluations of material use and carbon footprint, data from the ProBas database are applied. The ProBas database is published and maintained by the German Federal Environmental Agency (Umweltbundesamt UBA). According to ProBas, following amounts of materials are necessary for different lorry types (comp. Table 17).

Table 17: Material use for lorries according to ProBas

lorry type (maximal loading weight)		**3.5 tons**	**6.0 tons**	**12.0 tons**	**26.0 tons**
amount of [kg]	steel	2,800	3,500	4,338	9,100
	aluminum	509	636	789	1,655
	plastic granulate	588	734	910	1,910
	lead	55	68.8	85.2	179
	glass	34.7	43.4	53.8	113
	copper	13.3	16.6	20.6	43.3

The total carbon footprint of the manufacturing has to be calculated with the specific carbon footprint of every material (comp Table 18).

Table 18: carbon footprint of different materials

material	**steel**	**aluminum**	**plastic granulate**	**lead**	**glass**	**copper**
carbon footprint [$kgCO_{2e}/kg$]	1.35	17.6	2.46	1.11	1.11	3.55

The total carbon footprint for the lorry types consequently results in:

Table 19: Total carbon footprint for different lorry types

lorry type (maximal loading weight)	**3.5 tons**	**6.0 tons**	**12.0 tons**	**26.0 tons**
carbon footprint [$kgCO_{2e}$]	14,332	17,908	22,209	46,589
carbon footprint per tons [$kgCO_{2e}/t_{load}$]	4.094	2.985	1.851	1.792

As Table 19 shows, the carbon emissions for the manufacturing increase with the size of the lorry. But from a different kind of view, a larger lorry has a higher loading capacity. If one divides the total emissions for the manufacturing with the loading capacity, the largest 26.0 tons lorry becomes the most ecological one.

For the transportation of waste wood chips, roll-off containers are necessary. A typical size of such a container is a loading capacity of 36 m³ (Kappler, 2008). The transportation of these containers can be done with a 12.0 ton lorry or 26.0 ton road train. Hence, smaller lorries cannot be used for the transportation of waste wood.

For the manufacturing of each container, 2.2 tons of steel are required, which causes additional 2.97 tons carbon dioxide emissions (comp. Table 18). The emissions of the container manufacturing must be added to the lorry production to evaluate the total environmental impact of the waste wood chips transportation.

4.2.2 Environmental impact service time (per driven kilometer)

During service, the diesel combustion in the lorry engine produces air pollutions. A standardization for the calculation methods of lorry transports in the European Union is the DIN EN 16258 standard, published in 2013. The DIN EN 16258 is a calculation guideline for the average fuel consumption and carbon dioxide emissions of different lorry types. The average diesel consumption depends on the lorry type and load weight.

Following formula is given:

$$FC_{Lorry} = FC_{empty} + \frac{LW_{Lorry}}{LW_{max}} \cdot \left(FC_{max} - FC_{empty}\right) \quad \text{Eq. 4}$$

Table 20: Diesel consumption of different lorry types (DIN_EN_16258, 2013)

lorry type	**FC_{empty} [l/100 km]**	**FC_{max} [l/100 km]**	**LW_{max} [t]**
3.5 tons	13.0	14.4	3.5
6.0 tons	16.9	20.1	6.0
12.0 tons	19.3	23.5	12.0
26.0 tons	22.7	37.1	26.0

In a first step, the actual loading weight must be calculated for the application of Equitation 4. It is assumed, that every lorry drives empty to the loading point close to fields or forest and picks up the maximum amount of biomass. A density of 0.15 t/m³ is applied for straw bales and 0.3 t/m³ for waste wood chips (see paragraph 3.2.4 and 3.2.7). Therefore, one delivery cycle is a combination of empty and full load drive.

The diesel consumptions, which are calculated with Eq. 4, are given for residual straw and waste wood chips in Table 21 and Table 22, respectively.

Table 21: average fuel consumption for a straw delivery cycle

lorry type	volumetric loading capacity [m³]	loading weight (φ_{Straw} = 0,15 t/m³) [t]	FC_{empty} [l/100 km]	FC_{max} [l/100 km]	FC_{full} [l/100 km]	FC_{Lorry} [l/100 km]
3.5 tons	18.43	2.76	13.0	14.4	14.1	13.55
6.0 tons	34.56	5.18	16.9	20.1	19.7	18.30
12.0 tons	41.47	6.22	19.3	23.5	21.5	20.40
26.0 tons	78.34	11.75	22.7	37.1	29.2	25.95

Table 22: average fuel consumption for a waste wood chips delivery cycle

lorry type	volumetric loading capacity [m³]	loading weight (ρ_{Wood} = 0,30 t/m³) + container [t]	FC_{empty} [l/100 km]	FC_{max} [l/100 km]	FC_{full} [l/100 km]	FC_{Lorry} [l/100 km]
12.0 tons	36 m³ (1 container)	9.8 + 2.2 (maximum load)	20.1	23.5	23.5	21.8
26.0 tons	72 m³ (2 container)	21.6 +4.4 (maximum load)	25.1	37.1	37.1	31.1

The average fuel consumption for the lorry leads to driving emissions. The combustion of a liter diesel (6.75 Vol.% biodiesel) generates air pollution of 2.94 kilogram carbon dioxide (DIN_EN_16258, 2013). Hence one delivery cycle over 50 kilometer by a 12.0 tons lorry of straw bales would emit 59.78 kilograms of carbon dioxide.

4.3 Transportation scenario for biomass in Baden-Württemberg

The total environmental impact of transportation depends on the fuel consumption and number of required lorries. Both quantities depend on a large number of influencing factors such like lorry size, driving speed, transport distance and so on. Therefore assumptions for the calculations have to be made.

The first assumption is that refinery and biomass are always located in the middle of a county or city in Baden-Württemberg. Therefore just distances between the middle of counties and cities in Baden-Württemberg have to be applied. The distances for the calculation are given in Appendix C.

Furthermore, the average driving speed of lorries depends just on the transportation distance. The driving speed increases linear from 50 km/h to a maximum of 90 km/h after a distance of 184 km (Smaltschinski, 2008).

$$v_{Lorry} = 50\frac{km}{h} + \left(\frac{40\frac{km}{h}}{184\,km} \cdot distance\right), \qquad \text{Eq. 5}$$

$$\text{if distance} > 184\,km\ then\ v_{Lorry} = 90\ \text{km/h}$$

The daily driving time of every lorry is estimated with 5.2 hours. This value is figured out by assuming a 8 hour shift with 45 minutes for breaks and no working during the weekends (comp. Eq. 6).

$$\frac{\left(8\ {}^{h_{Shift}}/_{day} - 0.75\ {}^{h_{Break}}/_{day}\right) \cdot 5\ {}^{day}/_{week}}{7\ {}^{day}/_{week}} = 5.2\ {}^{h_{driving}}/_{day} \qquad \text{Eq. 6}$$

For loading and unloading, 1.3 minutes per ton straw bales (et. al, 2015) and 2 minutes per roll-off container are considered. For the calculation, an annual service time of the refinery of 8,260 hours or 344.2 day are estimated.

With these assumptions, the time for one delivery cycle was determined. The number of lorries results from the biomass potential and number of required delivery cycles.

Two examples for the determination of required lorries are given in

Table 23.

Table 23: Example for the calculation of required lorries for biomass transportation

refinery location	**Stuttgart, City**		**Ravensburg, County**	
biomass from	Esslingen, County		Heilbronn, County	
distance [km]	37.7		228.0	
straw bales potential [t]	12,467.2		71,744.8	
waste wood chips potential [t]	18,750		28,105	
biomass	straw	waste wood	straw	waste wood
daily delivery [t]	36.22	54.47	208.43	81.65
lorry type	26.0 tons	26.0 tons	3.5 tons	12.0 tons
loading capacity [t]	11.75	21.6	2.76	9.8
required delivery cycles	3.08	2.52	75.52	6.80
average speed [km/h]	66.2	66.2	90	90
driving time one direction [h]	0.57	0.57	2.53	2.53
time for un-/loading [h]	0.25	0.07	0.06	0.03
total time for a delivery cycle [h]	1.64	1.28	5.18	5.12
possible daily delivery cycles	3.17	4.06	1.00	0.98
required lorries	1	1	76	7

4.3.1 Excurse: Comparison between straw bales and waste wood chips

If only carbon dioxide emissions of biomass harvesting are considered, waste wood has a much better carbon footprint than straw. Though, the chemical composition and transportation must also be evaluated. For the biofuel production, carbon is the important component in biomass. Therefore, a comparison based on the mass of carbon is more suitable.
By the use of chemical composition and density, the required biomass weight for the supply of one hundred tons carbon is calculated (comp. Table 24).

Table 24: Comparison of the carbon supply from straw bales and waste wood chips

	straw bales (wheat)	waste wood chips	relative difference
C_{dry} [%]	45	50	10%
moisture [%]	14	35	40%
density [t/m³]	0.15	0.3	50%
C_{raw} [%]	38.7	32.5	19%
required biomass for hundred tons of carbon [t/t_C]	258.4	307.7	16%
biomass [m³]	1722	1026	68%
required delivery cycles [-] (up rounded)	42	32	31%
fuel consumption 12 ton lorry [l/100 km]	20.4	21.8	7%

According to the results in Table 24, the transportation of straw bales is the environmentally better option than the use of waste wood chips, if the impact of harvest and lorry production is not considered. For both types of biomass, one 12.0 ton lorry is used and 10 roll-off containers for the waste woodchips transportation are required.
By adding the carbon footprint for harvesting, the result is different. For harvesting and replacement of nutrient losses of 258.4 tons wheat straw, carbon dioxide emissions of 7.91 tons are caused (comp. Table 11). The chopping of 307.7 tons of waste wood on the other side has just a total carbon footprint of 1.132 tons carbon dioxide. Figure 7 shows the results for the given example and the influence of different transport distances for the carbon footprint of the biomass supply.

The environmental impact of waste wood is much less compared to straw bales (comp. Figure 7). Recognize that in the given example straw with the lowest carbon footprint wheat straw (comp. Table 11) was taken for the comparison. Other kinds of straw bales are even worse.

Waste wood chips and straw bales have the same environmental impact, if the transport distance of waste wood chips is approximately 354 km longer (Figure 7, black dashed line).
The longest distance in Baden-Württemberg however is just 324 km long (Lörrach, county to Heidenheim, county). Waste wood chips are consequently expected to be the better resource for the biofuel production if only ecology matters.

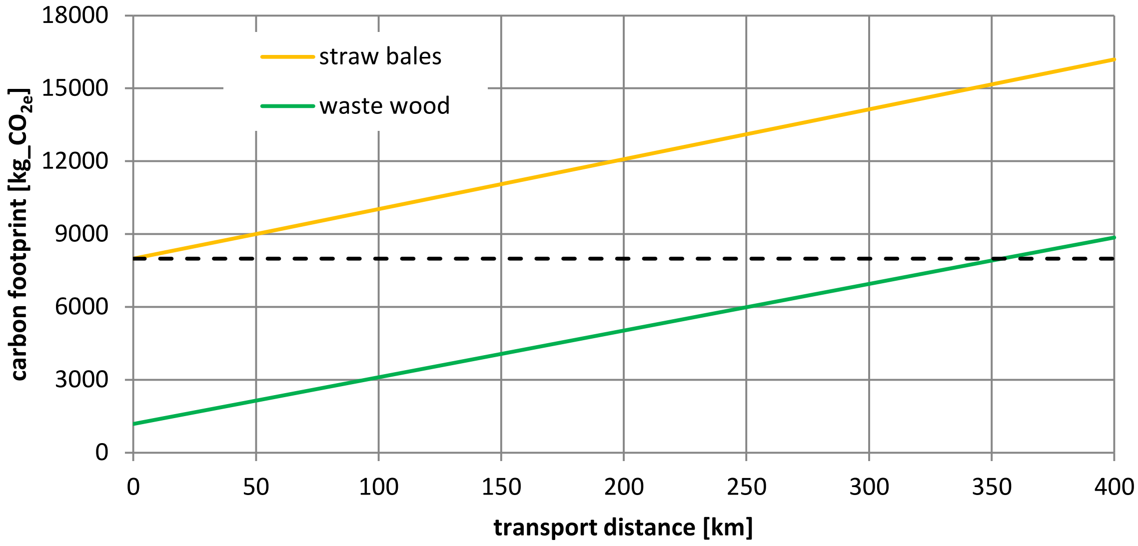

Figure 7: environmental impact of straw bales and waste wood chip with provision and different transport distances

5 Electrical energy

Electrical energy is an important input for the PBtL and PtL process, since electricity for the hydrogen electrolysis is required. In the BtL process electricity could be considered as credit for the fuel production (comp. Table 2). The carbon footprint of electricity must be discussed before the calculation of the green fuel carbon footprint could be started.

5.1 Grid electricity

In total power generation capacity with an electrical output of 204.5 GW are installed in Germany, including 97.8 GW from renewable energy sources (BNetzA, 2016). The maximum demand of electrical energy however is just about 75 GW (Agora, 2016).
This shows that the installed capacity is almost three times higher than the demand. Consequently many power systems are not running or must be shut down during the day to keep the grid balance. Conventional power plants could be shut down or just serve as cold reserve, while wind and solar energy are depending on daylight or wind and not running all the time.

The evaluation of the grid electricity carbon footprint requires the exact knowledge of the composition. The annual composition is calculated and recorded by the German Federal Environmental Agency (UBA, 2016). The composition development of the gird electricity between 1990 and 2015 is shown in Figure 8.

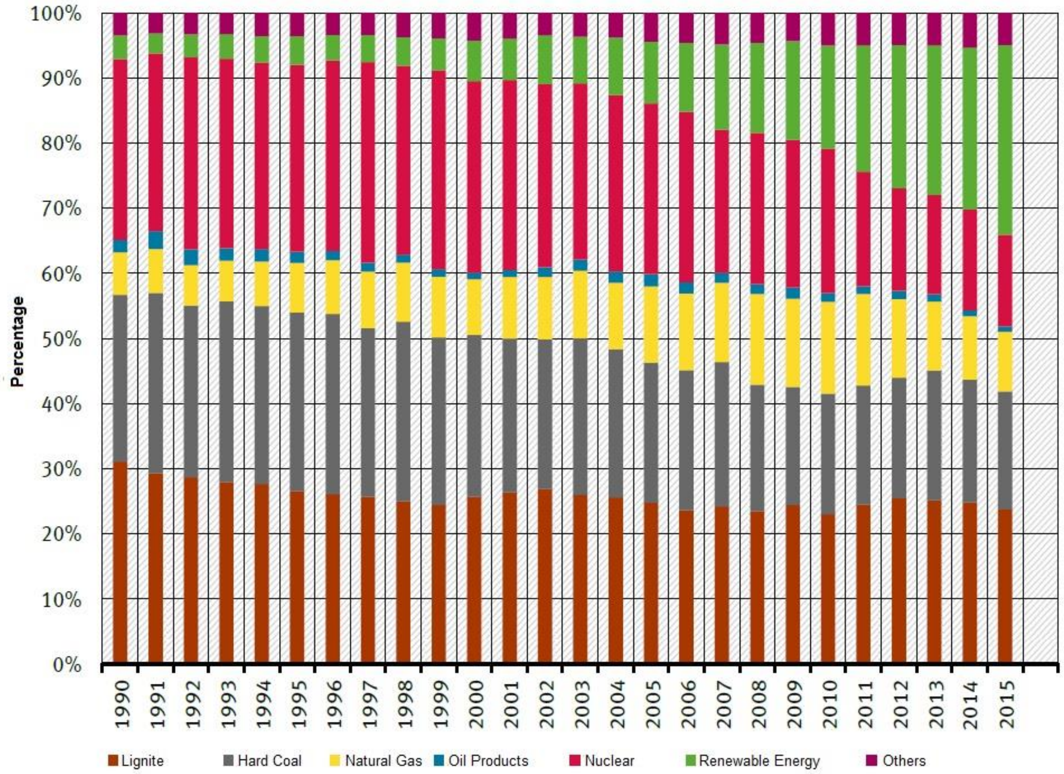

Figure 8: Composition of grid electricity in Germany between 1990 and 2015 (UBA, 2016)

Most of the electricity generation is based on lignite and hard coal. In 2015, roughly 42% of the gird electricity is produced by coal-fired power plants. On the other side production of renewable electricity increase, caused by the Renewable Energy Acts (Erneuerbare-Energien-Gesetz EEG). Since 2000, the share of renewable sources constantly grow from approximately 5% to 29% in 2015. 14.2% and 9.6% of the grid electricity are generated by nuclear and natural gas, respectively. These numbers can be used to calculate the carbon footprint of Germany's grid electricity mixture.

All renewable energy technologies are more environmental friendly then conventional coal or gas fired power plants (comp. Figure 9). The Carbon footprint of the grid electricity in Germany has therefore an average value between conventional and renewable power generation. The increasing percentage of renewable energy sources and improvements on conventional power plants, especially of lignite fired power plant, reduce the carbon footprint of the grid electricity (UBA, 2016). Over the last decades, specific CO_2-emissions decreases to the level of 535 g_CO_2/kWh in 2015 (comp. Table 25).

Table 25: specific CO_2-emissions of grid electricity between 2001 and 2015 (UBA, 2016)

year	2001	2003	2005	2007	2009	2011	2013	2015
specific CO_2-emissions [g_CO_2/kWh_{el}]	657	633	608	621	567	575	579	535

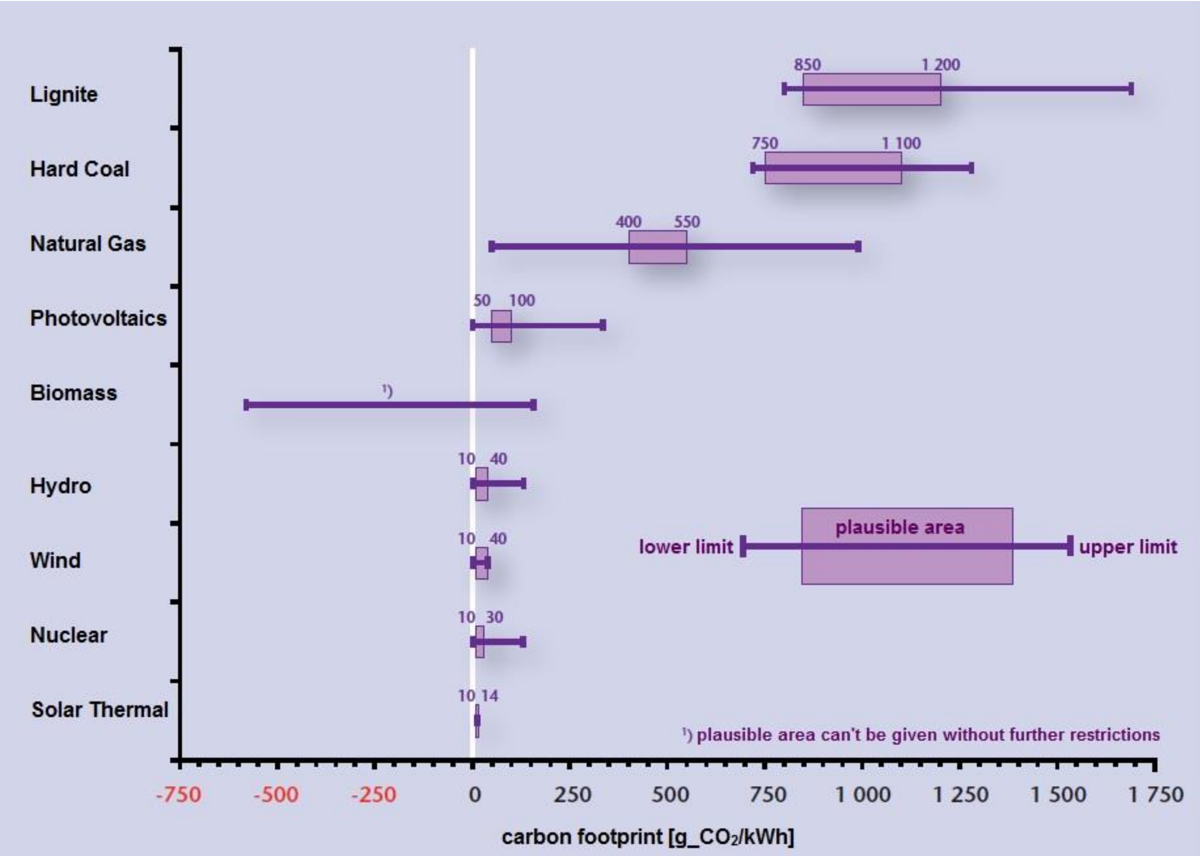

Figure 9: Carbon footprint of different energy technologies (Wagner, Koch, & Burkhardt, 2007)

5.2 Renewable energy systems in Germany

In 2010 the federal government developed a roadmap for the reduction of greenhouse gas emissions and the expansion of renewable energy systems, the so called “Energiekonzept”. Two targets of the “Energiekonzept” are the reduction of greenhouse gas emissions about minimum 80% compared to the level of 1990 until 2050 and a share of at least 80% electricity from renewable sources (BMWi, 2015). To achieve these ambitious targets, the following pathways for the expansion of renewable energy are proposed (comp. Table 26).

Table 26: Target for the expansion of renewable energy in Germany (BMWi, 2015)

wind on-shore	annual expansion between 2017 - 2019 **2.800 MW**	annual expansion from 2020 **2.900 MW**
wind off-shore	in 2020 expansion to **6.500 MW** installed total capacity	in 2030 expansion to **15.000 MW** installed total capacity
solar energy	annual expansion **2.500 MW**	
biomass	annual expansion between 2017 - 2019 **150 MW**	annual expansion between 2020 - 2022 **200 MW**

The “Energiekonzept” targets (comp. Table 26) show the increasing importance of wind and solar energy in future electricity supply in Germany. Biomass has no essential share for the expansion of renewable energies and is therefore not further discussed.
Hydro energy is also not considered in the “Energiekonzept”. Most of the hydro power potential is already used in Germany. According to a study from 2010, an expansion of hydro power between 12.3 TWh and 21.2 TWh is possible, which represents new installed capacities of 1.4 GW to 2.4 GW (BMUB, 2010). The part of hydro power will therefore not change significantly in the future electricity system in Germany.
The enormous planned expansion of installed wind and solar energy generation systems on the other side are reason to take a closer look to the wind and solar energy technology.

5.2.1 Wind energy

Wind energy is the most common and fastest growing renewable energy technology in Germany. In 2015, 12.3% of the total electricity or 42.4% of the renewable electricity were produced by wind with a total production of 80 TWh (UBA, 2016). In just five years between 2011 and 2015 the electricity production of wind energy has almost doubled, starting with 44 TWh in 2011 (UBA, 2016). This trend is expected to continue in the next years according to the targets of the federal government (BMWi, 2015).
Electricity from onshore facilities is currently the cheapest renewable energy and in cases with high capacity utilization (more than 2,500 full load hours per year) compatible to the price of lignite based electricity generation (ISE, 2013). On the other side offshore applications are much more expensive, because the installation work and investment cost are higher (ISE, 2013). Typical full load hours for onshore are 1.300 h/a to 2.700 h/a and for offshore 2.800 h/a to 4.000 h/a. Compared to conventional power plants, these are very low annual service times which is one important disadvantage of wind energy. The power generation depends on wind speed and generates a volatile electricity output.

The costs and carbon footprint is influenced by the annual service time, because wind mills don't need fuel and just the production of the wind mills must be considered. The power costs ranges from 4 ct/kWh to10 ct/kWh and 12 ct/kWh to 19 ct/kWh for onshore and offshore wind mills, respectively. For the carbon footprint of wind electricity, a range between 10 g_CO_{2e}/kWh to 40 g_CO_{2e}/kWh is realistic (comp. Figure 9).
For a fulltime electricity supply of a PBtL or PtL refinery by wind, many redundant wind mills or storage technologies for electricity are necessary. Such a high capacity storage device is today commercially not feasible.
Possible options today are the use of additional wind mills at different locations, large scale storage of hydrogen or limitation of the refinery operating time.

5.2.2 Solar energy

19.7% of the renewable electricity generation is solar energy, that corresponds to 6% of the total electricity generation in Germany. Solar energy had a rapid development during the last 10 years (UBA, 2016). Starting at 1 TWh in 2005 the solar electricity generations increases rapidly to 35 TWh in 2015 (UBA, 2016). Every year, 2.5 GW of new solar electricity generation systems shall be installed according to the "Energiekonzept" (comp. Table 26). The expansion trend will continue and solar energy is expected to become the second most important renewable energy source in Germany. Solar energy is therefore of interest regarding electricity supply for the PBtL and PtL process.
The disadvantages however are the higher production costs and environmental impact compared to wind energy and also a volatile electricity generation. For solar electricity production, costs between 7.8 ct/kWh and 14.2 ct/kWh are calculated by the Fraunhofer-Institute for Solar energy systems (ISE, 2013) by an annual full load time between 1000 h/a to 1200 h/a. The low number of full load hours indicates that a fulltime electricity supply of a green fuel refinery would require electricity or hydrogen storage systems and 7 to 8 times higher installed capacity of solar panels to match the refinery electricity demand.

The environmental impact of solar energy is worse compared to wind energy but better than grid electricity. For solar energy, a carbon footprint between 50 g_CO_{2e}/kWh to 100 g_CO_{2e}/kWh is given. That's the double but fifth to tenth of wind and grid electricity, respectively (comp. Figure 9 and Table 25).

As last major input for the PBtL and PtL process available carbon dioxide sources will be discussed and evaluated regarding the environmental impact of the carbon dioxide separation.

6 Carbon Dioxide Sources and Potential in Baden-Württemberg

Reduction of greenhouse gas emissions like carbon dioxide is the most important measurement to stop or at least slow down global warming. Carbon dioxide is a product of combustion processes of carbon-based fuels and can't be totally avoided. Today many options of carbon capture and storage (CCS) methods are discussed to reduce carbon dioxide emissions. The idea of every CCS-technology is to separate carbon dioxide from exhaust gas or carbon from the fuel. Later the separated carbon dioxide is compressed and stored.

The disadvantages of CCS and obstacles for a widely implementation are high energy demand for separation, compression and transportation of carbon dioxide and additional costs.

A way to avoid the problems of CCS is an usage of carbon dioxide, called carbon capture and usage (CCU). This way carbon dioxide is no longer a problem, but a valuable resource, which justify additional cost. However large scale implementation of CCU requires a market for large quantities of carbon dioxide. There could be a match between PtL process, the IATA targets and carbon dioxide usage.

But nevertheless often high thermal energy demand for carbon dioxide separation and following efficiency penalties of power plants or industrial processes exits. The German Aerospace Center plans therefore to use synthetic fuel production waste heat for carbon dioxide separation.

One idea of the German Aerospace Center is based on amine scrubbing. Amine scrubbing is a post combustion carbon capture method, which means that carbon dioxide is separated after the combustion from exhaust gas. Adding of post combustion technologies to existing plants is in general for all industrial processes applicable. An exemplary process flow scheme of amine scrubbing facility is shown in Figure 10.

Before the separation exhaust gas is cooled to a sufficient temperature for the process and lead into the absorber. In the absorber, an aqueous amine solution is sprayed into cold exhaust gas and carbon dioxide absorbed by contact with the amine droplets. Other exhaust gas components leave the absorber via a chimney. At the absorber bottom CO_2 rich solvent is collected and pumped to the desorber or regenerator.

Temperatures of approximately 120 °C are required to regenerate the solvent and desorb carbon dioxide (Fischdiek, Görner, & Thomeczek, 2015). The results of the desorbtion are an almost pure carbon dioxide stream and CO_2 lean sorbent, which is reused in the absorber.

Reboiler or hot steam usually supplies necessary heat for the regeneration. In a typical coal-fired power plant the high thermal energy demand for sorbent regeneration causes an efficiency penalty of 8% to 14% (TAB, 2007). This could be avoided, if the desorber is heated up by waste heat.

PtL refineries products large quantities of waste heat that could be utilized for sorbent regeneration (comp. Table 2). By connecting PtL process and amine scrubbing in an industrial process or power plant, no additional heat generation is required and less efficiency penalty will occur. By using the described arrangement of amine scrubbing and PtL refineries no additional heat is required and the environmental impact of the carbon separation minimized.

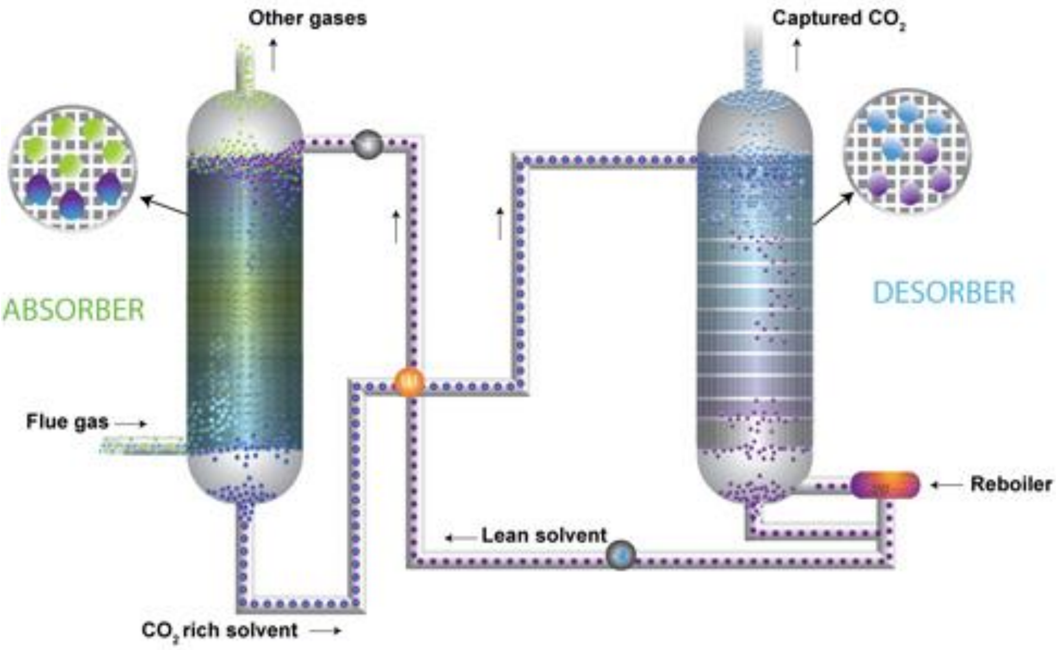

Figure 10: Function of amine scrubbing (CO2CRC, 2017)

6.1 Carbon Dioxide sources in Baden-Württemberg

6.1.1 Power plants

For the evaluation of carbon dioxide potential from power plants just facilities with an annual carbon dioxide output over 100.000 tons are considered. Smaller power plants can't be evaluated, because there annual carbon dioxide emissions are not publicly recorded.

In Baden-Württemberg eight power plants with an annual carbon dioxide output over 100.000 tons are in service (comp. Table 27). The carbon dioxide emissions of these 8 power plants are in total 16.078 million tons per year. Estimating a separation efficiency of 90%, results in an annual carbon dioxide potential of 14.470 million tons. By using the results of the life cycle inventory (LCI) 14.470 million tons carbon dioxide are enough input for the production of 4.682 million tons syncrude or 1.92 million tons green kerosene via PtL process. A satisfaction of the total bio kerosene demand in Germany is definitely possible.

If the CO_2 separation and the PtL-process would be implemented today, the potential would be five times higher than the demand of sustainable fuel defined by the IATA targets. However it is questionable which power plants will be running for the next decades and which will be shut down. The increasing share of renewable electricity generation in Germany replaces conventional power plants. The shutdown of some of the given power plants units like for example the Units WAL1 and WAL2 of the EnBW HKW Walheim is therefore already planned (KWSAL, 2016).

Table 27: CO_2 output and potential for carbon separation from power plants in Baden-Württemberg (thur, 2017)

Power Plant	CO_2-emissions [Mio. t_CO_2]	Potential for CO_2-separation [Mio. t_CO_2]	Potential PtL-production [Mio. $t_{SynCrude}$]
GKM Mannheim	6.190	5.571	1.802
Rheinhafen Dampfkraftwerk	3.620	3.258	1.054
EnBW HKW Heilbronn	3.280	2.952	0.955
EnBW HKW Altbach	2.120	1.908	0.617
EnBW HKW Walheim	0.300	0.270	0.087
HKW Pforzheim	0.270	0.243	0.079
EnBW HKW Stuttgart-Gaisburg	0.153	0.138	0.045
Wärmeverbundkraftwerk Freiburg	0.145	0.131	0.042
Total	16.078	14.470	4.682

If the power plants are not shutdown a, reduction of their annual full load hours and consequently carbon dioxide emissions must be expected for the future (AEE, 2013). The potential of carbon dioxide from power is all in all not secured for next decades. To avoid this problem the use of industrial processes as carbon dioxide sources is to recommend.

6.1.2 Cement plants

The production of cement bases on calcination of limestone (comp. Eq. 1). The calcination requires temperatures between 830°C to 950°C (VDZ_II, 2017). During the calcination carbon dioxide is detached from limestone and cement clinker (calcium oxide) is formed. Per every ton of cement clinker 0.525 tons of carbon dioxide are released.

These carbon dioxide emissions can’t be avoided by any changes of fuel or technology. Today additionally 0.275 tons carbon dioxide emissions are caused by the fuel combustion in the kiln. That’s 65% and 35% for the calcination and combustion, respectively (WWF, 2012).

$$CaCO_3 \rightarrow CaO + CO_2 \qquad \text{Eq. 1}$$

Right now seven cement plants with own clinker production are operating in Baden-Württemberg (VDZ_I, 2017). Together they produce 3.342 million tons of carbon dioxide (thru2, 2017). The potential for the carbon dioxide separations is approximately 3.0 million tons, which is enough for 973 kilotons syncrude or 398 kilotons green kerosene. This amount of green kerosene is 45% of the expected sustainable jet fuel demand in Germany (BMWi_II, 2014).

Table 28: Carbon dioxide emission from cement plants in 2015

Cement Plant	CO_2-emissions [Mio. t_CO_2]	Potential for CO_2-separation [Mio. t_CO_2]	Potential PtL-production [Mio. $t_{Syncrude}$]
HeidelbergCement AG Leimen	0.444	0.400	0.129
HeidelbergCement AG Schelkingen	0.804	0.724	0.234
Holcim GmbH Dotternhausen	0.529	0.476	0.154
Lafarge Zement Wössing GmbH	0.529	0.476	0.154
Schwenk Zement KG Allmendingen	0.496	0.446	0.144
Schwenk Zement KG Mergelstetten	0.540	0.486	0.157
Total	3.342	3.008	0.973

The advantages for the use of carbon dioxide emissions is that cements plants have a high number of annual full load hours and that cement production is a continues process. Additionally, most of the cement plants are located in rural areas with enough space for the construction of PtL refineries. The most important advantage however is that the cement industry in Germany is very stable with the almost the same level of clinker production every year (comp. Table 29).

Table 29: clinker production in Germany between 2008 and 2015 (VDZ_III, 2017)

year	2008	2009	2010	2011	2012	2013	2014	2015
clinker production [Mio. t]	25.366	23.232	22.996	24.775	24.581	23.127	23.871	23.355

In the future no change in the cement industry is expectable like the high investment quota indicates. In 2013 the investment quota for the cement industry was 6.52% (VDZ_IV, 2017) which is three times higher than the average investment quota in Germany at the same time (BMF, 2017).

After the investigation of carbon dioxide sources and separation potentials in Baden-Württemberg, the environmental impact of the carbon dioxide separation must be calculated for further calcualtions of the PtL carbon footprint.

6.1.3 Environmental impact of the CO_2-separation

For the evaluation of carbon dioxide it must at first be defined, if carbon dioxide of cement and power plants could be considered as carbon neutral. The carbon dioxide of cement and power plants is mostly caused by burning of carbon containing conventional fuels and must be considered in the carbon footprint of clinker or electricity. However is this carbon dioxide emitted in every case with or without carbon separation and usage for the green fuel production. Consequently, carbon dioxide is considered as waste product of clinker production or electricity generation and only the required effort for the separation will be analyzed for the carbon footprint of PtL fuel.

The CO_2-separation with sorbents reduces usually the process efficiency, because heat for the sorbent regeneration and electricity for pumps is required. For the sorbent regeneration, 0.722 MWh/t_CO_2 of thermal energy are necessary. The electricity demand can’t be avoided, but the use of waste heat has a potential for enhancements of the environmental impact. The regeneration heat is not directly considered in the carbon footprint of the CO_2-separation, because waste heat of the PtL refinery is utilized.

The mayor difference in CO_2-separation from power plants and cement plants is the concentration of carbon dioxide in the exhaust gas. The carbon dioxide concentration of coal-fired power plants is between 13% to 17% and 20% to 35% for cement plants (Fischdiek, Görner, & Thomeczek, 2015). The carbon dioxide concentration in cement plant exhaust gas is twice as high as in power plant exhaust gas. Additionally, the exhaust gas volume flow of cement plants is smaller which reduces the size of absorber vessels (WWF, 2012). Consequently a smaller mass flow of sorbent is necessary for the spray humidification and separation of carbon dioxide. This reduction of sorbent mass flow reduces the required electricity for pumps. 167 kWh/t_CO_2 and 278 kWh/t_CO_2 electricity are required for the separation of carbon dioxide from cement plant and power plants exhaust gas, respectively. The separation of carbon dioxide from cement plant saves 40% electricity compared to power plants.
If grid electricity with a carbon footprint of 0.535 kg/kWh is utilized for sorbent pumping, every ton of carbon dioxide got an environmental impact of 89.345 kg_CO_{2e} or 148.73 kg_CO_{2e}, depending if cement plant or power plant exhausts gas is the source.

7 Auxiliary materials

Beside the inputs which are directly related to syngas generation auxiliary materials are necessary for every type of green fuel refinery.

7.1 Water

Water is utilized as cooling water for exothermic reactors or as basic material for the hydrogen electrolysis. Depending on the utilization water has to match serval restrictions, which requires different cleaning technologies and energy efforts.

7.1.1 Cooling water

Cooling water has no strict requirements. It only must be free of larger pieces of dirt to avoid damages on pumps or blockings of heat exchangers. In Germany water is basically available everywhere and no complex water delivery has to be considered. According to the ProBas database, water pumping got a carbon footprint of 0.402 kg_CO_{2e}/t (ProBas, 2016).

7.1.2 Clean water

Clean water is essential for gasification of biomass and hydrogen generation via electrolysis. Clean water must be deionized, otherwise a deposition of salt in electrolyzer or gasifier can't be excluded. A water conductance under 5 µS/cm is required for electrolysis (Austria, 2016). The water requirements for the steam gasification are assumed to be the same.
For the production of deionized water, membrane methods are common today. In this process water dissolved ions are hold back by the membrane. The pressure loss over the membrane must compensated by pumps. The products of the membrane process are deionized water and ion-rich waste water. The ratio of deionized water to waste water is between 1.18 m^3_{deion}/m^3_{water} and 1.4 m^3_{deion}/m^3_{water} (EWT, 2016). Furthermore, 0.5 kWh/m^3_{deion} to 2.5 kWh/m^3_{deion} electricity is needed (EWT, 2016). An average ratio of 1.3 m^3_{deion}/m^3_{water} with 1.5 kWh/m^3_{deion} grid electricity demand are applied for further calculations. This assumptions lead to following carbon footprint of clean water (comp. Table 30):

Table 30: Carbon footprint calculation of clean water (UBA, 2016; EWT, 2016)

process step	ratio	carbon footprint
water pumping	1.3 m^3_{water}/m^3_{deion}	0.402 kg_CO_2/m^3_{water}
deionization via membrane process	1.5 kWh/m^3_{deion}	0.535 kg_CO_2/kWh
output	1.0 m^3_{deion}	1.3251 kg_CO_2/m^3_{deion}

Every cubic meter of clean water has a total carbon footprint of approximately 1.33 kilogram carbon dioxide.

7.2 Oxygen

For biomass gasification is oxygen used in the BtL-process. One possible oxygen production is the Linde process. In the Linde process common air is separated in its components. Oxygen is one of them with a mass fraction of 23.3%. Natural cooling during gas expansion and different boiling points of air components are the key of the Linde process. The process scheme is given in Figure 11.

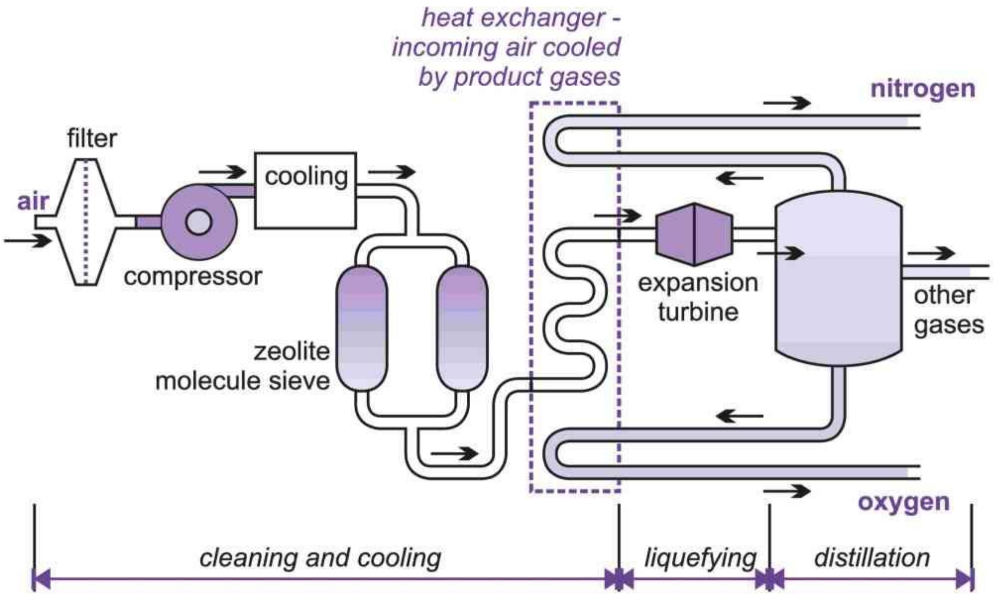

Figure 11: Linde process scheme

The first step is a cleaning and compression of the air up to 200 bars. In the next step the compressed air is cooled down and expanded to atmospheric pressure. A turbine is used for the expansion to recycle some of the compression work.

The temperature of the air decreases during the expansion to -190 °C. At this temperature oxygen condenses and could be separated from other air components like nitrogen or argon.

For the compression of air electricity is needed, which causes most of the environmental impact of liquid oxygen. For each ton of liquid oxygen 375 kilogram of carbon dioxide are emitted (ProBas, 2016).

8 Calculation of the carbon footprint of synthetic jet fuel

With the results of the lifecycle inventory and emission factors for all relevant inputs all data for the carbon footprint of jet fuel are available. The carbon footprint could now be calculated and checked, if the produced green kerosene has a carbon emission reduction of at least 35% (Biokraft-NachV, 2009).

8.1 Carbon footprint range for biomass in Baden-Württemberg

Before the calculation of the biofuel carbon footprint is started, plausible ranges for the environmental impact of biomass in Baden-Württemberg are discussed. The biomass carbon footprint depends on many factors, like kind of biomass, transportation distance and -vehicle. Following, the best and worst case scenarios are is chosen.

The best case is a small refinery for the use of wood chips exclusively with an average transportation distance of 10 km. As discussed before, waste wood chips are much more environmentally friendliy than straw bales. The refinery is in this case located in Sigmaringen, county, because Sigmaringen has a high forest concentration.

The worst case is modelled as one large refinery located in Ravensburg for the utilization of all straw bales of Baden-Württemberg. In the Ravenburg area all straw is needed for livestock keeping, additionally the city is located near the southern border of Baden-Württemberg. The average transportation distance for straw bales is therefore 159.2 km. To maximize the environmental impact a full balancing of removed straw nutrients with synthetic fertilizer and the transportation by 3.5 lorries is assumed. Both cases are calculated with the presented method (comp. chapter 3 and 0) and the results are given in Table 31.

Table 31: Best and worst carbon footprint of biomass in Baden-Württemberg

	best case	**worst case**
refinery location	Sigmaringen	Ravenburg
type of biomass	100% waste wood	100% straw bales
annual carbon supply [t]	5.000	489.856
lorry type / roll-off containers per lorry	26.0 t / 10	3.5 t / 0
average transportation distance [km]	5	159.2
number of lorries [-]	1	2067
specific carbon footprint [kg_CO_2/t_C]		
fertilizer use	0	108
pressing/chopping	11	26
transport	2	118
lorry manufacturing	0.6	3
total	13.6	255

A small refinery and waste wood utilization is much better ecologically than one large refinery with straw bales supply. The best case saves approximately 95% of specific carbon dioxide emissions per ton biomass carbon compared to the worst case. Every other type of biomass supply is within the given range between 13.6 kg_CO_{2e}/t_C and 255 kg_CO_{2e}/t_C.

8.2 Carbon footprint of synthetic fuels without credits

After the LCI and the evaluation of every input material all data for the carbon footprint calculation of biofuels are collected. For the calculation, specific values of inputs and electricity demand are used to analyze and compare the three processes (comp. Table 32). An annual full load time of 8260 hours for every process is estimated and average values of the small and large refinery of the PtL process are applied (comp. Table 2).

Table 32: Gross specific inputs of synthetic fuel production processes (Albrecht, König, Baucks, & Dietrich, 2016)

	BtL	**PBtL**	**PtL**
specific inputs [t/t$_{Syncrude}$]			
biomass carbon	3.729	0.988	0
carbon dioxide	0	0	3.094
oxygen	3.145	0	0
clean water	29.335	9.858	10.449
cooling water	0.436	0.654	0.508
electricity supply [MWh/t$_{Syncrude}$]	0	14.892	24.161

For every production process best and worst cases will defined and calculated to get an impression of the appropriate carbon footprint range. For BtL a distinction between best and worst biomass supply case (comp. Table 31) will be analyzed. Both biomass supply cases will also be evaluated for the PBtL process and combined with a distinction between renewable wind electricity and conventional grid electricity. Four production of PtL kerosene will be determined with carbon dioxide from cement and power plants and wind or grid electricity. In total ten cases, two BtL cases, four PBtL cases and four PtL, cases are defined Table 33. After the definition of all cases auxiliary energies for drying or sorbent regeneration will be calculated.

Table 33: Scenarios for the synthetic fuel production and auxiliary energy demand for drying and sorbent regeneration (c = cement plant; p = power plant)

process	BtL		PBtL				PtL			
case number	1	2	3	4	5	6	7	8	9	10
biomass case	best	worst	best		worst		-		-	
electricity	-	-	wind	grid	wind	grid	wind		grid	
carbon dioxide	-	-	-	-	-	-	c	p	c	p
heat output [MWh/t]										
steam 25 bar	6,18	6,18	1,87	1,87	1,87	1,87	3,06	3,06	3,06	3,06
steam 4 bar	0,61	0,61	0	0	0	0	0	0	0	0
district heating	4,51	4,51	1,36	1,36	1,36	1,36	0,86	0,86	0,86	0,86
heat demand for drying or sorbent regeneration [MWh/t]										
required heat	7.08	1.16	1.87	1.87	0.31	0.31	2.23	2.23	2.23	2.23
remaining heat output [MWh/t]										
steam 25 bar	4.22	6.18	1.36	1.36	1.87	1.87	1.69	1.69	1.69	1.69
steam 4 bar	0	0.61	0	0	0	0	0	0	0	0
district heating	0	3.35	0	0	1.05	1.05	0	0	0	0
Additional heat required?	no	no	no	no	no	no	no	no	no	no

Even if only waste wood chips with the highest drying energy demand are used for the synthetic fuel production, enough waste heat for drying is available (comp. Table 33). An external heat source is not necessary and doesn't have to be considered for the carbon footprint. By combining the LCI results (comp. Table 32) and emission factors the carbon footprint is determined (comp. Table 35).

In a second step sensitivity analysis for the carbon footprint are performed. The influence of different emissions factors for feedstocks in than discussed. As base case for the sensitivity analysis average values between best and worst case are applied (comp. Table 34)

Table 34: Average emission factors for the sensitivity analysis

input	best case	average	worst case
biomass [kg_CO_{2e}/t]	13.6	134.3	255.0
electricity [kg_CO_{2e}/MWh]	10.0	272.5	535.0
carbon dioxide [kg_CO_{2e}/t]	89.3	119.0	148.7
oxygen [kg_CO_{2e}/t]	375.0	375.0	375.0
clean water [kg_CO_{2e}/t]	1.33	1.33	1.33
cooling water [kg_CO_{2e}/t]	0.4	0.4	0.4

Table 35: Carbon footprint of biofuels without credits

process	**BtL**		**PBtL**		
case number	1	2	3	4	5
emission factors					
biomass [kg_CO_2/t_C]	13.6	255	13.6	13.6	255
electricity [kg_CO_2/MWh]	-	-	10	535	10
carbon dioxide [kg_CO_2/t]	-	-	-	-	-
oxygen [kg_CO_2/t]	375	375	-	-	-
clean water [kg_CO_2/t]	1.33	1.33	1.33	1.33	1.33
carbon footprint by source [kg_CO_2/$t_{SnyCrude}$]					
biomass	50.7	950.9	13.4	13.4	251.9
electricity	0.0	0.0	148.9	7967.2	148.9
carbon dioxide	0.0	0.0	0.0	0.0	0.0
oxygen	1179.4	1179.4	0.0	0.0	0.0
clean water	39.0	39.0	13.1	13.1	13.1
cooling water	0.2	0.2	0.3	0.3	0.3
total [t_CO_2/$t_{SnyCrude}$]	1269.3	2169.5	175.7	7994.0	414.2
Conventional kerosene got a carbon footprint of 87.5 g_CO_2/MJ. For a certification of bi sequently a maximum carbon footprint of 56.875 g_CO_2/					
carbon footprint kerosene (LHV = 43,904 MJ/kg) [g_CO_2/MJ]	28.9	49.4	4.0	182.1	9.4

8.2.1 Conclusion BtL process

In the both defined scenarios, BtL kerosene has a lower carbon footprint then 56.875 g_CO_2/MJ, which sticks to the biofuel sustainability ordinance requirement of 35% emission reduction (comp. Table 35). The calculated carbon footprint range of kerosene from BtL process is 28.9 g_CO_2/MJ to 49.4 g_CO_2/MJ. In an ecological point of view the implementation of BtL refineries is today in every case viable for the production of synthetic jet fuels.

Another result of the LCA is that biomass harvest and transportation are not the most important factors. In the worst case with full use of synthetic fertilizers and smallest lorry the biomass causes approximately 44% of the total production emission and in the best case just 4%. The oxygen supply on the other side causes 54% to 93% of all caron dioxide emissions. The optimization of the oxygen generation is consequently the most important measurement to enhance the environmental performance of the BtL process (comp. Figure 12).

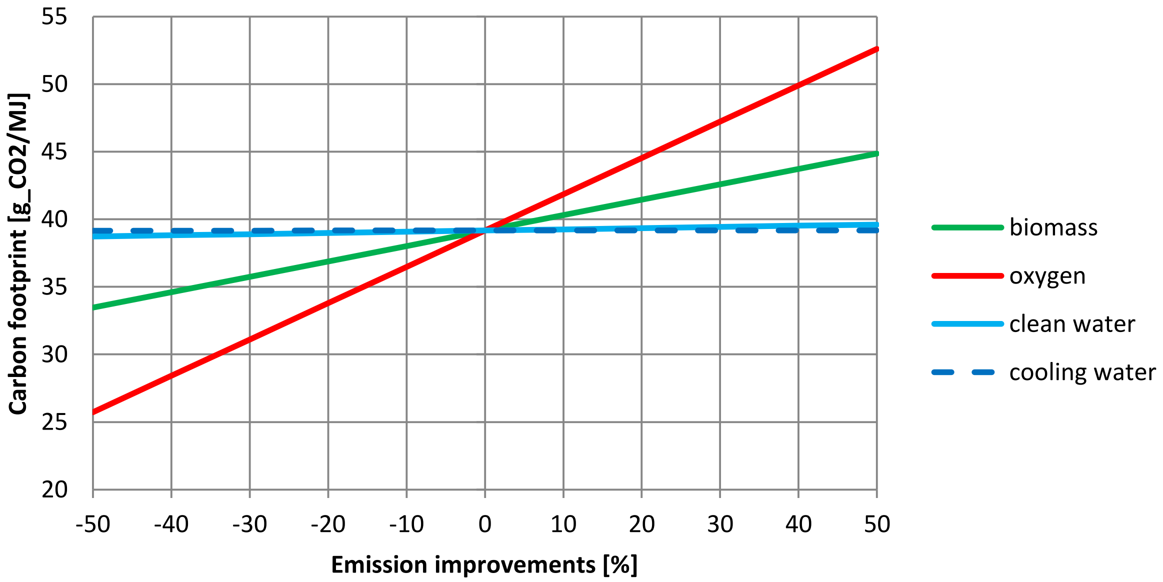

Figure 12: Influents of input emission factors for the BtL process

In Figure 12 are all changes related average values of best and worst case in Table 35. As said before, the influence of biomass carbon and oxygen supply can’t be neglected for production emissions.

Changes in the environmental impact of the water supply got no note worthily impact for the whole process if the refinery is located in Baden-Württemberg. The situation in other areas around the world may be different but is not discussed any further according to the restrictions of this thesis.

8.2.2 Conclusion PBtL process

In the best case PBtL processes produce the environmentally most friendly fuel with a carbon footprint of only 4.0 g_CO_2/MJ. Even if the worst biomass supply case for Baden-Württemberg is assumed, the carbon footprint increases slightly about 5.4 g_CO_2/MJ (comp. Table 35). Consequently, biomass is not the most defining factor. Overall, the ecological impact of PBtL fuel is determined by the utilized electricity (comp. Figure 13). As depicted in Figure 13 a change in emission factors of biomass or water supply got no notable impact on the carbon footprint.

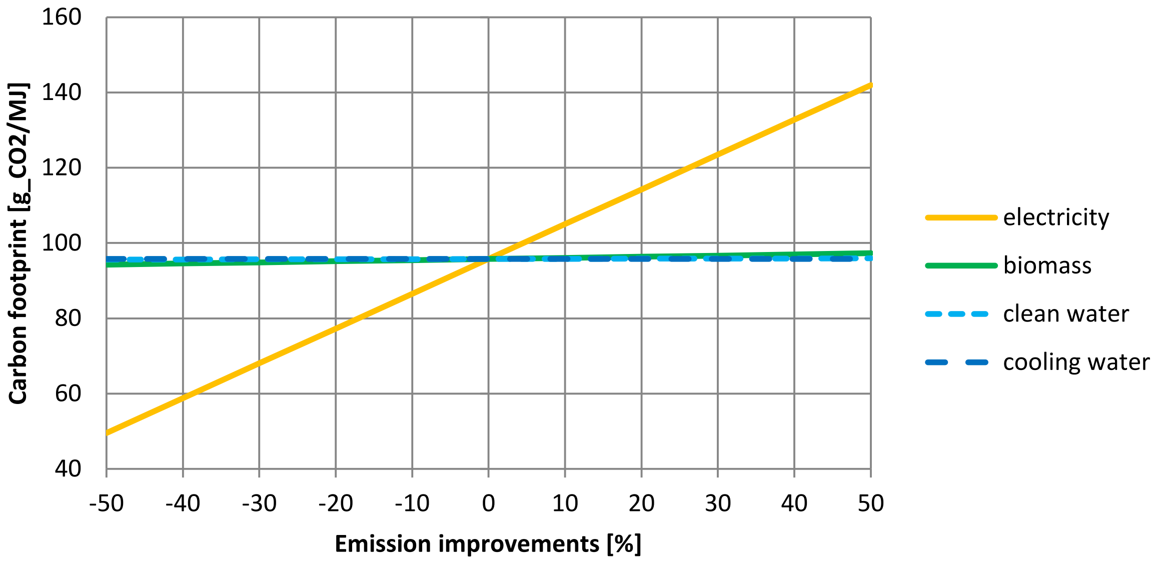

Figure 13: Influents of input emission factors for the PBtL process

On the other side electricity production is responsible for most of the total carbon dioxide emissions. Depending on the biomass supply different carbon footprints of electricity are acceptable for a production of bio kerosene.

Table 36: Maximum carbon footprint of electricity for PBtL processes

carbon dioxide source	**best biomass case**		**worst biomass case**	
carbon footprint electricity [kg_CO_2/MWh]	535.0 (grid)	165.88 (for biofuel)	535.0 (grid)	149.86 (for biofuel)
carbon footprint by source [kg_CO_2/$t_{SnyCrude}$]				
biomass carbon	13.4	13.4	251.9	251.9
clean water	13.1	13.1	13.1	13.1
cooling water	0.3	0.3	0.3	0.3
electricity	7967,2	2470,2	7967,2	2231,7
total	7994,0	2497.0	8232,5	2497.0
carbon footprint kerosene [kg_CO_2/MJ]	182.1	56.875	187.5	56.875

To match emission requirements of the biofuel sustainability ordinance an electricity supply with approximately 70% less emissions of today's grid electricity is necessary. Only renewable energy technologies or a mixture with high shares of renewables would be able to achieve this (comp. Figure 9). Today the use of the PBtL process for the production of bio kerosene is possible only if an extra electricity supply beside the grid is guaranteed.
However grid electricity in Germany will become more environmentally friendly during the next decades if the "Energiewende" continues. After the conclusion of the PtL process is therefore the future carbon footprint of grid electricity discussed to answer the question when an extra electricity supply system will be unnecessary for the PBtL process.

8.2.3 Conclusion PtL process

Two of the four production cases save enough carbon dioxide emissions to be certificated as biofuel. These cases are number 7 and 8, where wind energy for the electrolysis is used. In these cases PtL kerosene is even better than the BtL fuel. By using wind energy synthetic fuel with a carbon footprint between 12.1 g_CO_2/MJ and 16.3 g_CO_2/MJ could be produced, which saves 50% emissions of the best case BtL fuel production. If cement plant instead power plant exhaust gas is used as carbon dioxide source the total carbon footprint decreases byabout 4.2 g_CO_2/MJ. But the electricity supply is the major issue for the PtL process. To produce of one ton syncrude 24.16 MWh of electricity are necessary. The carbon footprint of electricity must consequently be multiplied by this factor, which results in an enormous sensitivity on the electricity supply (comp. Figure 14).

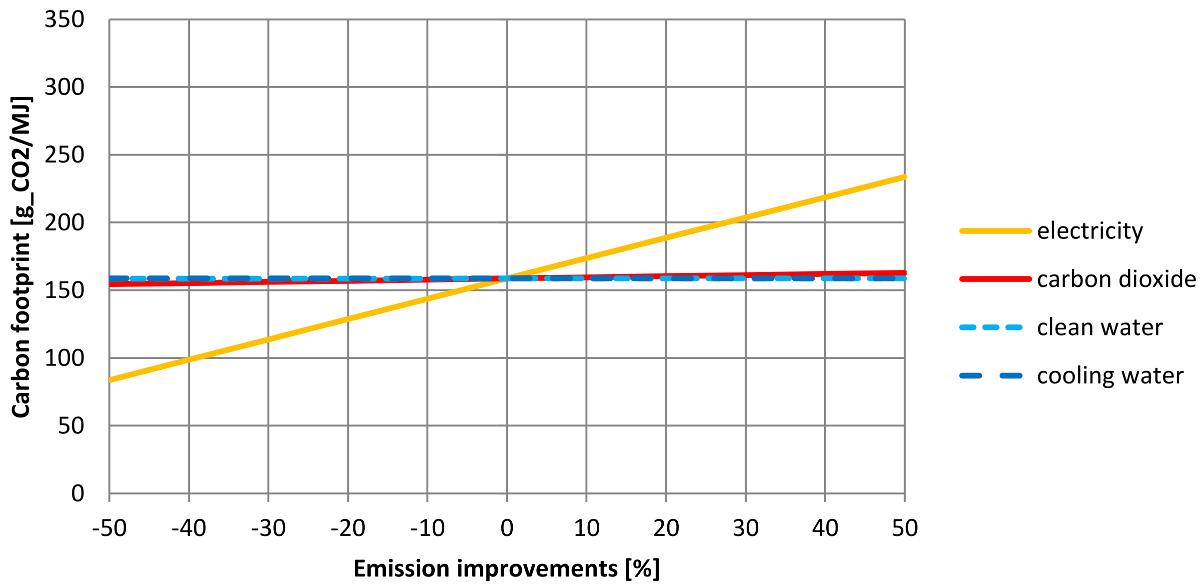

Figure 14: Influents of input emission factors for the PtL process

In Figure 14 average values between best and worst for the determination of a PtL base case refinery are applied. The total carbon footprint of PtL fuel is just influenced by the environmental impact of the electricity supply. All other inputs got a neglectable influence to the whole process. If no renewable electricity source is used, neither improvements of water neither carbon dioxide supply are able to balance off the environmental impact of the used electricity.

Right now the implementation of PtL refineries in Baden-Württemberg can't be recommended without restrictions. The carbon footprint of grid electricity is despite the massive expansion of the renewable electricity generation (comp. Figure 8) too bad for the PtL process. For a better evaluation of the PtL process the maximum carbon footprint is calculated if cement and power plant exhaust gas is utilized (comp. Table 37).

Table 37: Maximum emission factors for the production of biofuel via PtL process

carbon dioxide source	**power plant**		**cement plant**	
carbon footprint electricity [kg_CO_2/MWh]	535.0 (grid)	83.7 (for biofuel)	535.0 (grid)	91.3 (for biofuel)
carbon footprint by source [kg_CO_2/$t_{SnyCrude}$]				
carbon dioxide	460.1	460.1	276.3	276.3
clean water	13.9	13.9	13.9	13.9
cooling water	0.2	0.2	0.2	0.2
electricity	12926.1	2022.9	12926.1	2206.6
total	13400.3	2497.0	13216.5	2497.0
carbon footprint kerosene [kg_CO_2/MJ]	305.2	56.875	301.0	56.875

If cement and power plant exhaust gas is used for the carbon supply, the carbon footprint of electricity has to be below 91.3 kg_CO2/MWh and 83.7 kg_CO2/MWh, respectively (comp. Table 37). Today the carbon footprint of electricity is approximately six times higher. Just a massive expansion of the renewable electricity generation is able to improve the environmental impact of grid electricity production to make the application in PtL refineries ecologically acceptable. The required share of renewable electricity in the grid electricity will be discussed later (comp. chapter 9.2).

8.2.4 When could grid electricity be used for the PBtL or PtL process?

The future carbon footprint of grid electricity could be figured out with targets of the "Energiekonzept" in Germany. For the PtL process and PBtL process a maximum carbon footprint of 91.3 g_CO_2/kWh and 83.7 g_CO_2/kWh is acceptable.

The target for the expansion of renewable electricity generation in Germany is a share of 80% in the total electricity generation in 2050. The remaining 20% shall be produced by conventional combustion based technologies like coal or gas fired power plants. The exact composition is not further determined, but in the ecologically best case grid electricity will be a mixture of onshore wind and gas power plant electricity with a carbon footprint of 10 g_CO_2-/kWh and 400 g_CO_2/kWh, respectively. However other cases are more realistic. Following the expansion pathways of the "Energiekonzept", renewable energy will consist of solar and wind energy in a ratio of 1 to 2 (comp. Table 26) For the fossil energy technologies a composition like today is assumed (BMWi, 2015). Another difference is made by the carbon footprints of every technology. For the "Energiekonzept" cases the best and average emission factors are applied. The emission factors refer in all cases to Figure 9. The appropriate carbon footprints are calculated and results are given in Table 38.

.

Table 38: Carbon footprint scenarios for 2050

	best case		**Energiekonzept (minimum)**		**Energiekonzept (average)**	
	share [%]	**carbon footprint [g_CO_2/kWh]**	**share [%]**	**carbon footprint [g_CO_2/kWh]**	**share [%]**	**carbon footprint [g_CO_2/kWh]**
lignite	0	850	8.9	850	8.9	1,025
hard coal	0	750	6.5	750	6.5	925
natural gas	20	400	4.6	400	4.6	475
wind	80	10	53.33	10	53.33	25
solar	0	50	26.67	50	26.67	75
total	100	88.0	100	161.5	100	206.5

The results in Table 38 indicate that just the best case with 80% wind energy and 20% electricity generation from natural gas could deliver energy with a carbon footprint suitable for bio kerosene production of via PBtL or PtL processes. The more realistic cases with use of coal and solar energy doesn't fit to the electricity requirements of PtL process. Even for PBtL process is a generally statement for utilization of gird energy in 2050 not possible.

If an average carbon footprint for electricity generation technologies is assumed, grid electricity still causes approximately 60 g_CO_2/kWh too much for use in the PBtL process (comp. Table 36 and Table 38). Just the “Energiekonzept (minimum)” case would be suitable for a production of bio kerosene via PBtL process, if waste wood chips are used as carbon source. All in all it must be concluded that even the ambitious expansion of renewable energy systems in Germany until 2050 are not enough to enhance the grid electricity carbon footprint for an use in PBtL or PtL processes. For these two processes always an extra solution for the supply with renewable electricity is needed.

However utilization of solar energy is not in every case adequate for PtL processes. In some studies emission factors for solar electricity over 100 g_CO_2/kWh are reported, which is too high for the bio kerosene production (comp. Table 37). But the application of wind or hydroelectricity for the synthetic fuel production is possible in every analyzed case.

Options for the implementation of a full time supply with renewable electricity could be the connection of different wind and solar parks, the use of larger electrolyzers in connection with hydrogen storage or electricity storage. The discussion of these options must be part of every of future PBtL or PtL refineries project.

8.3 Carbon footprint of synthetic fuels with credits

According to the biofuel sustainability ordinance only the use of carbon capture and storage technologies or electricity generation via combined power and heat systems are allowed as credits (Biokraft-NachV, 2009). But nevertheless potential saving from credits for all usable outputs are calculated to show the impact of law changes for the future.

Credits are given for the production of all side products. A comparison with the environmental impact of the conventional creation of these products delivers the credit for synthetic fuel. In case of synthetic fuel production side products are waste heat, oxygen or electricity (comp. Table 39). Again specific values for outputs are determined by using the simulation result from AspenPlus® (comp. Table 2) to allow an easier comparison between the three processes.

The BtL process got the lowest carbon conservation efficiency but the highest output of side products or overall plant efficiency (comp. Table 2). Per each ton of BtL syncrude 4.23 MhW and 4.22 MWh to 10.14 MWh of electricity and thermal energy are generated, respectively. The amount of thermal energy depends on the used biomass supply (comp. Table 39). PBtL and PtL got no electricity output, but oxygen is a side product of fuel synthetization or more specifically the electrolysis. The PBtL causes 1.10 tons oxygen and the PtL process 3.46 tons oxygen for every ton of syncrude.

The amount of waste heat varies from 1.36 MWh/$t_{syncrude}$ to 2.92 MWh/$t_{syncrude}$ in the PBtL and again the required heat for biomass drying is the determined factor. PtL processes always generate 1.69 MWh//$t_{syncrude}$ independed of production scenario, because the same amount of heat is needed for the sorbent regeneration (comp. paragraph 6.1.3).

Table 39: In- and outputs of synthetic fuel production pathways

process	BtL		PBtL				PtL			
specific inputs [t/$t_{SynCrude}$]										
biomass carbon	3.729		0.988				0			
carbon dioxide	0		0				3.094			
oxygen	3.145		0				0			
clean water	29.335		9.858				10.449			
cooling water	0.436		0.654				0.508			
electricity supply [MWh/$t_{Syncrude}$]	0		14.892				24.161			
case number	1	2	3	4	5	6	7	8	9	10
biomass case	best	worst	best		worst		-		-	
electricity	-	-	wind	grid	wind	grid	wind		grid	
carbon dioxide	-	-	-	-	-	-	c	p	c	p
remaining heat output [MWh/t]										
steam 25 bar	4.22	6.18	1.36	1.36	1.87	1.87	1.69	1.69	1.69	1.69
steam 4 bar	0	0.61	0	0	0	0	0	0	0	0
district heating	0	3.35	0	0	1.05	1.05	0	0	0	0
electricity output [MWh/t]										
	4.23	4.23	0	0	0	0	0	0	0	0
oxygen output [t/t $t_{Syncrude}$]										
	0	0	1.10	1.10	1.10	1.10	3.46	3.46	3.46	3.46

As reference for the power generation grid electricity is applied. The other outputs are evaluated by using data from ProBas. For the credit of oxygen gaseous oxygen was assumed, because an electrolyzers doesn’t produce liquefied oxygen.

By combining emission factors and outputs the credits are calculated (comp. Table 40).

Table 40: Carbon footprint of biofuels with credits

process
case number
biomass case
electricity
carbon dioxide
remaining heat output
steam 25 bar
steam 4 bar
district heating
electricity output [M
oxygen output [t/t t_s
emission factors
steam 25 bar [kg_CO_2/
steam 4 bar [kg_CO_2/M
district heating [kg_C
electricity [kg_CO_2/MW
oxygen (gaseous) [kg_
credits [kg_CO_2/t_{syn}
steam 25 bar
steam 4 bar
district heating
electricity
oxygen (gaseous)
total credits
carbon footprint with c
carbon footprint with c
difference

If credits are considered, even negative carbon footprints are possible if renewable wind energy is used for electricity supply. A negative carbon footprint however should not be interpreted as a carbon dioxide reduction in the atmosphere via biofuel production. The negative carbon footprint is just an indicator for the avoidance of air emissions and an additional argument for an implementation of biofuel refineries or funding by the possibility to sell CO_2 certificates.

Another interesting fact is that a biomass supply by straw bales becomes more environmentally friendly than waste wood chips. Drying of waste wood chips is far more energy intensive than the use of straw bales (comp. Table 16). Less thermal energy is therefore creditable. The difference between waste wood chips and straw bales in the BtL process is a credit of 1,371.7 $kg\_CO_2/t_{Syncrude}$ and the BtL kerosene from straw bales becomes the most environmentally friendly fuel of all analyzed cases (comp. Table 40/case 2). The same influence can be seen to a lesser degree for the PBtL process, because less biomass input is required.

The considering of credits improves the carbon footprint by 9.1 g_CO_2/MJ or 17.3 g_CO_2/MJ and 14.8 g_CO_2/MJ for the PBtL and PtL process, respectively (comp. Table 40). However this does not change the general statement of the previous chapter. In all four cases, where grid electricity is utilized, the kerosene carbon footprint is still too high for a biofuel certification (comp. Table 40). The use of grid electricity today must therefore be totally excluded for the production of biofuels if the IATA target should be achieved.

Grid electricity could possibly be used for biofuel production in 2050 if credits are considered. The requirement to the carbon footprint of electricity is furthermore calculated (comp. Table 41).

Table 41: Required carbon footprint of electricity if credits are considered

process	**PBtL**		**PtL**	
electricity required [kg_CO_2/MWh]	192.6	200.8	118.3	110.7
case number	4	6	9	10
biomass case	best	worst	-	-
carbon dioxide	-	-	c	p
carbon footprint without credits [kg_CO_2/$t_{Syncrude}$]				
	2,894.5	3,256.0	3,147.8	3,147.8
credits [kg_CO_2/$t_{syncrude}$]				
steam 25 bar	315.1	433.3	391.6	391.6
steam 4 bar	0.0	0.0	0.0	0.0
district heating	0.0	243.3	0.0	0.0
electricity	0.0	0.0	0.0	0.0
oxygen (gaseous)	82.4	82.4	259.2	259.2
total credits	397.5	759.0	650.8	650.8
carbon footprint with credits [kg_CO_2/$t_{syncrude}$]				
	2,497.0	2,497.0	2,497.0	2,497.0
carbon footprint with credits [g_CO_2/MJ]				
	56.875	56.875	56.875	56.875

The considering of credits does enhance the carbon foot print of PtL and PBtL fuel enough for use of grid electricity if the best case scenario with 80% wind and 20% natural based power generation is assumed (comp. Table 38). The more realistic “Energiekonzept” cases are still not acceptable for the PtL fuel production, but the “Energiekonzept (minimum)” case for the PBtL process. Depending on the exact composition of grid electricity and possible future improvements in power generation systems, grid electricity could be used for PBtL fuel generation, but during the next decades is will most likely not become an acceptable solution.

For power based biofuel generation processes extra options for a full time and large scale supply with renewable electricity are still essential. The considering of credits can’t overcome this requirement. Especially because it is questionable if future sustainably laws in Germany will allow the use of credits.

9 Potential fuel production in Baden-Württemberg

9.1 Potential for using biomass as carbon source

The annual potential of residual biomass in Baden-Württemberg is 1.32 million tons and 1.37 million tons of straw and dry waste wood, respectively (comp. Chapter 3). This potential represents a sustainable biomass carbon supply of 1.196 million tons every year (comp. Chapter 3). By applying the carbon conservation efficiencies the possible syncrude production via BtL and PBtL could be estimated (comp. Table 2).

BtL refineries are able for an annual syncrude production of 321 kilotons or 131 kilotons of sustainable kerosene. The utilization of all residual biomass in Baden-Württemberg would cover approximately 15% of the total bio kerosene demand in Germany for 2020, which is assumed to be 880 kt/a (BMWi_II, 2014).

Carbon conversion efficiency of PBtL refineries however is with 97.7% four times higher. A production of 1.171 million tons syncrude or rather 485 kilotons kerosene would be possible. If all residual biomass in Baden-Württemberg would be mobilized for PBtL refineries, 55% of the assumed annual bio kerosene demand could be produced for 2020. However are additional 17.6 TWh of electricity required, which must be mostly renewable to fulfill the biofuel sustainability ordinance emission reduction targets (Biokraft-NachV, 2009). The discussion of electricity utilization will follow in the next paragraph 9.2.

Overall it must be concluded, that BtL refineries would be able to produce environmental friendly kerosene, which would match the IATA target. Unfortunately today's biomass potential is too low for a total satisfaction of Germany's bio kerosene demand. Just 15% of the annual necessary 880 kilo tons of bio kerosene could be produced by mobilizing the whole residual biomass of Baden-Württemberg.

Consequently, the quantities of usable biomass must be increased, if BtL shall be used for a future large scale kerosene production. Possible events for an increase of the biomass potential in Baden-Württemberg are a decrease in animal keeping, an expansion of short rotational plants cultivation and shutdown of biogas plants.

Since the last decades, the number of kept animals like cows and pigs is constantly declining (StaLa, 2017). 985,100 cows and 1,951,000 pigs were kept in 2013 and 1,014,986 cows and 2,132,799 pigs in 2010 that is a decline of 3% and 9%, respectively. According to this trend less straw would be utilized as bedding material or animal feed in the future. Consequently, the potential for residual straw would increase. As mentioned before no other alternative for large scale utilization of residual straw is available today. The selling of straw bales for bio fuel production could become an interesting option for farmers to increase their revenue.

The second option, the cultivation of short rotational plants is focused by the ministry for rural area and consumer protection (MLR, 2014). The yield of plants like poplar and willow is between 7 tons to 15 tons per hectare on dry bases (Kaltschmitt M. , 2016) or rather 3.5 tons to 7.5 tons biogenic carbon. Compared to the yield of one hectare forest or cereal field this is multiple times higher. The required area and transportation effort could be reduced and the biomass carbon potential in Baden-Württemberg increased.

Another possible option, to increase the future biomass potential in Baden-Württemberg, could be the shutdown of biogas plants. According to the German Renewable Energy Act (EEG), subsidies for biogas are assigned for 20 years (EEG, 2000). After these 20 years the future of the biogas plants is uncertain, because the production costs for electricity form biogas is too high to be commercially competitive to other renewable or conventional technologies (LU, 2016). For 1,043 biogas plants in Germany the subsidies period ends in 2020 (comp. Figure 15). If biogas plants are shutdown, less biomass for biogas generation would be demanded and the cultivation of typical feedstock plants like maize could be reduced (Kaltschmitt M. , 2016). More cultivation area to plant cereal plants or in the best case short rotational plant could become available, which increases the biomass potential for the bio fuel production.

Figure 15: Development of biogas power generation in Germany (FNZ, 2016)

9.2 Potential for using carbon dioxide as carbon source

3.008 Mio.t and 14.470 Mio.t of carbon dioxide are emitted by cement and power plants in Baden-Württemberg in 2015, respectively (comp. Table 27 and

Table 28). If these amounts of carbon dioxide would be used for green kerosene production via the PtL process, only by utilization of cement plant carbon dioxide, 399 kilotons of green kerosene could be produced and additional 1,920 kilotons from power plant carbon dioxide (comp. Table 39). Overall 2.6 times more green kerosene could be produced than required to cover the sustainable kerosene demand of Germany in 2020 (BMWi_II, 2014). However shutdowns of power plants must be expected in Baden-Württemberg during the next decades (comp. paragraph 6.1.2), but even if just cement plant carbon dioxide is applied as feedstock of PtL refineries, still 45% of the necessary green kerosene could be produced. After the comparison of the production potential for BtL, PBtL and PtL fuel is must be concluded, that the utilization of electricity is essential, if the required kerosene quantities shall be delivered to fulfil the IATA targets.

On the other side PtL refineries must be supplied with renewable electricity, to produce emission reducing kerosene (comp. Table 35). Beside the carbon dioxide from cement and power plants, additional 23.5 TWh and 113.0 TWh of electricity are necessary for the PtL fuel production, respectively. An additional electricity consumption of 12.5% and 60% of the total renewable electricity generation of Germany in 2015 is represented by these values (BMWi, 2015). These large quantities of renewable electricity can't be supplied right now, especially without out decreasing the carbon footprint of grid electricity (comp. Figure 9). All the required electricity for PtL refineries should be generated by new installed power generations systems.

By applying the assumed 8,260 full load hours per year for PtL refineries, the appropriate electricity demand could be calculated. PtL refineries for utilization of cement plant carbon dioxide would have an electrical power consumption of 2.85 GW and to use all power plant carbon dioxide in Baden-Württemberg additional 13.68 GW are necessary. If an average value of 1,500 full load hours per year for renewable electricity generation via solar and wind is assumed (ISE, 2013), 15.69 GW and 75.33 GW of installed capacity would be required for the electricity supply of cement and power plant carbon dioxide using PtL refineries, respectively.

According to the planned expansion of wind and solar energy technologies in Germany, (comp. Table 26) an annual expansion of 5.3 GW installed capacity, combining on-shore wind mills and solar systems, is intended (BMWi, 2015). Therefore, three years and 14 years would be necessary, to install the required electricity generation capacity for cement plant and power plant carbon dioxide utilization in PtL refineries, respectively.

However the planned renewable energy expansion is only intended to deliver grid electricity to replace conventional power plants. Consequently, all the described electricity generation capacities must be installed in addition to the plans of the german government, if the environmental improvements of grid electricity supply shall not be influenced.

All in all it must be concluded, that the expansion pathways of the “Energiekonzept” (comp. Table 26) are ambitious, but by far not enough for a large scale production of sustainable PtL kerosene.

A technical potential for additional wind electricity capacities of 200 GW and 85 GW is assumed for on-shore and off-shore generation systems in Germany, respectively (IWES, 2011). The technical potential for solar electricity generation systems of approximately 400 GW is even larger (ISE_II, 2012). According to the mentioned technical potentials in Germany, only a lack of political will and financial support could prevent a future installation of renewable electricity capacities for the PtL fuel production in Germany. The construction of wind and solar parks, beside the german power supply gird, for PtL refineries should be focused in future projects.

10 Summery and Outlook

In this thesis, three pathways for the production of synthetic jet fuels via FT-Synthesis were ecologically analyzed. Furthermore a model for the calculation of the ecological best biomass supply in Baden-Württemberg by usable straw and waste wood chips was developed and implemented in a VBA macro. All other inputs like electricity, water or oxygen are evaluated by using public assessable literature or databases like ProBas or BioGrace. With the investigated data field-to-gate carbon footprints for sustainable jet fuel are performed (comp. chapter 8).

The expectable carbon footprint range, for green fuel production in Baden-Württemberg, was shown by calculation of ten production scenarios, which are representing the ecologically best and worst input supply. The results indicate that not all production scenarios of synthetic jet fuel are suitable to generate sustainable fuel. Only the BtL process would be able in every analyzed case to produce fuel with a minimum emission reduction of 35% compared to conventional jet fuel (comp. Table 35 and Table 40), which is required by the biofuel sustainability ordinance. If electricity is utilized for the green fuel production, only renewable energy sources allow the production of carbon dioxide saving fuel. The use of grid electricity is not an option for the production of green fuels, which stick to the restrictions of the biofuel sustainability ordinance.

Furthermore, the effect of waste heat, oxygen and electricity credits was analyzed. The application of credits improves the carbon footprint of BtL fuel enormously and even negative carbon footprints were calculated. The carbon footprint of PBtL and PtL fuel is not changed significantly by the consideration of credits.

Beside the carbon footprint of green jet fuel production via FT-synthesis, the production potentials by using biomass, electricity and carbon dioxide were discussed for Baden-Württemberg. A technical potential for the BtL kerosene production of 131 kilotons or 15% of the expected sustainable kerosene demand in Germany 2020 was determined. By using the PBtL process, 485 kilotons of synthetic kerosene could be produced, if only residual straw and waste wood from Baden-Württemberg is used. For the PtL process, a total kerosene production potential of 2,319 Mio.tons was determined, if cement and power plants are used as carbon dioxide source.

The low production potential of the BtL process, in comparisons to the analyzed production potentials of the PBtL and PtL process, indicate that a future utilization of electricity is necessary to fulfill the IATA targets. However, large quantities of renewable electricity would become necessary for the sustainable kerosene production. Consequently, a further and faster expansion of renewable electricity generation capacities would be required. It must be expected, that most difficult challenge for the implementation of PBtL and PtL fuel production, won't be the feedstocks supply of carbon dioxide or biomass, but the large renewable electricity demand.

In further studies more detailed production scenarios must be evaluated. Local potentials for renewable electricity generation in Baden-Württemberg must be investigated in more detail. In case of PtL refineries the connection of carbon dioxide separation and waste heat utilization must be further discussed.

For the evaluation of the economically feasibility costs for feedstock supply must be analyzed. In case of the BtL process costs for biomass harvesting and transportation must be determined. Fulltime supply scenarios for PBtL and PtL refineries must be developed. It should be analyzed, if a use of different generation technologies in different locations could cover the annual refinery electricity demand or if syngas storage would be necessary.

The effort for waste water cleaning was not discussed and considered in the carbon footprint, because the waste water pollution is not known right now. Experimental studies for the investigation of waste water pollution must be performed, before the large scale green fuel production could be started.

Even if some more investigations must be done, the large scale implementation of green fuel refineries and bio kerosene could be considered as technically possible. In the end, the political will and financial support will decide in which quantities synthetic kerosene will be used in the future.

11 Literature

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12 Appendix

Appendix A: Composition of syncrude and product frations with LHV

	carbon content [%]	hydrogen content [%]	LHV (Boie) [MJ/kg]	mass fraction [%]	According to Table 3 $LHV_{frac} = \frac{massfraction_{spec} \cdot LHV_{spec}}{\sum massfraction_{spec}}$			
					Gas	Gasoline	Kerosene	Diesel
CH4	75,00	25,00	49,58	0,012	0,2			
C2H6	80,00	20,00	46,62	0,090	1,3			
C3H8	81,82	18,18	45,55	0,655	9,6			
C4H10	82,76	17,24	44,99	2,350	34,0			
C5H12	83,33	16,67	44,65	5,297		6,4		
C6H14	83,72	16,28	44,42	7,983		9,6		
C7H16	84,00	16,00	44,26	10,054		12,0		
C8H18	84,21	15,79	44,13	10,972		13,1		
C9H20	84,38	15,63	44,03	10,979		3,3	8,9	
C10H22	84,51	15,49	43,96	10,453			11,2	
C11H24	84,62	15,38	43,89	9,958			10,7	
C12H26	84,71	15,29	43,84	8,652			4,6	11,0
C13H28	84,78	15,22	43,79	5,405			2,9	6,9
C14H30	84,85	15,15	43,75	4,295			2,3	5,5
C15H32	84,91	15,09	43,72	3,469			1,9	4,4
C16H34	84,96	15,04	43,69	2,673			1,4	3,4
C17H36	85,00	15,00	43,67	1,987				5,0
C18H38	85,04	14,96	43,64	1,423				3,6
C19H40	85,07	14,93	43,62	0,959				2,4
C20H42	85,11	14,89	43,60	0,595				1,5
				LHV_{frac} [MJ/kg]	**45,2**	**44,3**	**43,9**	**43,7**

Appendix B: Names and Abbrevation for counties and cities in Baden-Württemberg

German name	**Abbrevation**	**German name**	**Abbrevation**
Stuttgart, Kreisfreie Stadt	Stu, T	Calw, Landkreis	Calw, C
Böblingen, Landkreis	Böb, C	Enzkreis	Enz, C
Esslingen, Landkreis	Ess, C	Freudenstadt, Landkreis	Freu, L
Ludwigsburg, Landkreis	Lud, C	Göppingen, Landkreis	Göp, C
Freiburg im Breisgau, Kreis-freie Stadt	Frei, T	Breisgau-Hochschwarzwald, Landkreis	BHK
Rems-Murr-Kreis	RMK, C	Emmendingen, Landkreis	Emme, C
Heilbronn, Kreisfreie Stadt	Heil, T	Ortenaukreis	Orten, C
Heilbronn, Landkreis	Heil, C	Rottweil, Landkreis	Rott, C
Hohenlohekreis	HLK, C	Schwarzwald-Baar-Kreis	SBK, C
Schwäbisch Hall, Landkreis	SH, C	Tuttlingen, Landkreis	Tutt, C
Main-Tauber-Kreis	MTK, C	Konstanz, Landkreis	Kons, C
Heidenheim, Landkreis	Heid, C	Lörrach, Landkreis	Lörr, C
Ostalbkreis	OAK, C	Waldshut, Landkreis	Wald, C
Baden-Baden, Kreisfreie Stadt	Baden, T	Reutlingen, Landkreis	Reut, C
Karlsruhe, Kreisfreie Stadt	Karl, T	Tübingen, Landkreis	Tüb, C
Karlsruhe, Landkreis	Karl, C	Zollernalbkreis	ZAK, C
Rastatt, Landkreis	Rast, C	Ulm, Kreisfreie Stadt	Ulm, T
Heidelberg, Kreisfreie Stadt	Heidel, T	Alb-Donau-Kreis	ADK, C
Mannheim, Kreisfreie Stadt	Mann, T	Biberach, Landkreis	Bib, C
Neckar-Odenwald-Kreis	NOK, C	Bodenseekreis	BSK, C
Rhein-Neckar-Kreis	RNK, C	Ravensburg, Landkreis	Rav, C
Pforzheim, Kreisfreie Stadt	Pfor, T	Sigmaringen, Landkreis	Sig, C

Appendix C: Middle to middle distance between counties and cities in Baden-Würrtemberg

	Stu, T	Böb, C	Ess, C	Göp, C	Lud, C	RMK, C	Heil, T	Heil, C	HLK, C	SH, C	MTK, C
Stu, T	5	28.8	37.3	47.9	15.6	38.8	61.5	60.6	79.9	70.9	118
Böb, C	28.8	5	50.9	70.3	45.7	67.1	85	83.9	103	107	141
Ess, C	37.3	50.9	5	32.9	51.7	50.3	103	102	118	93	159
Göp, C	47.9	70.3	32.9	5	59.4	39.7	105	104	87.3	68	129
Lud, C	15.6	45.7	51.7	59.4	5	30.4	36	45	64.2	67.5	102
RMK, C	38.8	67.1	50.3	39.7	30.4	5	50.6	57.4	61.4	42.1	115
Heil, T	61.5	85	103	105	36	50.6	5	16.6	37.2	50.9	79.8
Heil, C	60.6	83.9	102	104	45	57.4	16.6	5	54.2	68.6	92.4
HLK, C	79.9	103	118	87.3	64.2	61.4	37.2	54.2	5	22.2	50.2
SH, C	70.9	107	93	68	67.5	42.1	50.9	68.6	22.2	5	63.5
MTK, C	118	141	159	129	102	115	79.8	92.4	50.2	63.5	5
Heid, C	93.2	109	74.1	45.1	96.9	70.8	134	146	97.9	77.9	138
OAK, C	81.7	110	78.1	56.8	93	54	92.6	120	71.7	50	97.9
Baden, T	108	109	130	149	109	145	108	96.1	152	169	187
Karl, T	77.2	76.1	97.3	116	69.9	113	68.1	55.8	112	134	150
Karl, C	50.4	55.4	76.5	94.2	43.6	91.8	53.5	39.3	103	116	141
Rast,C	97.2	79.1	120	150	99.8	146	110	97.4	154	166	188
Heidel, T	126	131	155	159	110	123	62.4	52.4	104	119	106
Mann, T	133	138	162	177	117	130	81.4	71.5	111	126	126
NOK, C	98.1	120	139	141	79.7	92.7	43.7	52.8	51	70.2	51.4
RNK, C	98.8	115	139	143	82.1	96.2	46.4	36.4	77.2	92.1	102
Pfor, T	50.2	49	73.1	94.1	46.8	87.6	56.8	47.5	111	114	149
Calw, C	56.9	43.7	86.4	105	66	96.2	95.5	90.3	122	126	160
Enz, C	46.3	54.5	82.6	90.1	39.5	69.5	47.4	31.6	99.9	115	138
Freu, L	91.2	68.4	96.8	130	101	130	138	121	157	172	204
Frei, T	183	156	207	226	202	222	207	195	253	268	292
BHK	192	173	216	235	211	231	215	203	261	276	300
Emme, C	177	157	200	219	194	216	193	180	239	254	271
Orten, C	148	135	181	204	165	197	164	152	210	225	243
Rott, C	99.5	63	89.7	136	118	137	131	137	157	161	195
SBK, C	119	99.2	120	161	137	158	167	174	193	190	231
Tutt, C	113	93.5	103	149	139	151	175	178	202	199	240
Kons, C	149	130	150	192	168	189	197	204	224	221	262
Lörr, C	207	187	230	249	225	246	262	261	281	296	319
Wald, C	185	165	191	227	203	224	233	240	260	275	298
Reut, C	57.3	55.6	33.4	61	78.9	95.5	115	122	142	128	180
Tüb, C	47.4	28.1	37.6	68.8	71.7	151	105	108	130	136	170
ZAK, C	72.7	53.4	62.8	94.1	97	111	131	137	157	161	195
Ulm, T	91.2	106	66.6	51	102	82.5	152	158	144	124	184
ADK, C	75.9	78.6	47	44.6	104	71	136	141	162	149	200
Bib, C	114	112	87.8	96.1	146	130	179	179	204	162	222
BSK, C	161	162	132	152	190	190	226	251	260	218	278
Rav, C	146	137	119	122	171	159	221	228	207	187	247
Sig, C	105	85.6	89.9	109	133	143	163	170	190	175	227

	Heid, C	OAK, C	Baden, T	Karl, T	Karl, C	Rast, C	Heidel, T	Mann, T	NOK, C	RNK, C	Pfor, T
Stu, T	93.2	81.7	108	77.2	50.4	97.2	126	133	98.1	98.8	50.2
Böb, C	109	110	109	76.1	55.4	79.1	131	138	120	115	49
Ess, C	74.1	78.1	130	97.3	76.5	120	155	162	139	139	73.1
Göp, C	45.1	56.8	149	116	94.2	150	159	177	141	143	94.1
Lud, C	96.9	93	109	69.9	43.6	99.8	110	117	79.7	82.1	46.8
RMK, C	70.8	54	145	113	91.8	146	123	130	92.7	96.2	87.6
Heil, T	134	92.6	108	68.1	53.5	110	62.4	81.4	43.7	46.4	56.8
Heil, C	146	120	96.1	55.8	39.3	97.4	52.4	71.5	52.8	36.4	47.5
HLK, C	97.9	71.7	152	112	103	154	104	111	51	77.2	111
SH, C	77.9	50	169	134	116	166	119	126	70.2	92.1	114
MTK, C	138	97.9	187	150	141	188	106	126	51.4	102	149
Heid, C	5	31.5	204	155	134	205	212	218	185	159	149
OAK, C	31.5	5	188	155	135	189	164	171	161	143	133
Baden, T	204	188	5	39.4	61.4	16.2	92.5	104	134	88.9	55.7
Karl, T	155	155	39.4	5	27.5	41.9	57.3	65.3	94.9	53.7	24.6
Karl, C	134	135	61.4	27.5	5	54.9	86.5	94.5	85.7	59.5	8.4
Rast,C	205	189	16.2	41.9	54.9	5	94.6	103	136	91.1	39.4
Heidel, T	212	164	92.5	57.3	86.5	94.6	5	20.9	58.3	20	78.2
Mann, T	218	171	104	65.3	94.5	103	20.9	5	78.2	40.9	90.2
NOK, C	185	161	134	94.9	85.7	136	58.3	78.2	5	50.1	97.6
RNK, C	159	143	88.9	53.7	59.5	91.1	20	40.9	50.1	5	68
Pfor, T	149	133	55.7	24.6	8.4	39.4	78.2	90.2	97.6	68	5
Calw, C	161	146	59.1	47.1	44	43.9	114	120	151	109	32.9
Enz, C	139	123	65.2	29.7	7.7	67.3	73	76.4	86.5	57	16.4
Freu, L	189	170	54.5	77.7	74.6	39.3	135	142	175	130	63.6
Frei, T	302	287	107	139	160	130	194	201	234	189	155
BHK	310	276	115	147	168	138	202	209	242	197	163
Emme, C	288	272	92.7	125	146	115	180	186	219	175	141
Orten, C	259	243	64	96.2	117	86.5	151	158	191	146	112
Rott, C	181	165	92.7	108	105	77.5	174	180	186	169	94.2
SBK, C	200	201	124	156	148	105	212	218	222	207	137
Tutt, C	188	194	137	95.5	156	122	237	243	230	220	145
Kons, C	175	198	181	200	179	144	259	266	253	242	167
Lörr, C	324	289	181	213	234	203	268	274	307	263	229
Wald, C	255	267	180	212	214	180	267	273	288	262	210
Reut, C	84.7	127	141	118	96.6	126	177	183	170	154	92.1
Tüb, C	123	129	101	95.5	86.7	86	165	173	146	150	72.6
ZAK, C	148	154	113	124	112	97.6	192	199	186	169	108
Ulm, T	149	80.1	185	154	133	170	213	220	207	197	128
ADK, C	62.1	78.3	169	138	117	154	198	204	191	181	111
Bib, C	93.9	117	218	198	177	213	234	240	227	217	149
BSK, C	150	174	228	222	201	191	281	287	274	290	196
Rav, C	119	143	255	224	202	203	283	272	259	266	180
Sig, C	144	167	155	165	144	140	225	231	218	208	140

	Calw, C	Enz, C	Freu, L	Frei, T	BHK	Emme, C	Orten, C	Rott, C	SBK, C	Tutt, C	Kons, C
Stu, T	56.9	46.3	91.2	183	192	177	148	99.5	119	113	149
Böb, C	43.7	54.5	68.4	156	173	157	135	63	99.2	93.5	130
Ess, C	86.4	82.6	96.8	207	216	200	181	89.7	120	103	150
Göp, C	105	90.1	130	226	235	219	204	136	161	149	192
Lud, C	66	39.5	101	202	211	194	165	118	137	139	168
RMK, C	96.2	69.5	130	222	231	216	197	137	158	151	189
Heil, T	95.5	47.4	138	207	215	193	164	131	167	175	197
Heil, C	90.3	31.6	121	195	203	180	152	137	174	178	204
HLK, C	122	99.9	157	253	261	239	210	157	193	202	224
SH, C	126	115	172	268	276	254	225	161	190	199	221
MTK, C	160	138	204	292	300	271	243	195	231	240	262
Heid, C	161	139	189	302	310	288	259	181	200	188	175
OAK, C	146	123	170	287	276	272	243	165	201	194	198
Baden, T	59.1	65.2	54.5	107	115	92.7	64	92.7	124	137	181
Karl, T	47.1	29.7	77.7	139	147	125	96.2	108	156	95.5	200
Karl, C	44	7.7	74.6	160	168	146	117	105	148	156	179
Rast,C	43.9	67.3	39.3	130	138	115	86.5	77.5	105	122	144
Heidel, T	114	73	135	194	202	180	151	174	212	237	259
Mann, T	120	76.4	142	201	209	186	158	180	218	243	266
NOK, C	151	86.5	175	234	242	219	191	186	222	230	253
RNK, C	109	57	130	189	197	175	146	169	207	220	242
Pfor, T	32.9	16.4	63.6	155	163	141	112	94.2	137	145	167
Calw, C	5	49.9	37.1	152	161	138	109	67.8	95.4	112	135
Enz, C	49.9	5	82.3	168	176	154	125	120	156	164	186
Freu, L	37.1	82.3	5	100	109	93.8	66	37.5	67	83.9	106
Frei, T	152	168	100	5	10.3	25.3	60	80.4	60.2	93.6	100
BHK	161	176	109	10.3	5	34.2	68.5	117	67	106	107
Emme, C	138	154	93.8	25.3	34.2	5	36.3	81.5	68.3	102	122
Orten, C	109	125	66	60	68.5	36.3	5	66.2	72.2	107	122
Rott, C	67.8	120	37.5	80.4	117	81.5	66.2	5	39.1	44.5	82.9
SBK, C	95.4	156	67	60.2	67	68.3	72.2	39.1	5	38.8	58.9
Tutt, C	112	164	83.9	93.6	106	102	107	44.5	38.8	5	33.2
Kons, C	135	186	106	100	107	122	122	82.9	58.9	33.2	5
Lörr, C	197	242	164	53.6	51.5	82	112	140	86	118	119
Wald, C	170	222	142	74.7	67.9	104	134	118	76.5	83	84.2
Reut, C	101	104	103	179	185	172	157	90.6	117	88.6	95.6
Tüb, C	53	94.4	63.7	155	162	150	129	55.5	93.9	76.1	113
ZAK, C	66.5	120	63.7	129	136	123	108	37.9	60.5	48.4	72.9
Ulm, T	142	141	173	207	213	236	241	146	155	124	124
ADK, C	127	123	127	216	223	234	225	119	149	122	116
Bib, C	138	184	136	178	185	207	176	106	126	95.6	83.9
BSK, C	172	208	153	147	154	176	176	122	106	70.3	48.2
Rav, C	172	210	162	181	188	210	196	122	131	100	82.9
Sig, C	108	152	102	130	136	149	133	66.1	77.6	47.4	39.6

	Lörr, C	Wald, C	Reut, C	Tüb, C	ZAK, C	Ulm, T	ADK, C	Bib, C	BSK, C	Rav, C	Sig, C
Stu, T	207	185	57.3	47.4	72.7	91.2	75.9	114	161	146	105
Böb, C	187	165	55.6	28.1	53.4	106	78.6	112	162	137	85.6
Ess, C	230	191	33.4	37.6	62.8	66.6	47	87.8	132	119	89.9
Göp, C	249	227	61	68.8	94.1	51	44.6	96.1	152	122	109
Lud, C	225	203	78.9	71.7	97	102	104	146	190	171	133
RMK, C	246	224	95.5	151	111	82.5	71	130	190	159	143
Heil, T	262	233	115	105	131	152	136	179	226	221	163
Heil, C	261	240	122	108	137	158	141	179	251	228	170
HLK, C	281	260	142	130	157	144	162	204	260	207	190
SH, C	296	275	128	136	161	124	149	162	218	187	175
MTK, C	319	298	180	170	195	184	200	222	278	247	227
Heid, C	324	255	84.7	123	148	149	62.1	93.9	150	119	144
OAK, C	289	267	127	129	154	80.1	78.3	117	174	143	167
Baden, T	181	180	141	101	113	185	169	218	228	255	155
Karl, T	213	212	118	95.5	124	154	138	198	222	224	165
Karl, C	234	214	96.6	86.7	112	133	117	177	201	202	144
Rast,C	203	180	126	86	97.6	170	154	213	191	203	140
Heidel, T	268	267	177	165	192	213	198	234	281	283	225
Mann, T	274	273	183	173	199	220	204	240	287	272	231
NOK, C	307	288	170	146	186	207	191	227	274	259	218
RNK, C	263	262	154	150	169	197	181	217	290	266	208
Pfor, T	229	210	92.1	72.6	108	128	111	149	196	180	140
Calw, C	197	170	101	53	66.5	142	127	138	172	172	108
Enz, C	242	222	104	94.4	120	141	123	184	208	210	152
Freu, L	164	142	103	63.7	63.7	173	127	136	153	162	102
Frei, T	53.6	74.7	179	155	129	207	216	178	147	181	130
BHK	51.5	67.9	185	162	136	213	223	185	154	188	136
Emme, C	82	104	172	150	123	236	234	207	176	210	149
Orten, C	112	134	157	129	108	241	225	176	176	196	133
Rott, C	140	118	90.6	55.5	37.9	146	119	106	122	122	66.1
SBK, C	86	76.5	117	93.9	60.5	155	149	126	106	131	77.6
Tutt, C	118	83	88.6	76.1	48.4	124	122	95.6	70.3	100	47.4
Kons, C	119	84.2	95.6	113	72.9	124	116	83.9	48.2	82.9	39.6
Lörr, C	5	50.3	198	179	153	226	235	197	164	200	149
Wald, C	50.3	5	161	160	134	208	190	162	121	155	114
Reut, C	198	161	5	39.3	55.9	65.1	37.8	59.6	98.7	83.8	52
Tüb, C	179	160	39.3	5	33.5	90.2	67.6	90.6	122	115	65.7
ZAK, C	153	134	55.9	33.5	5	102	87.3	79.8	102	104	42.4
Ulm, T	226	208	65.1	90.2	102	5	24.4	46.2	102	71.8	80.5
ADK, C	235	190	37.8	67.6	87.3	24.4	5	50.9	111	80.5	77.8
Bib, C	197	162	59.6	90.6	79.8	46.2	50.9	5	67.4	37.2	51.8
BSK, C	164	121	98.7	122	102	102	111	67.4	5	37.9	54.7
Rav, C	200	155	83.8	115	104	71.8	80.5	37.2	37.9	5	60.8
Sig, C	149	114	52	65.7	42.4	80.5	77.8	51.8	54.7	60.8	5

Appendix D, part 1: Residual biomass in Baden-Württemberg

	cultivation area [ha]					
	Wheat	**Rye**	**Winter B.**	**Summer B.**	**Oat**	**Triticale**
Stu, T	445	0	42	247	41	0
Böb, C	4919	108	1230	3189	694	210
Ess, C	3016	95	928	984	418	129
Göp, C	3313	73	1993	1214	647	495
Lud, C	7890	148	1997	3486	342	98
RMK, C	3164	79	1607	612	478	289
Heil, T	1005	0	10	808	11	0
Heil, C	13701	758	2349	6767	342	558
HLK, C	9759	112	6385	1105	854	695
SH, C	14737	160	12279	1474	2221	2546
MTK, C	18952	954	7868	10560	776	883
Heid, C	5320	140	2196	2131	632	642
OAK, C	8968	193	8015	2176	1067	917
Baden, T	57	0	42	0	7	0
Karl, T	363	34	112	36	38	32
Karl, C	7675	1880	1603	3501	464	197
Rast,C	1467	353	401	511	200	256
Heidel, T	294	0	92	384	13	0
Mann, T	635	79	112	488	29	0
NOK, C	11713	500	4237	3844	1052	683
RNK, C	8863	611	2511	3677	390	180
Pfor, T	146	17	54	0	43	0
Calw, C	2218	115	816	1523	603	201
Enz, C	3747	273	989	1289	418	151
Freu, L	2768	124	1004	1114	712	303
Frei, T	130	0	8	21	37	33
BHK	2357	278	466	1030	302	262
Emme, C	1148	157	212	262	216	356
Orten, C	4185	0	908	818	355	410
Rott, C	4411	67	2651	1392	1716	708
SBK, C	3699	157	2238	1589	701	1131
Tutt, C	2134	110	1045	1304	519	429
Kons, C	4593	358	2554	1602	636	319
Lörr, C	1546	79	470	62	209	211
Wald, C	2966	89	1669	1694	749	947
Reut, C	4665	69	2002	3679	1243	903
Tüb, C	4878	145	964	1579	806	304
ZAK, C	3708	181	1010	1517	1856	329
Ulm, T	1337	67	668	503	87	80
ADK, C	16788	145	9652	7694	1862	1539
Bib, C	13977	255	8070	3714	2350	991
BSK, C	2655	34	1332	396	362	118
Rav, C	5116	107	3049	875	879	413
Sig, C	9208	170	6069	2799	2698	911

Appendix D, part 2: Residual biomass in Baden-Württemberg

	yield [t/ha]						straw production [t]						
	Wheat	Rye	W. B.	S. B.	Oat	Tri	Wheat	Rye	W. B.	S. B.	Oat	Triticale	total
Stu, T	8,35	5,63	7,64	5,84	4,81	7,62	2973	0	225	1154	217	0	4568
Böb, C	9,23	5,63	7,87	7,04	4,81	7,62	36322	547	6776	17960	3672	1440	66718
Ess, C	7,55	5,63	7,23	6,68	4,81	7,62	18217	481	4697	5258	2212	885	31749
Göp, C	7,96	5,63	7,95	5,84	4,81	7,62	21097	370	11091	5672	3423	3395	45048
Lud, C	8,21	5,63	7,94	4,81	4,95	7,62	51822	750	11099	13414	1862	672	79619
RMK, C	7,41	5,63	6,86	5,74	4,73	6,07	18756	400	7717	2810	2487	1579	33749
Heil, T	8,35	5,63	7,64	5,84	4,81	7,62	6713	0	53	3775	58	0	10600
Heil, C	8,55	5,63	7,71	6,29	4,81	7,62	93715	3841	12678	34052	1810	3827	149921
HLK, C	8,88	5,63	7,85	6,11	4,09	7,85	69328	568	35086	5401	3842	4910	119135
SH, C	9,04	5,63	8,06	6,02	6,08	8,22	106578	811	69278	7099	14854	18835	217455
MTK, C	8	6,3	7,25	5,64	4,07	7,02	121293	5409	39930	47647	3474	5579	223332
Heid, C	7,5	5,63	7,64	5,84	4,81	7,62	31920	709	11744	9956	3344	4403	62076
OAK, C	8,71	5,63	8,01	6,93	3,94	7,42	62489	978	44940	12064	4624	6124	131219
Baden, T	7,8	4,6	6,91	5,69	4,42	5,43	356	0	203	0	34	0	593
Karl, T	7,8	4,6	6,91	5,69	4,42	5,43	2265	141	542	164	185	156	3453
Karl, C	7,86	4,56	7,35	5,46	4,07	5,43	48260	7716	8247	15292	2077	963	82556
Rast,C	7,8	4,6	6,91	5,69	4,42	5,43	9154	1461	1940	2326	972	1251	17105
Heidel, T	7,8	4,6	6,91	5,69	4,42	5,43	1835	0	445	1748	63	0	4091
Mann, T	7,8	4,6	6,91	5,69	4,42	5,43	3962	327	542	2221	141	0	7194
NOK, C	8,06	4,6	6,56	5,58	5,11	5,43	75525	2070	19456	17160	5913	3338	123462
RNK, C	7,29	4,6	6,7	5,71	3,99	5,43	51689	2530	11777	16797	1712	880	85383
Pfor, T	7,8	4,6	6,91	5,69	4,42	5,43	911	70	261	0	209	0	1452
Calw, C	9,04	4,6	7,42	6,09	5	5,43	16041	476	4238	7420	3317	982	32474
Enz, C	7,08	4,6	7,04	5,69	4,42	5,43	21223	1130	4874	5868	2032	738	35865
Freu, L	9,6	4,6	8,01	5,88	5,05	5,43	21258	513	5629	5240	3955	1481	38077
Frei, T	8,37	5,89	7,41	5,63	5,42	7,36	870	0	41	95	221	219	1446
BHK	9,51	5,89	7,41	6,03	5,42	7,36	17932	1474	2417	4969	1801	1735	30328
Emme, C	8,11	5,89	7,41	5,63	5,42	7,36	7448	832	1100	1180	1288	2358	14206
Orten, C	8,36	5,89	6,48	5,63	5,42	7,23	27989	0	4119	3684	2117	2668	40577
Rott, C	8,61	5,89	7,23	5,53	5,7	7,28	30383	355	13417	6158	10759	4639	65711
SBK, C	9,06	5,89	8,21	4,72	5,03	7,78	26810	832	12862	6000	3879	7919	58302
Tutt, C	7,76	5,89	8,11	5,7	5,08	6,42	13248	583	5932	5946	2900	2479	31089
Kons, C	7,63	5,89	6,71	6,42	5,27	7,36	28036	1898	11996	8228	3687	2113	55957
Lörr, C	8,37	5,89	7,41	5,63	5,42	7,36	10352	419	2438	279	1246	1398	16132
Wald, C	7,11	5,89	7,09	6,15	5,29	7,88	16871	472	8283	8334	4358	6716	45035
Reut, C	7,19	6,15	7,69	6,35	5,9	6,38	26833	382	10777	18689	8067	5185	69933
Tüb, C	8,27	6,15	7,95	6,48	5,85	7,72	32273	803	5365	8186	5187	2112	53924
ZAK, C	7,9	6,15	7,9	6,07	5,72	7,72	23435	1002	5585	7367	11678	2286	51352
Ulm, T	8,7	6,15	7,95	6,48	5,85	7,72	9306	371	3717	2608	560	556	17117
ADK, C	9,12	6,15	8,07	7,12	5,92	7,72	67182	941	34284	15943	17569	6330	142248
Bib, C	9,42	6,15	8,43	6,45	6,33	8,74	105331	1411	47621	19164	16363	7795	197686
BSK, C	8,7	6,15	7,86	6,48	5,85	7,72	18479	188	7329	2053	2329	820	31198
Rav, C	9,18	6,15	7,37	6,48	5,85	7,72	37572	592	15730	4536	5656	2870	66956
Sig, C	9,12	6,15	8,07	7,12	5,92	7,72	67182	941	34284	15943	17569	6330	142248

Appendix D, part 3: Residual biomass in Baden-Württemberg

	animals	straw demand		residual biomass		carbon
	[LU]	animals [t]	humus [t]	straw [t]	wood [t]	
Stu, T	969	658,92	1563,6844	2345,5266	4972	3394
Böb, C	11687	7947,16	23508,2496	35262,3744	21397	24345
Ess, C	11159	7588,12	9664,5236	14496,7854	18750	14985
Göp, C	28015	19050,2	10399,086	15598,629	20667	16370
Lud, C	16816	11434,88	27273,7136	40910,5704	12494	22079
RMK, C	20153	13704,04	8018,1616	12027,2424	33652	21481
Heil, T	325	221	4151,6228	6227,4342	1419	3120
Heil, C	16001	10880,68	55616,1316	83424,1974	28105	46338
HLK, C	37196	25293,28	37536,5184	56304,7776	21895	32737
SH, C	98978	67305,04	60059,9688	90089,9532	47032	58381
MTK, C	30447	20703,96	81051,1144	121576,6716	38624	66362
Heid, C	23761	16157,48	18367,5552	27551,3328	26969	24147
OAK, C	72635	49391,8	32730,8432	49096,2648	59330	48665
Baden, T	355	241,4	140,5872	210,8808	8634	4399
Karl, T	563	382,84	1227,9184	1841,8776	4527	2976
Karl, C	7410	5038,8	31006,796	46510,194	36756	36377
Rast,C	3540	2407,2	5878,9924	8818,4886	37514	22170
Heidel, T	637	433,16	1463,0312	2194,5468	4431	3065
Mann, T	532	361,76	2732,7272	4099,0908	1812	2492
NOK, C	23412	15920,16	43016,9188	64525,3782	47438	48690
RNK, C	14188	9647,84	30294,0848	45441,1272	37901	36536
Pfor, T	345	234,6	486,8336	730,2504	5025	2795
Calw, C	11670	7935,6	9815,2892	14722,9338	49278	30337
Enz, C	9891	6725,88	11655,5684	17483,3526	21959	17746
Freu, L	12279	8349,72	11890,994	17836,491	54628	34217
Frei, T	972	660,96	313,9144	470,8716	6563	3464
BHK	26147	17779,96	5019,0592	7528,5888	65591	35709
Emme, C	12715	8646,2	2223,9636	3335,9454	31128	16855
Orten, C	27933	18994,44	8632,872	12949,308	87498	48760
Rott, C	19049	12953,32	21103,148	31654,722	33028	28764
SBK, C	28175	19159	15657,3416	23486,0124	46951	32565
Tutt, C	14416	9802,88	8514,2964	12771,4446	36733	23309
Kons, C	23014	15649,52	16123,1472	24184,7208	27402	23060
Lörr, C	14088	9579,84	2620,726	3931,089	41616	22329
Wald, C	29736	20220,48	9925,6796	14888,5194	55793	33658
Reut, C	28074	19090,32	20337,1428	30505,7142	39706	31659
Tüb, C	7724	5252,32	19468,8404	29203,2606	17963	20283
ZAK, C	14338	9749,84	16640,9004	24961,3506	37392	28356
Ulm, T	3868	2630,24	5794,7128	8692,0692	2291	4509
ADK, C	72085	49017,8	72394,2016	108591,3024	40259	62154
Bib, C	89026	60537,68	54859,1932	71472,4872	40179	47749
BSK, C	23458	15951,44	6098,5648	9147,8472	18638	12859
Rav, C	124975	84983	-7210,8684	0	46917	23459
Sig, C	40861	27785,48	45785,1708	68677,7562	46774	49965