TECHNO-ECONOMIC ASSESSMENT OF CONVERSION PROCESSES FOR BIOMASS TO PRODUCTS

–

TECHNOLOGY CONCEPTS FOR THE CONVERSION OF BIOMASS AND BIOGENIC RESIDUES

By

Nils Jäger

A thesis submitted to the University of Birmingham for the degree of

DOCTOR OF PHILOSOPHY

Department of Chemical Engineering
College of Engineering and Physical Sciences
University of Birmingham

January 2018

ABSTRACT

Within the framework of this techno-economic assessment, the possible contribution of the platform technology Thermo-Catalytic Reforming (TCR®) to reduce CO_2 emissions, save resources, and solve waste problems was evaluated. The selection of the feedstocks included samples of sewage sludge, woody biomass, algae, organic fraction of municipal solid waste, leather residues, peat, lignite, and selected mixtures thereof. These feedstocks were processed in a lab-scale TCR plant with a capacity of 2 kg/h and converted into oil, gas, and carbonisates. It is targeted to utilize these products as substitutes for fossil resources for energetic and material usage. For each feedstock, optimum process parameters, correlations regarding feedstock and product composition and yields, and measures to optimize the technology, were identified. The experimental results were used as a basis for the economic evaluation. To identify promising value chains, the levelized costs/levelized revenues approach was adopted for multi-product processes. State of the art technologies and the products thereof were the benchmark. By linking the results of the technical and economic evaluation, the optimum utilization pathways for the processed feedstocks, related products, and potentials to increase the competitiveness of the technology were identified.

to my beloved parents

ACKNOWLEDGEMENTS

The present Ph.D. thesis was elaborated under the framework with close collaboration of the University of Birmingham and Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT.

First and foremost, I express my special thanks to Prof. Dr. Andreas Hornung for the opportunity to prepare this thesis under the umbrella of Fraunhofer and the University of Birmingham. I would like to thank Prof. Dr. Hornung for the constructive scientific support beyond the monthly monitoring meetings. In the same breath, I would like to thank my co-supervisor, Prof. Dr. Joe Wood, and my former co-supervisor, Prof. Dr. Gary Leeke, for their guidance.

Further thanks are addressed to the Department of Renewable Energy of Fraunhofer UMSICHT. Particularly, I want to thank my head of department, Dr.-Ing. Robert Daschner, and my group leader Dr. Andreas Apfelbacher. This work was supported by the interplay of intense dialogue and development opportunities of the aforementioned parties.

It was my pleasure to work with Dr. Roberto Conti, Dr. Peter Hense, Johannes Neumann, and Simon Meidenbauer. Special thanks for the support and open, constructive discussions. I would also like to cordially thank the technical team of Fraunhofer UMSICHT for their great support.

I would like to acknowledge my family, friends, and especially my girlfriend who supported me throughout the last three intense years.

Last but not least, I would like to express my gratitude to my parents. I am eternally grateful for your endless commitment and support.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF FORMULAS

LIST OF ABBREVIATIONS

BBQ	*Barbeque*
BtL	*Biomass to Liquids*
BtP	*Biomass to Products*
BUND	*Association for environmental and nature protection (NGO)*
CCS	*Carbon Capture and Sequestration*
CHP	*Combined Heat and Power*
COD	*Chemical Oxygen Demand*
DME	*Dimethyl Ether*
DSC	*Differential Scanning Calorimetry*
DSS	*Digested Sewage Sludge*
DVGW	*German technical and scientific Association for Gas and Water*
EBC	*European Biochar Foundation*
EDXRF	*Energy Dispersive X-Ray Fluorescence*
EEG	*Germany's Renewable Energy Sources Act*
EO	*Evergreen Oak pruning residues*
ESP	*Electrostatic Precipitator*
FID	*Flame Ionization Detector*
GC	*Gas Chromatograph*
GC-MS	*Gas Chromatography/Mass Spectrometry*
HDN	*Hydrodenitrogenation*
HHV	*Higher Heating Value*
IBI	*International Biochar Initiative*
IEA	*International Energy Agency*
ISS	*Industrial Sewage Sludge*
LC	*Levelized unit Costs*
LHV	*Lower Heating Value*
LLR	*Limed Leather Residues*
LR	*Levelized unit Revenues*
mLR	*mixed Levelized Revenues*
MSW	*Municipal Solid Waste*
NPV	*Net Present Value*
OL	*Olive pruning residues*
oMSW	*organic fraction of Municipal Solid Waste*

Opex	*Operational expenditures*
PSA	*Pressure Swing Adsorption*
RSS	*Raw Sewage Sludge*
SWF	*Swarf*
TAN	*Total Acid Number*
TCD	*Thermal Conductivity Detector*
TCR	*Thermo-Catalytic Reforming*
TGA	*Thermal Gravimetric Analysis*
VS	*Vine Shoots*
waf	*water and ash free*
WEO	*World Energy Outlook*

1 INTRODUCTION

The global energy mix is strongly depending on fossil fuels. To meet the climate targets regarding carbon dioxide reductions, it is mandatory to reduce the consumption of non-renewable carbon sources. Despite the effort of individual countries to replace fossil fuels, their current share of approximately 81% is still at the same level as they were 25 years ago [1].
For the heat and power sector, the expansion of solar and wind energy is the primary approach to substitute fossil energy carriers. One of the main challenges in this context is the fluctuation of these alternative sources, which must be compensated to meet the demand.

Unfortunately, the intuitive expectation that an increase of solar and wind power capacities from the perspective of a large area could mitigate this effect is not correct. Linnemann and Vallana disproved this assumption and proved that negative and positive peak loads reinforce even in a European perspective. [2–4]

To avoid reducing the possible output of wind and solar power stations in periods with peak production and the fall back on fossil fuels like natural gas within periods of low wind and solar production, energy storage systems with high capacity are needed. However, today's market approved storage systems are only able to cover output and input over a short period [5].
This requires the conjunction of different technologies. Biomass is one building block for a sustainable and demand-oriented heat and power supply. However, there are also high expectations that these resources should contribute to a sustainable transport sector. Only a holistic perspective in the climate debate is ecologically beneficial. For

example, Crutzen and coworkers have reported that first and second-generation biofuels emit over the whole life cycle more climate-relevant gases than fossil fuels counterparts. Therefore, these types of biofuels are not sustainable because they contribute more to climate change than fossil fuels. [6]

The substitution of fossil fuels in the material utilization is even more difficult. The industrial value chains are designed and optimized for fossil fuels. Hence the integration of biogenic feedstocks is difficult. Thus, many sectors in the European Union and especially in Germany are highly dependent on oil and gas imports.

One sector is the organic chemical industry, which is mainly based on carbon compounds. Over 85% of the yearly carbon consumption of 20 million tons in Germany is based on fossil resources. 14.8 million tons are derivates of petroleum, 2.2 million tons natural gas, and 0.4 million tons are coal-related raw materials. Although the utilization of biomass to products is well established in the chemical industry, only approximately 13% of the feedstocks in organic chemistry in Germany are from renewable resources. The reason is that the utilization of biomass is only established in processes with a technical and economic advantage or where biomass has a unique selling point over fossil fuels. Examples of these process chains are cellulose, starch, sugar, natural rubber, vegetable and animal oils and fats. However, only 35% of the consumed biomass is produced in Germany. Due to the limited availability of land and the climate conditions in Germany, over 65% of this biomass has to be imported. [7]

Consequently, the substitution of coal, natural gas, and oil coming from fossil resources would have a significant impact on the reduction of carbon dioxide emissions and the dependency on imports at the same time. The goal must be to create a substitute for fossil resources that can be utilized in the same infrastructure and processes with no or only minor adjustments. The market entry barriers for these kinds of products would then be lower.

Within this framework, the purpose of this work is to evaluate the possible contribution of the platform technology Thermo-Catalytic Reforming (TCR®[1]) using biogenic residues and low-rank fossil fuels to reduce carbon dioxide emissions, save resources, and solve waste problems. State of the art technologies and the products thereof are the benchmark for the techno-economic evaluation of the TCR technology.

In the technical evaluation, a broad range of different feedstocks are going to be processed, the products evaluated, and the optimum utilization pathway highlighted. In a subsequent analysis, correlations between feedstocks, products, and process parameters are investigated to broaden the impact of the results. Furthermore, it is targeted to identify connection points for downstream processes, market entry barriers, and potentials for the optimization of the technology.

Within the economic section, an evaluation of the technology regarding competitiveness and sustainability in comparison to state of the art utilization pathways of the feedstocks and products is targeted. The goal is also to adapt the concept of evaluating long-term investment decisions on the basis of levelized costs and levelized revenues for a multiproduct process. This valuation method has proven its reliability in the power industry for single product technologies.

---

[1] TCR® is an international registered trademark of Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. (filing number 1248797). Hereinafter referred as *TCR.*

By linking the results of the technical and economic evaluation, proposals to meet present energy, environmental, and resource challenges are going to be developed.

2 BIOMASS RESOURCES AND PRODUCTS

The term *biomass* is not used consistently in academics, business, society, and politics [8,9].

The definition of the German legislation of biomass to produce power is, for example, completely different to the scientific definition. It excludes among others, the organic fraction of municipal solid waste (oMSW), sewage sludge, and residues from the leather industry [10]. Within this work, biomass is defined as organic matter according to the general definition used by Römpp [11].

The composition of biogenic resources is diverse, and therefore their utilization pathways are diverse as well [9,12].

The history of biomass utilization is closely linked to the history of human development. Except for the last 200 years, biomass was the most important feedstock. Interestingly, below 1% of the worldwide biomass resources are used for food, energy and raw material applications [13].

Within the middle of the 19th century, the prosperity of a nation was measured by its biomass potentials. Fossil fuels were at the beginning of their utilization as an energy carrier considered as a more inferior alternative to biomass [14]. The development of fossil fuels moved forward quickly. From the beginning of the 20th century, fossil feedstocks fueled the world economy [15,16]. From then on, technologies and processes were optimized for specifications of fossil fuels.

The growing awareness of the correlation between carbon dioxide emissions and climate change led to a rethinking. Biomass as a sustainable feedstock shifted back in the focus of research [17–19]. It was targeted to reduce the dependency on fossil fuels and CO_2 emissions. Therefore, biomass could ideally substitute char, natural gas and crude oil and the products thereof.

However, the composition of biomass differs significantly from fossil fuels (Figure 1). The elemental composition and the ratio of oxygen to carbon (O:C) and hydrogen to carbon ratio (H:C) illustrate this difference. Biomass has significantly higher oxygen content, and the variation within the different types of biomass is more significant than within the fossil fuels. Furthermore, properties regarding lower heating value (LHV) and bulk density can be different. [17]

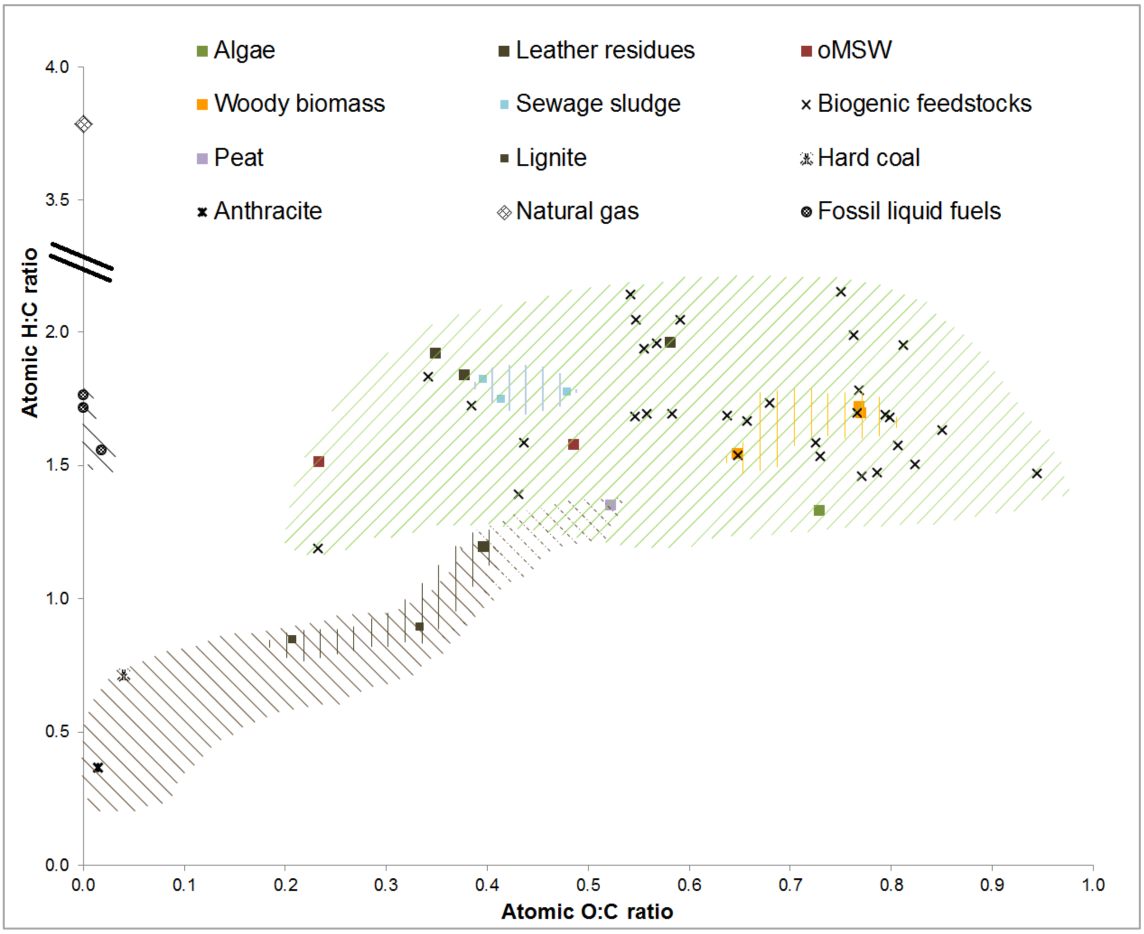

Figure 1: Van-Krevelen diagram of biogenic feedstocks and fossil fuels (calculated on water-free basis)

Therefore, biomass needs to be upgraded to be applicable as a substitute for fossil fuels [20].

First and second generation biofuels were the first approach to substitute fossil transportation fuels. These fuels had kindled the food or fuel discussions but didn't start the discussion of sustainable biofuel utilization. On top, Crutzen and coworkers have reported that first and second-generation biofuels emit over the whole life cycle more climate-relevant emissions than fossil fuels counterparts. Therefore, these fuels are environmentally non-sustainable. [6]

The supra-regional impact of such a non-sustainable use of biomass to an environment on a geographical area is also well documented. During the Roman period, the excessive utilization of wood in the Mediterranean basin had a climate impact on the region [21,22]. The consequences were equal to the effects of the climate change caused by the utilization of fossil fuels and are still present.

It is important to highlight that sustainable biomass sources are limited and often in conflict with other utilization pathways. Therefore, the utilization of biomass should be as efficient as possible. The concept of multiple sequential uses of biomass is most promising to loosen competition for feedstocks and related price increases. Therefore, residue biomass is a promising alternative source. Ideally, the utilization of these resources solves a disposal issue and saves resources.

2.1 Biomass Resources

In the following section, five different biomass feedstocks are described. The focus was to select resources that represent a broad range of biomass, not only regarding elemental composition and ash content, but also in terms of origin, utilization or recycling path.

Inspired by the biomass classification of Vassilev et al., the feedstocks were chosen to cover six different groups [9]: woody, aquatic, contaminated and industrial, and mixtures thereof. Results of herbaceous and agriculture biomass were already published by Fraunhofer UMSICHT in several publications [23–26]. Animal and human biomass waste was not investigated due to the stronger focus on processed human and animal waste (sludge). The potentials and demands of these feedstocks were demonstrated from a European and German perspective.

2.1.1 Sewage Sludge

Sewage sludge is the residue from wastewater processing plants. The awareness of wastewater with its organic pollutants has changed from a health issue residue to a valuable energy carrier. Sewage sludge can be classified depending on the stage of treatment. Raw sludge is the residue of the biologically treated wastewater. If raw sludge is used in a digester to stabilize it and for methane production, it is named digested sludge. The composition and the energy content of the sludge samples are different. [27]

The composition of sewage sludge changed significantly in the last decades. The heavy metal concentration has significantly decreased in Germany [28]. On the other hand, the contamination with synthetic polymers and residues of medical products has gradually increased. Recent studies in Europe have proven that microplastics are present in wastewater treatment plants [29–31].

There is no historical data on the contamination of sludge of the last centuries available. A trend of the contamination with plastics cannot be empirically verified. However, the significant increase of plastic production and usage within the last 70 years implies this.

The world plastic production has risen by the factor of 190 from 1.7 million tons in 1950 to 322 million tons in 2015 [32,33]. The same conclusion can be drawn with regards to the increased consumption of pharmaceuticals [34].

In Europe, the material use of sewage sludge has prevailed so far. Based on data for the period 2013–2015, approximately 47 wt% of the generated sludge is used as a fertilizer in agriculture, and 13 wt% is utilized in composting and other biological transformation processes. Approximately 26 wt% is incinerated (mono-incineration and co-incineration) and more than 10 wt% is deposited. [35] In Germany, 63 wt% of the sewage sludge is disposed of thermally. Mono-incineration and co-incineration have approximately the same market share. [36]

In Germany, the amendment of the sewage sludge ordinance in 2017 reinforced this development. The use of sewage sludge for fertilization purposes on agricultural soils is further restricted. For wastewater treatment plants with a capacity of greater than 50,000 population equivalents, it will be prohibited entirely after a 15 years transition period (plants with a capacity of greater than 100,000 have a transition period of 12 years). Furthermore, the recovery of phosphorus from sewage sludge is made obligatory in the year 2032 [37]. Although the amendment concerns only 6% of the wastewater treatment plants in Germany, these plants handle over 61 wt% of the municipal sewage sludge [38]. It is expected that the amendment has an impact on the future pricing of the sewage sludge disposal. Missing mono-incineration capacities and more complex processing steps will lead to an increase in prices. This will foster the search for alternative routes for sewage sludge. [39]

2.1.2 Woody Biomass

Wood is a biogenic composite material consisting of hemicellulose and lignin polymers and cellulose as well as additional organic and inorganic compounds and water [40]. The composition of wood is dependent on the nature and origin of the material. On a dry ash free basis, the hemicellulose content is around 15–35 wt%, lignin 18–41 wt%, and cellulose 40–60 wt% but differ broadly depending on the source of information [40,41].

Wood is a raw material, and its cultivation and utilization are fully industrialized. The production of wood in Europe in 2014 was 425,351,000 m and consists of 327,143,000 m of industrial round wood and 98,208,000 m fuelwood [42]. In addition, Europe is importing wood.

The utilization of wood is diverse. It is used as a fuel, raw material for the chemical industry, construction material, and as a feedstock for furniture industry [14]. This high degree of added value at different levels of wood processing enables the cascade use of wood [43]. This is an important building block for a sustainable utilization of woody biomass and leads to a significant decrease of competition, therefore lower prices, and increases the social acceptance for the utilization of wood. This is one of the reasons why the prices of wood were in the last 50 years more or less stable. [44]

The material and energetic utilization of woody biomass increased in the last years [42,45]. Wood as a fuel is used for power and heat production in industrial through to household applications [46]. The consumption of wood pellets for energy purposes exceeded the production in Europe. In 2014, over 8,070,000 t of wood pellets were imported [42]. It is expected that the demand will increase in the next 30 years to meet climate targets [44,47]. Lauri et al. concluded that the global wood resources could sustainable supply the demand. Indeed, the local discrepancy between harvesting and consumption increases the costs [47]. Therefore, unexploited local potentials are moving into the focus. One example is the utilization of pruning residues. These unused potentials have a great potential as a feedstock. [48]

2.1.3 Algae

Algae are plants with worldwide dissemination in freshwater and salt water. The assemblage of algae is not restricted to aquatic habitats. Indeed, some species are also present in terrestrial habitats. [49]

Algae are distinguished between microalgae and macroalgae species, also called seaweed. The exact amount of algae species is still unknown, and estimates reveal astonishing numerical differences. According to conservative estimates, there are about 50,000–200,000 different types of microalgae. Only 20,000–40,000 of them are yet identified, and only 15 strains of microalgae are cultivated on an industrial scale. [50–52] The global species diversity of macroalgae is even more undefined. The estimation varies widely. Approximately 200 species are identified and described in literature, but only ten are cultivated in industrial scale. [52]

The usage of algae is diverse. Algae species are already used in industrial scale as standard in the food industry, cosmetic industry, and for food supplements for humans and animals. Seaweed as a feedstock for the production of fuels or chemicals is still under research. [50,53]

A point that makes algae so particularly interesting is the high photo-conversion efficiency in comparison with up to date agriculturally and forestry used plants. Algae have up to five times higher efficiency in photosynthesis compared to terrestrial plants.

In addition, the water and land demand are reduced with no specific demands on the soil. [50]

As well as the extraction of algae from the sea (cultivated or directly harvested), algae are cultivated onshore in open and closed ponds at industrial scale. The annual production of macroalgae in 2010 was approximately 12 million tons (dry) [54]. The annual production of microalgae was approximately 7.25 million tons (dry) [52].

Some utilization pathways of algae do not use the whole plant. Ingredients like pigments or fatty acids are extracted out of the algae [50]. The residue is used for thermal applications or even just discharged [55].

In addition to the industrial cultivation, algae also occur as a residue biomass with an environmental and health issue impact [56,57]. On the one hand, there are algal blooms resulting from the increased availability of nutrients or minerals caused by leakage of nutrients from agriculture [58]. On the other hand, there are so-called invasive alien plants that also have negative environmental, economic, social, and health effects on the affected area [59]. Due to climate change, it can be assumed that the phenomena of algal blooms and invasive alien plants are going to increase [60,61]. Seaweed is collected and thermally processed or deposited as landfill; it is not recycled yet [62]. This seaweed can be viewed as a biogenic material with promising potential for the recycling or production industry. The utilization of seaweed from algal blooms or invasive alien plants has therefore many positive effects on the affected areas.

2.1.4 Organic Fraction of Municipal Solid Waste (oMSW)

Municipal solid waste (MSW) is a heterogeneous mixture of different waste streams. In the framework of the Waste2Go project funded by European Union’s Seventh

Framework Programme, Fraunhofer Institute for Building Physics defined the following waste streams as the primary source of MSW: household, collected waste recycling collections, bulky waste, litter and street sweepings, commercial waste, and waste collected at recycling centers [63]. However, there is no uniform definition of MSW. This is due to the different waste management systems, consumer habits, and various regulations [63,64]. Therefore, the composition of the MSW is diverse and depends on the origin of the feedstocks with additional seasonal fluctuations [65–67]. MSW comprises of paper, vegetable and animal matter, synthetic materials, glass and ceramics, metals, textiles, and other miscellaneous combustible and non-combustible substances [63]. For an EU27 citizen, the production of MSW was in average 476 kg/a in 2015. The minimum amount was incurred in Romania (247 kg/a) and the maximum amount in Denmark (789 kg/a). [68]

The utilization is dependent on guidelines set by regulation and is even across Europe diverse [69]. Landfilling, incineration, material recycling, composting, and digestion are the most common pathways [63]. The rise of awareness of environmental risks of landfilling and the need for increased recycling rates lead to more restrictions and taxes for this method of disposal [64,70]. Therefore, in the last 20 years, the landfilling rate decreased by 58 wt% [71]. The recycling rates for MSW in Europe (2010) differ between below 10 wt% to over 60 wt%, material recycling rates to over 40 wt%, bio-waste recycling is below 35 wt% [64]. This underlines that the thermal recycling of MSW is at a high level in Europe, but the material and bio-waste recycling has further potentials.

The bio-waste share in the MSW also differs significantly across Europe. Less than 20 wt% are present in Lithuania, Norway, and Slovenia, but over 60 wt% in Malta. [64]

Therefore, the utilization of the organic fraction of MSW is in the focus of the thesis. State of the art technologies for the recycling of oMSW are digestion (anaerobic) and composting [64]. To increase the efficiency and usability, the organic fraction must be separated from the MSW. For this purpose, it is beneficial to keep the amount of impurities, non-degradable biomass, as low as possible. One example of a modern separation system is described by Ouadi and coworkers [72]. These computer-aided separation systems have a very high efficiency. A good overview of automated sorting technologies is given by Gundupalli et al. [73]. It is shown that today's technology does not have a 100% efficiency in terms of identifying and sorting off non-biogenic residues. Therefore, the products (composting) and residues (composting and digestion) of the processing of oMSW have a specific content of inorganics and non-degradable components. New processes must be able to handle this issue.

2.1.5 Leather Residues

The processing of skin to leather is a waste intensive process. To produce 200–250 kg of leather, 450–730 kg of solid residues and 15,000–50,000 kg of liquid wastewater is generated [74]. The high consumption of different kinds of chemicals is the main issue in processing and recycling these residues. The production of leather requires a long process chain of several different treatment steps. As a result, the waste streams of these single processes vary significantly in their characteristics [75]. The chemical load of the residue depends on additives used in the process. Therefore, some residues are not contaminated with chromium while others have a high chromium load.

Approximately 6 million tons of solid leather processing residues are produced worldwide every year [76]. With a market share of 17% of the worldwide leather production, it can be estimated that over 1 million tons of leather residues arise annually in Europe [77].

The utilization of leather residues is diverse. On the one hand, these residues are used as raw material for other processes like the production of split leather or leather particulate-polymer composites (LPPC) [78]. In contrast, a significant fraction of these residues is only used for thermal processes or landfilling which are not sustainable and should be replaced in the future [75]. This optional utilization of the residues is strongly dependent on their chemical load. It also has to be considered if the applied process oxidizes chromium(III) to the carcinogenic compound chromium(VI). [75] This conversion would transform a harmless residue to a health and environmentally hazardous substance.

2.2 Products

To meet the climate targets regarding carbon dioxide reduction, it is mandatory to reduce the consumption of non-renewable carbon sources. For the heat and power sector, the substitution of fossil fuels is from a technical perspective possible. This requires the conjunction of different technologies. Biomass is one building block for a sustainable and demand-oriented heat and power supply.

The substitution of fossil fuels in the material utilization is more difficult. The industrial value chains are designed and optimized for the application of fossil fuels. The integration of biogenic feedstocks is hence difficult. However, for an overall reduction of the dependency on non-renewable fuels, the energetic and material substitution of fossil fuels is essential.

In the following section, different biogenic products are introduced which are related to fossil fuels. They are classified by the fossil product (char, oil, and gas) which is substituted.

2.2.1 Charcoal

Charcoal produced from biogenic feedstocks can be utilized for several different applications. A good overview of applications for charcoal has been published by Haubold-Rosar et al. [79]. The large variety of applications can be attributed to the diverse properties of the charcoal. These properties are directly dependent on the feedstock characteristics and the carbonisation technology. The following section contains selected charcoal applications, divided into energetic and material utilization pathways and does not purport to be complete. Applications that are successfully integrated into the market and are not only niche applications are in focus. The following section does not comprehensively address all classifications that are mandatory for the specific utilization pathway. The target is to identify the main characteristics for an initial assignment of the solid products and the highest possible utilization pathway.

2.2.1.1 Energetic Utilization

The energetic utilization of charcoal to produce heat and power is related to the history of charcoal and fossil fuels. As described earlier (section 2), charcoal was superseded from fossil fuels in 1900. Since then, the technical development of the energy processes was correlated closely with the properties of the fossil feedstocks. Rising market prices of the fossil fuels and CO_2-certificates have led to attempts for co- and mono-firing charcoal in power plants.

One question that arises in this context is why charcoal is used and not the biomass directly. As described earlier, coal power plants are optimized for fossil fuels, and biomass has a lower energy density, higher water content, and is inhomogeneous. Therefore, the feeding system is a limiting factor as well as the size of the boiler. For the co-combustion of charcoal in a coal power plant, the grindability of the charcoal is very important and needs to be in a similar range as fossil coal. [80]

Furthermore, the comparability of the charcoal must also be considered regarding behavior in the combustion chamber and the downstream processes. The impact of the different composition of the ashes (melting point) and the volatile components (higher temperature in the combustion chamber) are well known.

However, that also high-quality properties, like a lower water content of charcoal in comparison to fossil fuels, have a negative impact on the overall plant performance is not well known. Lower water content reduces the volume flows and the heat transfer. Therefore, the plant is not operating in the optimum parameter range, and this causes lower efficiencies. [80]

In general, the more similar the properties of biogenic and fossil fuels are, the lower are the entry barriers for the integration in a fossil fuel process. Thus, investment and operating costs can be reduced, and the utilization of charcoal for energetic utilization is more competitive [80]. The utilization of torrefied biomass was evaluated, investigated and tested in commercial scale [80,81].

It can be concluded that the use of charcoal as a substitute for fossil fuel is both possible and proven, but depends on the composition of the specific charcoal and the application.

2.2.1.2 Material Usage

The material utilization of charcoal is diverse. In general, biochar could substitute all fossil carbon applications. A list of additional possible utilization pathways was published by Schmidt [82]. In this section, five different utilization pathways are presented. Additional possible utilization pathways like biochar as a reductant in modern steelmaking processes were not considered.

2.2.1.2.1 Soil-related Utilization

The positive effect of charcoal as a soil enhancer is well described in literature. Several publications and books were published in recent years on this topic [80,83–88].

One significant strength of biochar is also the central barrier to market entry: the versatility of feedstocks and technologies to produce biochar. Consequently, biochar is not a standardized product with specific characteristics and properties.

To expand the possible market of biochar beyond the utilization as a niche product, standardization of the product biochar is needed. [89]

Two different classification standards of biochar are further investigated within this work. The standards from the European Biochar Foundation (EBC), called European Biochar Certificate, and from the International Biochar Initiative (IBI) called IBI Biochar Standards [90,91]. Both systems classify biochar in three different biochar categories. Crucial factors for both systems are the carbon content, the H:C ratio, and the metal content. In addition, the EBC regulated the O:C ratio and the source of heating. These criteria are displayed in Table 1. They are a good starting point to classify chars from biogenic residues and make it possible for initial estimations if a char can be classified as biochar or not. However, it should be highlighted that these classifications have no legally binding status in the EU. They should be interpreted as possible recommendations.

Table 1: Selected criteria for biochar certification according to EBC and IBI (*only wood logs allowed as feedstock) [90,91]

		C_{min} [wt%]	$O:C_{min}$	H:C	Metal load	Heating the plant
European Biochar Certificate V4.8	**EBC basic**	50	0.4	0.7	Restricted	8% external sources
	EBC premium quality	50	0.4	0.7	Restricted	4% external sources
	EBC premium quality for animal feed*	80	0.4	0.7	Restricted	4% external sources
IBI Biochar Standards V2	**Class 1**	60	×	0.7	Restricted	×
	Class 2	30	×	0.7	Restricted	×
	Class 3	10	×	0.7	Restricted	×

An up-to-date list of biochar producers, retailers, and biochar producing technologies published by the German non-governmental association for environmental and nature protection (BUND[2]) gives an overview of the biochar market in Germany, Austria, and Switzerland [92]. The document stated clearly that the EBC standard is the most widely used classification in central Europe and therefore used for further investigations in this work.

2.2.1.2.2 Barbeque Fuels

Even the end usage of barbeque (BBQ) char is energetic utilization; it is classified as a material usage.

---

[2] Bund für Umwelt und Naturschutz Deutschland e.V.

BBQ fuels are regulated in the European Union with European Standard EN 1860-2:2005 [93]. A distinction is made between BBQ char and BBQ briquettes. The most significant differences are regarding the ash and fixed carbon content. BBQ char must have an ash content below 8 wt% and briquettes below 18 wt%, on dry matter respectively. The carbon content of char must be above 75 wt%, for briquettes 60 wt%.

The market of chars for BBQ application in Germany is met by over 98% of imports [94]. In 2015, Germany imported 227,000 tons of charcoal for BBQ applications with an overall value of nearly 100 million euros [95]. The market for BBQ chars in the UK is about half as large as the German market [94].

2.2.1.2.3 Activated Carbon

Activated carbon is defined as a porous carbon structure that is characterized by its chemical adsorption characteristics [96]. Active carbon is dependent on the area of application regulated in the European Union with European Standard. A distinction is made between the grain sizes of the carbon. Within these regulations, the maximum ash content of the active carbon is classified with 15 wt%. Also, the metal content is restricted. [97–99]

The ultimate utilization of active carbon depends on the specific characteristics such as density, thermal conductivity, surface area, pore size and distribution, and ash content [80,96]. Active carbon is used in many fields of applications like water treatment, organic synthesis processes, exhaust gas cleaning, catalyst, and for medical purposes [96]. Each of these utilization pathways has different requirements. Therefore, a complete characterization of the coal is crucial to integrate the coal into the optimum process chain.

2.2.1.2.4 Animal Feeding

The utilization of char as an animal feed additive is a special application of active carbon. The advantage is the integrated cascade use of the administered coal with an effect on the animal's health, their manure, the soil, and the carbon cycle. A good overview of the utilization of char as an animal feed additive is described by Shackley et al. [87]. Additional information is given by Quicker and Weber [80].

The utilization of charcoal as a feed additive is regulated in Europe by the EU regulation No 68/2013 [100]. The products which are established in the market are certified by the EBC with the EBC premium quality standard for animal feed depictured in Table 1. The main differences to the standard premium quality are on the one hand the higher carbon content of 80 wt% and the feedstock determination (wood logs). As previously mentioned, these classifications are not official certifications or licenses to use the charcoal as a feed additive. It is only based on the EU regulation and could serve as a basis for the official permission. Therefore, this standard is used for further investigations.

2.2.1.2.5 CO_2 Sequestration

Recent studies reveal that to achieve the climate targets, it is not sufficient to reduce CO_2 emissions. Indeed, CO_2 has to be extracted from the natural carbon cycle [101].

One approach could be the sequestration of carbon that is fixed in the biochar structure and remove it from the natural CO_2 cycle by sequestration (CCS) [83,84,102]. In Germany, fixed carbon could be backfilled in open cast lignite mines. Due to the existing infrastructure and storage capacities, this could be an economical approach depending on the revenue system. An additional advantage is that it would also be possible to utilize chars that can’t be classified as biochar because of their higher ash content or inappropriate metal load. One essential precondition is the long-term persistence of the carbon in the char structure. Hornung and Schröder recommend a molar O:C ratio of below 0.25 as an appropriate indicator. [85]

2.2.2 Oil

Bio-oils are classified into three different categories, called generations, according to the feedstock they were derived from. The first generation of biofuels are fuels derived only from a small fraction of the overall feedstock; for example seeds of a plant or fats of an animal. These sources compete with food production. The second generation is made from parts like straw. The third generation is produced from algae. The so-called fourth generation is producing high-grade biofuels, such as bio-gasoline from biodiesel. It is therefore not an own real classification by the origin, more like a classification of the end use. [103]

The composition of liquid fuels from biogenic sources is different than fossil fuels. For a sustainable energetic utilization of these oils, upgrading is required to substitute liquid fossil fuels. Talmadge and coworkers, as well as Mante and Agblevor, have published the state of science and technology to upgrade biogenic oils from thermal processing to standard fuels that meet international requirements. [12,104]

Fossil crude oil is a complex mixture of more than 11,000 compounds and has therefore, a wide range of properties [105].

It is mainly composed out of four types of hydrocarbons: paraffin, naphthenes, olefins, and aromatics. The composition and properties of fossil fuels are varying, and therefore a refinery blends several crude oils to balance fluctuations. A good overview of the industrial fossil refinery processes is given by Talmadge and his coworkers. [12]

The integration of biogenic oils within a standard fossil refinery process would have economic and ecological advantages as well as a positive impact on the social acceptance of the fuels. No additional competencies would be needed to investigate the refining of the bio-oils. The experience and equipment of a whole industry could be used to produce standard fuels. This would also eliminate the need to establish a new standard for biogenic fuels. A new standard is not only a very costly and timely process; the consumer acceptance of the new fuel is not guaranteed. [12] Even in a progressive society like Germany, consumers have concerns about biogenic fuels [106].

The processing of bio-oils in standard refinery process would also enable the production of platform chemicals [107]. Thus, the material utilization would also be accomplished.

2.2.3 Gas

The main component of natural gas is methane with over 83 vol%. Natural gas is used for energetic and material purposes and is distributed in gas grids to the consumer. Natural gas that is processed in the grid is specified. These specifications are varying across Europe. For example, in the German market, these specifications are bundled in the German technical and scientific Association for Gas and Water (DVGW[3]) codes of practice G 260 [108]. The composition and quality regarding impurities are regulated.

---

[3] Deutscher Verein des Gas- und Wasserfaches e. V.

Gases from renewable sources have a different composition than fossil gas, and this is considered in the technical rule G 262 for the integration of renewable gases into the grid [109].

It is important to highlight that for material utilization of these off-spec gases this could be an advantage. The refining step that is needed for natural gas to achieve the optimum syngas parameters for synthesis processes is therefore not entirely necessary.

The syngas is used for several synthesis reactions like Fischer-Tropsch or synthesis of methanol, dimethyl ether (DME), and urea. The majority of the worldwide syngas production is based on natural gas and coal [110,111].

For synthesis processes or the production of hydrogen, gases from renewable sources are also competing with gases from gasifiers in which coal is used. For example, the worldwide hydrogen demand is over 96% produced from fossil fuels [112]. This practice leads to 5% of the global CO_2-emissions [113]. Therefore, gases from natural sources should not only be evaluated by their heating value and their composition in terms of integrability into the natural gas network, but also in terms of suitability for synthesis processes or as a sustainable hydrogen source.

3 CONVERSION PROCESSES FOR BIOMASS TO PRODUCTS (BTP)

The utilization of biomass is of great importance to reduce the dependence on fossil fuels. Thus, it is not surprising that it has significantly gained importance as a research topic. Bioenergy receives significant attention in the alternative energy research sector [114]. Several bioenergy conversion processes have been developed and are currently still being optimized and developed further, including biochemical and thermochemical processes, to produce sustainable biofuels, chemicals, and power [114–116].

In the following section, a short overview of market approved biomass to products (BtP) technologies is given. Biochemical and thermochemical processes for the conversion of feedstocks described in section 2.1 are briefly presented. The focus is to determine the respective feedstock, basic functions, and the specific products for each technology. The focus of the section is to determine the fundamentals and unique characteristics of the TCR technology.

3.1 Overview of Biomass to Products (BtP) Technologies

3.1.1 Combustion

The combustion of biomass or biogenic residues is established in industrial scale and is applied worldwide as the most common energetic utilization pathway for biomass [117]. A good overview of combustion technologies is given in several publications [118,119]. Plants can be differentiated into two categories: mono-incineration and co-incineration. Within a mono-incineration, the feedstocks are not mixed. Only a specific feedstock is utilized. The advantage is that the ashes are single-origin and can be used for material processes like phosphor recycling. The disadvantage in comparison with co-incineration is the lower energy output due to a lower efficiency of the process. [120] The main products are heat and power. The hot gas temperatures are around 1100–1300 K. The electric-conversion efficiencies are dependent on the size of the plant and are in a range of 20–40%. [20]

The combustion of residue waste streams in combustion plants becomes increasingly important in Germany due to the amendment of several laws and directives. Several waste streams are restricted from landfilling. In addition, the conventional material utilization pathway of sewage sludge in agriculture is more and more restricted [37,121]. There are several reasons for this development described in section 2.1.1. This has led to an increased utilization of several waste streams in incineration plants. Incineration plants are state of the art, and there is no promising approach to improve this technology.

3.1.2 Gasification

Gasification converts solid biomass and biogenic residues into a gaseous intermediate product by partial oxidation. This intermediate product is easier to integrate into other conversion processes than the inhomogeneous raw feedstock. Therefore, the gasification product is a substitute for natural gas. A good overview of different gasifier technologies is given by McKendry and Hofbauer et al. [122,123]. McKendry claimed the efficiency regarding feedstock to product for biomass is between 75–80% [122]. The composition and the properties of gases from biomass gasification are heavily dependent on the type of the gasifier and the used gasification agent as well as operating conditions like temperature and pressure [122].

There are several gasification databases available giving an overview of biomass gasifier projects [124–126].

3.1.3 Anaerobic Digestion

Another technology to produce a gaseous fuel from solid biomass is anaerobic digestion. This biochemical conversion process has the advantage over thermochemical conversion processes that it is favorable for biogenic material with high moisture content [20]. Weiland, Dieckmann et al., and Melville et al. give each a comprehensive overview of the fundamentals of anaerobic digestion and different process variations [127–129].

As mentioned earlier in section 2.2.3, the gases from renewable sources have a different composition than fossil gas. Gases from anaerobic digestion are classified in Germany as biogas and are considered in the technical rule G 262 for the integration of renewable gases into the grid [109]. Therefore, these gases are a substitute for natural gas.

3.2 Pyrolysis

Pyrolysis is the thermochemical conversion of organic components without additional oxygen supply. In comparison to gasification and incineration, only the fixed oxygen within the feedstock is present in the pyrolysis reactions. However, pyrolysis is an essential sub-process of gasification and combustion. The idea of the pyrolysis process is to decouple the pyrolysis from these processes and utilize the pyrolysis products as a final product and not as an intermediate product to produce fuel gas (gasification) or heat (incineration). The missing oxygen ($\lambda \approx 0$) prevents partial oxygenation ($\lambda < 1$, gasification) or full oxygenation (λ>1, combustion) of the pyrolysis products. The overall efficiency of pyrolysis regarding energy transferred from feedstock to product is in the same range as for gasification. [122]

A comprehensive overview of different biomass pyrolysis technologies and their classification is given by Hornung [130].

It is anticipated that pyrolysis was human's first controlled chemical process [131]. This means pyrolysis is in no way a revolutionary new technology, but the focus has changed since the first developments in the early human history [132]. The initial idea was the production of pyrolysis liquids for material use. Wood vinegar, tar, and pitch were used, among other things, as adhesives, insecticides or sealing agents [131].

The utilization of solid pyrolysis products for energy purposes enabled the production of bronze and iron [133,134]. Charcoal only became less important after the demand increased as a result of the industrial revolution and cheaper alternatives like hard coal and crude oil were developed [15,16].

Garcia-Nunez et al. provides an up-to-date overview of the state of the slow, intermediate, and fast pyrolysis technologies [132]. Various reactor designs and configurations have been investigated in the field of fast pyrolysis. The most important reactor types like fluidized bed, rotating cone or flow reactors, among others, have been described well in literature. [135]

Thermo-Catalytic Reforming TCR

The Thermo-Catalytic Reforming (TCR) technology has been developed at Fraunhofer UMSICHT in Sulzbach-Rosenberg, Germany in 2013. The TCR technology converts solid biogenic feedstocks into storable energy carriers. The technical innovation is the combination of an intermediate pyrolysis process with a downstream reforming step at increased temperatures (650–1100 K) and slightly elevated pressure (20–150 mbar). The important development steps of two decades of intermediate pyrolysis have been presented at the 2017 European Biomass conference [136]. Through continuous enhancement and innovations, the wide range of feedstocks and the utilization of the products were achieved.

Fraunhofer UMSICHT has protected its knowledge and technology of the TCR technology and its products through a total of so far two patents and several patents are pending [137,138].

The core of the TCR technology consists of two consecutive reactors that are externally heated: a horizontal screw reactor where the intermediate pyrolysis takes place and a downstream vertical reactor for the additional reforming of the products (Figure 2).

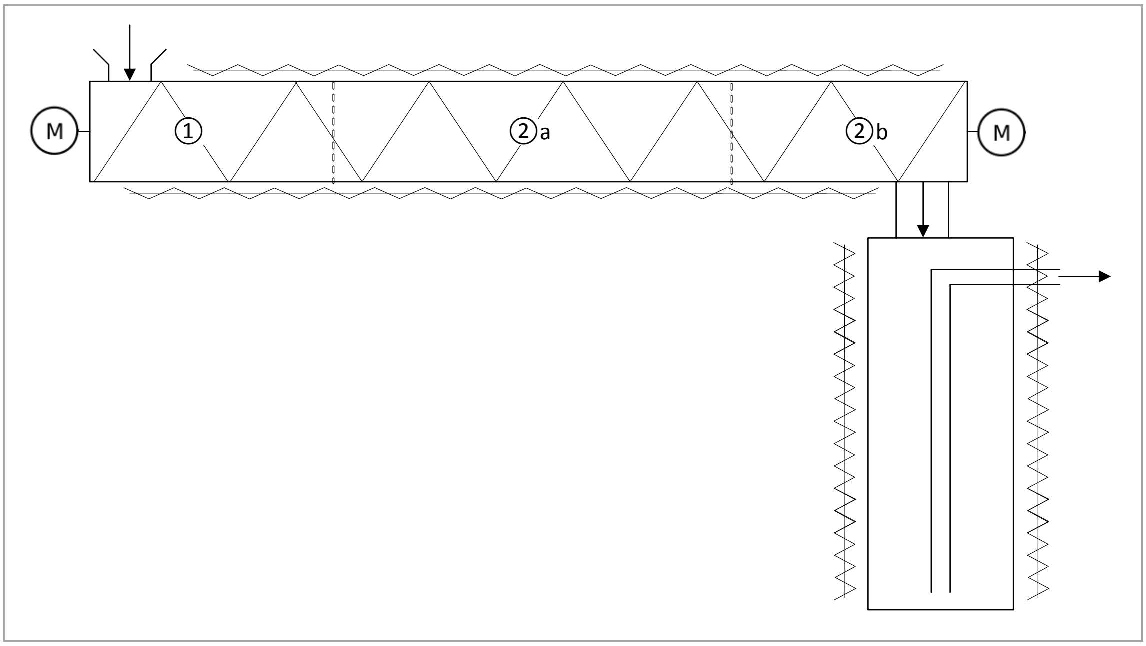

Figure 2: Core components of the Thermo-Catalytic Reforming technology (①:drying zone; ②a: mixing zone; ②b: transportation zone)

The first reactor is a tubular screw reactor and can be divided into two functional zones by temperature. The first zone (further referred to as zone 1) is the drying zone where the moisture and light condensables evaporate out of the feedstock. The feedstock is conveyed by means of a screw within this zone. The temperature window of this zone ranges from room temperature up to 473 K. The second zone (further referred to as zone 2) is the pyrolysis zone. The condensable hydrocarbons, degradation water, and low-temperature carbonisation gases are built by decomposition, distillation, and redox reactions [139]. The temperature ranges from 473 K to 823 K. This zone can be further divided into two sub-zones by the design of the screw: mixing (zone 2a) and transportation (zone 2b).

A unique characteristic of the TCR technology is the patented partial internal recycling of the solid pyrolysis products. The recycling and mixing of the solid intermediates is achieved by the design of the middle screw. Within the pyrolysis zone 2, a part of the pyrolyzed solid intermediate products is moved back to the beginning of the pyrolysis zone.

Dried feedstock from zone 1 is mixed with entirely and partially pyrolyzed solids. This has several positive effects. The recycled solid particles have a higher surface temperature which can be approximated by the temperature in zone 2b and is therefore significantly higher than the feedstock from zone 1. Due to the thorough mixing of the solids by the screw, an enhanced heat transfer between the particles is achieved. Also different gaseous pyrolysis products are produced, mixed, and can interact with the gases from zone 1. Another synergy effect is based on the surface area of the different stage pyrolysis solids. The increased surface area of the recycled solid is catalytically active. However, due to the complex mechanisms within the pyrolysis zone, not all reactions are fully investigated. An overview of the current state of research is available within the two international granted patents [137,138].

The residence time within the horizontal reactor depends on the size, density, and the thermal conductivity of the feedstock. It is targeted that the feedstock is fully pyrolyzed at the end of the horizontal reactor. Depending on the process parameters and feedstock conditions, it usually takes 8–15 minutes. This is the reason why this pyrolysis step is an intermediate pyrolysis technology. The heating rate of the feedstock in the horizontal reactor is in the range of 2–6 K/s and depends inter alia on the feedstock, conditioning, and the speed of the screws. [137] Within the last zone of the horizontal reactor, the solid pyrolysis intermediates are moved by the screw to the second attached reactor.

The vertical reactor is attached to the bottom at the end of the horizontal reactor. The solid intermediate pyrolysis products are transported forwards through the rotation of the last screw of the horizontal reactor to the transition zone. The solids are partially carried with the gas flow and by gravity into the vertical reactor. The solid pyrolysis products are collected in the vertical reactor. For a continuous operation of the plant, the solid products, further referred as carbonisates[4], are discharged by a screw. The vertical reactor is built on the same principle as a downstream gasifier with an oxygen-free gasifying medium. The solid pyrolysis products in the vertical reactor can be divided into three zones from top to bottom: high-temperature pyrolysis zone, reacting char zone, and non-reacting char zone. [140] Within the high-temperature

---

[4] The common definition of solids from thermochemical processes is biochar. Because the TCR technology is able to process biogenic and non-biogenic biomass, the nomenclature bio is misleading. In addition, the high carbon content of the solids on ash free basis should be expressed by the nomenclature carbonisate. This is in line with previous TCR publications.

pyrolysis zone, the pyrolyzed solids from the horizontal reactor are rapidly heated, and further pyrolysis reactions take place. In comparison to the heating rate of feedstock and intermediates within the horizontal reactor, the heating rate of the intermediate products within the vertical reactor is much higher due to the higher temperature gradient.

In the next zone, the temperature of the solids is in the range of gasification. Thus, mainly gasification reactions take place. Apparently, there is no clear dividing line between the pyrolysis zone and the reacting char zone. In the last zone of the vertical reactor, the solid products are fully carbonized and still reacting with the gaseous phase. The deoxygenation, denitrification, and dehydrogenation of the carbonisates are completed at that temperature level.

The temperature within this reactor is set between 750–1100 K depending on the feedstock and the targeted utilization of the products. Within this reactor the catalytic reforming of the pyrolysis products takes place. The pyrolysis gases pass through the char, interact with it, and then evacuate the reactor through a riser pipe to the downstream condensing and processing. Within the vertical reactor, all intermediate pyrolysis products are upgraded to their final product qualities.

The principle to guide the condensable and non-condensable gases over hot char to clean the crude gas has been successfully implemented in coke oven plants. The hot coke oven flue gases crack long chain components in the crude gas over the hot coke. Like the coke gas reaction, the gases are also free of tars. [141] The gases are separated from the carbonisates and then condensed in a downstream condensing unit. As a result, the installation of costly downstream processes for the tar separation is not needed [142]. Gabriele Migliavacca et al. investigated that within the pyrolysis process the char reactivity is strongly related to the hydrogen content [143]. On first thought, this is in contrast with the composition of the TCR carbonisates. In comparison with other pyrolysis chars, TCR carbonisates have only minor hydrogen content [48]. However, within the vertical reactor, the solid pyrolysis products are dehydrogenated. Therefore, freshly pyrolyzed material from zone 2 of the horizontal reactor has a higher hydrogen yield [26]. Within the vertical reactor, the water-gas reaction is also apparent and therefore partly responsible for the high hydrogen content of the TCR gas. The intermediate pyrolysis gases charged with steam flows over the hot carbonisate in the vertical reactor.

Fraunhofer UMSICHT works on the development and validation of the TCR technology with a lab scale (2 kg/h) and a demonstration scale (30 kg/h) plant at their site in Sulzbach-Rosenberg. The TCR technology is currently validated in an industrial environment within two projects, each with a capacity of 300 kg/h [144,145]. Therefore, the technology has a technology readiness level of five (TRL 5) [146].

Products of the TCR

The Thermo-Catalytic Reforming (TCR) technology converts biogenic feedstocks into three main products: carbonisates, bio-oil, gas and one by-product, aqueous phase. All three main products can be utilized straight out of the process in various applications. The carbonisates can be utilized for energetic and material applications [147]. The focus is on the in section 2.2 described pathways. Due to the high dependency of feedstock characteristics and process parameters between composition and properties of the solid products, it is necessary to elaborate for each feedstock possible utilization pathways [148].

The investigations regarding the utilization of TCR oil are advanced. In the last three years, several publications regarding the utilization of TCR oil were published. Due to the properties of TCR oils, it can be compared to fossil crude oil. It is thermally stable and mixable with fossil and biogenic fuels. Due to the thermal stability, it can be distilled and fractionated. [25] The TCR oil blends with biodiesel were successfully tested in a combined heat and power (CHP) engine and for heavy-duty transport applications in a heavy-duty diesel pickup truck [136,149]. The upgrading of the oils to achieve standard fuel for transport applications by hydrotreatment has been reported by Neumann et al. in 2016 [150]. Therefore, the integration of TCR oil within petrol processing industry is a promising option for utilization. In particular, to extract valuable compounds from the oils like aromatic compounds and aliphatic hydrocarbons that were detected in the TCR oils by Gas Chromatography/Mass Spectrometry (GC-MS) [26,72]. It is of interest to prove if the composition of TCR oils from the feedstocks, described in section 2.1, is suitable for the integration within an industrial petroleum-processing industry.

The compositions and properties of the TCR gas vary depending on the feedstock and the experimental parameters. The syngas composition is therefore adjustable and direct out of the process ready for energetic utilization [148]. A combustion chamber with a capacity of 150 kW_{th} and a CHP with a dual fuel engine with a capacity of 40 kW_{th} and 20 kW_{el} were successfully operated in long duration trials with TCR gas in demonstration scale [149]. The material utilization of TCR gas was not investigated up to date. The composition of the gases is very promising for synthesis processes due to the high H_2 and CO content. An initial step in this direction is the combination of TCR with pressure swing adsorption (PSA) in the EU’s Horizon 2020 project [151].

It should be emphasized that the quality of the TCR products is strongly dependent on the composition of the feedstocks. That means that the possible product utilization pathways are specific for each feedstock. This is particularly the case for the solid products.

Within the framework of the thesis, possible correlations of the feedstock composition and the related quality of the products are investigated. The focus is on the energetic and material utilization of the products for the specified feedstocks (section 2.1) and the potential for further upgrading of the products.

4 CONVERSION OF LIGNITE

Lignite is a sedimentary rock, which consists of organic and mineral components. Through the process of coalification—increased pressure under the exclusion of additional oxygen—the carbon molecules of plants such as proteins, resins, and lignin are cracked into smaller molecules. In a comparison of lignite to higher rank coals, the coalification is not completely finished. [152,153] Due to this, lignite has a high content of volatiles, and it is considered the lowest rank of fossil coals. In the following chapter, the fundamentals of lignite and lignite conversion processes will be discussed. Furthermore, an overview of the state of the art utilization of lignite in Germany, as well as the future challenges and opportunities is given.

4.1 Lignite Resources and Products

Lignite is the fossil resource with the longest statistical range of coverage. The proven reserves of lignite and sub-bituminous coal are approximately 488.3 billion tons [154]. Due to the fact that coal is derived from different fossilized organic materials rather than crude oil and natural gas, the reserves are not distributed in correlation with the oil and gas reserves. In comparison to high-grade coal and other fossil fuels, raw lignite is not globally traded. This is because lignite has a relatively high water content and therefore a low heating value.

The composition of lignite depends on the deposit. The water, carbon, oxygen, sulfur, and ash content can vary greatly, which can be attributed to the different processes of creation of the lignite. Because of the variation in lignite composition, a homogeneous feedstock cannot be utilized for every process. For example, the lignite reserves in the middle part of Germany have a high salt content that restricts their utilization in power plants. [155]

The utilization of lignite has a long tradition in Germany. Germany has only limited gas and oil, but large lignite reserves which can be extracted for economic value. This is the reason why Germany is the world's leading lignite producer. [156] Since the beginning of industrialization, Germany has the highest output of lignite worldwide [157,158].

Lignite is extracted from three open mining fields in the western, middle, and eastern part of Germany. Currently, over 36 billion tons of economically exploitable lignite reserves exist. In 2016, over 171 million tons of lignite were mined. At today's mining production rate, it is estimated that the reserves should last over 200 years. [159] Over 90% of the mined lignite in Germany is used for the production of heat and power, leading to 24.5% of the German net electricity production [160].

The success of Germany's Renewable Energy Sources Act (EEG[5]) governing the promotion of electricity from renewable sources will affect lignite use in the near future. Lignite power plants will shift from baseload to medium or even peak load electricity production. [161] These freed-up capacities of lignite are moving in the focus of a material usage. As previously described, this has the potential to decrease the dependency on imports and to improve the real net output ratio of the German industrial sector as well as securing jobs in the coal-related sector. This approach is not only pursued by the energy companies that operate the power plants and the mining fields, but also from the government authorities. [162,163]

---

[5] Erneuerbare-Energien-Gesetz

Current material utilization of lignite in Germany is limited. The majority of the 10% that is not used for heat and power production is used in lignite refinements such as briquetting and the production of pulverized lignite. Thus, the final use of the products is not a material use of the carbon; it is mainly a straight refining for energetic utilization to produce heat, power, and steam beyond the power plants that are located next to the open mining fields.

However, German mined lignite is used for material purposes. A small share of the mined lignite in Germany is upgraded to high-quality products like waxes. The fossil wax is extracted from bitumen-rich lignite and upgraded. It must be considered that only a small fraction of the lignite resources is appropriate for this processing. Only the coal from a specific mining field, Mitteldeutsches Braunkohlerevier located in Saxony-Anhalt, has a sufficiently high content of bitumen. [164] Furthermore, a small share of lignite is upgraded for use as a filter medium for wastewater or flue gases [165,166]. Lignite as a carbon source is also used in metallurgy processes [163].

The utilization as a soil enhancer is based on the humic acid content of lignite. The humic acids are also used as a feed additive. In Germany, the company Humintech GmbH is successfully extracting humic acids from sedimentation layers of soft lignite.

A material usage of lignite as implied in the Enquete-Commission from the North Rhine-Westphalian Parliament does not yet exist in Germany and the rest of Europe; therefore coal chemistry does not yet exist [163]. The reasons for this are the low oil and gas prices. The technologies for coal-based chemistry have been developed and were in use during the Second World War in Germany and the apartheid era in South

Africa. Due to the restricted access to the world market, the utilization of lignite for the production of chemicals and fuels was a crucial element of the economy. [155]

4.2 Fundamentals of Conversion Processes for Lignite to Products

Over 98% of the world wide mined lignite is utilized for the heat and power production. The majority of this lignite is fired in power plants, leaving only a fraction available for upgrading to briquettes or dust used in smaller industry applications for heat, steam or power production. [167]

The fundamentals of the conversion processes of lignite for heat and power production resemble the processes described for biomass. One of the main differences is the large-scale industrial implementation of up to 1100 MW_{el} per unit [168]. Biomass incineration plants are due to logistic reasons smaller (<300 MW_{el}), but there is a trend of co-firing biomass in existing coal-fired plants or even converting coal-fired plants into mono biomass incineration plants [169,170].

As described earlier in section 4.1 there are several applications for lignite beyond the energetic usage. These alternative uses can be classified in three techniques: extraction, thermal upgrading, and direct and indirect liquefaction. Extraction of substances that are present in the lignite is a standard process to produce waxes or humic acids. Thermal upgrading increases the carbon content of the product. Low-quality lignite is upgraded to higher value carbon carriers. Two different approaches for the liquefaction of lignite are described in literature and were successfully implemented in industrial scale. Technologies are distinguished between direct and indirect liquefaction. Direct liquefaction breaks down the coal molecules with the help of a catalyst and hydrogen at elevated pressures and temperatures. The aim of this process is to create a substitute for liquid fuels such as diesel and benzene. Gasification is the main process of the indirect liquefaction of lignite. The gaseous intermediate product can be utilized with the same technologies that are used on natural gas to produce several different products, such as Fischer-Tropsch diesel and waxes, dimethyl ether or urea.

Each of the aforementioned processes involves the pretreatment of the lignite. The reduction of lignite’s high water content is mandatory for the utilization of lignite.

4.3 Current State of Research in the Field of Conversion Processes for Lignite to Products

The success of the conversion of biomass with the Thermo-Catalytic Reforming (TCR) process had raised the question if the TCR could also be a solution for the utilization of lignite. This could address the upcoming structural changes in the German lignite market (section 4.1).

Because lignite has a similar structure to other kinds of biomass, a few technologies described in literature for lignite can be adapted for the use of biomass. However, it must be taken into consideration that there are differences between a fossil feedstock like lignite and a biomass feedstock. [171] Vassilev et al. highlighted that the experience of fossil fuel utilization was not one-to-one transferable for biomass. Vice versa, it is not possible to adopt experiences gained from biogenic to fossil feedstocks [9]. Proven technologies, like gasification, are sufficiently investigated for use with biomass feedstocks [172].

The current state of the art technologies use multi-stage process combinations for the pyrolysis of solid fossil fuels. They also generally include a catalytic upgrading of the pyrolysis products or a gasification step. Furthermore, the gaseous products of the processes are combusted to provide the energy required for the process. Also, the preconditioning of the feedstock is a mandatory process step. An example is the high-temperature coking process described in DD patent 0004630 A1 [173]. An industrially proven preconditioning technology called briquetting is used to achieve the needed feedstock characteristics for the coking process. The lignite is dried, degassed, and then coked in an indirectly heated, high-temperature, inclined chamber oven at temperatures between 1073 K and 1473 K. Besides the (quantitative) main product char for use in a blast furnace, gases and condensate are valuable by-products of the process. The disadvantage of the processes described according to the state of the art technologies is the required preprocessing of lignite, such as briquetting, and high complexity of the equipment.

Walz et al. described a technology which converts both biomass and fossil carbon into a high carbon solid product. One claim of the patent is the catalytic effect of the water vapors at temperatures between 373 K to 723 K and a pressure between 1 and 5 bar. Due to the process design, only a minor liquid and gaseous fraction is obtained. [174]

The aim of the application of TCR for low-rank fossil feedstocks, like lignite or peat, is the utilization of the solid, liquid, and gaseous fuels for industry applications beyond the energy market. The solid product should have a carbon content that resembles the carbon content of hard coal and should be usable for several applications. Depending on the parameters of the reforming step, the carbonisates could be used for metallurgy processes, filter processes or as a carbon sequestration. The gaseous products are aimed at the production of hydrogen or synthesis processes like Fischer-Tropsch or DME-synthesis. The H_2:CO ratio must be optimized for these processes, and the specific process conditions and upgraded natural gas has set the benchmark. The target line for the liquid fuels is in the same range as for TCR liquid fuels from biogenic residues. This would enable a material use of lignite in line with the goals of the Enquete-Commission from the North Rhine-Westphalian Parliament.

Furthermore, due to the low carbon content and a high water content of lignite, the utilization has a common basis for the conversion of biomass.

4.4 Co-Pyrolysis of Lignite and Biogenic Feedstocks

The successful utilization of solid low-rank fossil fuels like lignite or peat with the TCR technology opens up new possibilities. There are several advantages of mixing biogenic feedstocks with fossil fuels beyond just an ecological upgrading of fossil fuels; however, this is the most obvious advantage. The CO_2 footprint of products from low-rank coal could be significantly decreased from mixing biogenic feedstock in the process. Not only for the product char but also the CO_2 footprint of syngas and liquid fuels can be decreased.

Another advantage of co-pyrolysis of fossil with biogenic fuels is the scale-up of the technology. It is well known that biogenic feedstocks fluctuate with the seasons, both in available quantities and composition [169,175]. Fossil fuels can counterbalance such fluctuations. The capacity of a plant can be increased, and larger plants can be installed. The co-pyrolysis of biomass and lignite would, therefore, improve the cost-effectiveness of a plant.

Fossil fuels are also easy to access and reasonably priced in relation to the heating value. Trippe concluded in his work that the use of coal in the bioliq BtL technology is the only economic medium-term scenario. The use of the fossil and biogenic feedstock mixture (90% coal) enables the implementation of an economic scale plant. Currently, the infrastructure required to operate these large-scale plants using only straw as the biogenic feedstock is not realistic. In addition, the fossil feedstock enables the inexpensive production of syngas, due to the more straightforward processing of the char and the cheaper feedstock. [176]

Another advantage to the aforementioned co-pyrolysis is the production of tailor-made fuels which can provide great value for industrial applications. Some industrial processes need feedstocks with concrete compositions. Upgraded biogenic and fossil fuels cannot always meet these specifications, because the ash content in the char may not be appropriate. This problem can be observed in the steel making industry. [177]

It is conceived that the products from co-pyrolyzing a biogenic feedstock with a low ash content, such as pruning residues, with lignite, which has a medium ash content, could achieve the needed parameters required for industrial applications. Vice versa feedstocks with high ash content, like sewage sludge, could be upgraded by mixing lignite in the process.

Some lignite deposits have a high amount of alkali compounds, which are known for reducing the softening temperature of the ashes [178]. This restricts the possible utilization pathways of these chars. Biogenic feedstock with a high amount of calcium and/or alkali binding ingredients can increase the ash melting point [179].

There is also the opportunity to not only achieve the minimum standards of the feedstock but also to improve the composition of the products to increase the value of the products. Kalde et al. developed the concept of adding calcium-rich paper mill residues into the steel making process. Calcium is an essential material in the steelmaking process for binding impurities like chlorine. The high calcium content in the residues could reduce the required amount of calcium-rich fossil feedstocks such as limestone in an electric arc furnace. [180]

It is also possible to utilize biogenic residues with a high content of metals that have a positive impact on the steel making process. This would enable a material use of the residues from the leather industry which have a high content of chromium.

The beneficial effects of co-pyrolyzing fossil with biogenic fuels are not limited to the solid products. Furthermore, it can be expected that there are also significant synergistic effects for the gaseous and liquid products.

It has been proved that alkali binds sulfur components in the solid residue [179]. The absence of sulfur could have a positive impact on the oil and syngas quality.

It is also possible that co-pyrolysis of lignite and biogenic fuels would have an impact on the acidity of the oils.

Further synergistic effects of the co-pyrolysis of lignite and biogenic fuels are related to the water content. Some biogenic residues, such as sewage sludge, leather residues, and algae, often have a high water content. To utilize these feedstocks in the TCR, the water content must be below 30 wt%. Therefore, it is often necessary to dry the material beforehand. There are biogenic feedstocks with low moisture content—woody biomass, solar dried sewage sludge—that do not need an additional drying process. When integrating lignite into the process, the water content requirement creates two possible scenarios. In the first, crude lignite or peat could be mixed with naturally dried biomass to reduce the overall water content to an appropriate level. The second option is to use dried lignite and mix this with wet biomass. There are large scale lignite drying technologies in operation that have higher efficiencies in comparison to small-scale biomass drying technologies. [181,182]

The mixture of feedstocks might also influence the pyrolysis process. In literature, several mechanisms are described which indicate that there is no linear correlation between co-pyrolysis and mono-pyrolysis of fossil and biogenic feedstocks [183–186]. This means that the modeling of a co-pyrolysis process is not possible by transferring results from mono-pyrolysis directly. In the two reviews by Tchapda and Quan, the main effects are summarized in three main synergetic mechanisms: [187,188]

Heat Transfer: The thermal decomposition process of fossil fuels and biomass is different. Several studies based on thermal gravimetric analysis (TGA) and differential scanning calorimetry (DSC) analysis have proven this [189,190].

Hydrogen Transfer Reaction: The pyrolysis of biomass results in higher H:C ratio when compared to fossil fuels, due to variation in composition. This could have a positive effect on the lignite pyrolysis caused by the presence of hydrogen-rich molecules in the gaseous phase (H_2, CH_4, and H_2O).

Catalytic Effects of Alkali Compounds: In addition to the effects of alkali compounds mentioned above, it is well known that these compounds can also have a catalytic effect [178].

This may contribute to catalytic activity within the pyrolysis zone – including gas and solid phase re- and interactions.

Although these mechanisms have already been described in literature, these results are not directly derivable for the TCR process. These synergistic mechanisms have been investigated for the pyrolysis zone, but it is not currently possible to identify the influence of the downstream reforming process. It is possible that the reforming step in the TCR can increase or overshadow the previously mentioned synergistic effects.

For this reason, an experimental investigation regarding possible interactions between the co-pyrolysis of lignite and biomass in the TCR technology has been performed. This is the basis for further calculations and discussions about the described synergistic effects on the products and their utilization, as well as of product yields and compositions. The results are summarized in section 7.1.3.

The co-utilization of lignite with biogenic feedstocks offers advantages. Using lignite as a competitive domestic energy resource with biomass can reduce the dependency on raw material imports. Moreover, tailor-made products with improved properties can be provided via combined use of biomass and lignite with a reduced carbon footprint. A successful utilization would add value in domestic industries. For example, broadening of the raw materials base of the chemical industry and reduce the up-to-date high dependency on crude oil and natural gas imports. In addition, lignite can compensate the fluctuating composition and availability of the biomass and residues. It would also enable an upscaling of the capacities compared to only biogenic processing plants with a positive effect on the efficiency and profitability of the process.

5 EXPERIMENTAL METHODS (TCR TRIALS)

The following section contains a comprehensive description of the used experimental methods of the applied TCR trials as well as the analytics of the feedstocks and products. In addition, the theoretical background of the energy and mass balance is described.

5.1 Materials and Methods

5.1.1 Lab Scale TCR

The TCR plant was designed and assembled in 2013 for the conversion of solid biomass and biogenic residues with a particle size larger than 3 mm (Figure 3). The capacity of the plant is around 2–3 liters of solid feedstock per hour. The batch-scale design simplifies the complexity of the plant. No continuous feeding and carbonisate extraction system is needed. Due to the size of the hopper (approximately 7 liters) and the vertical reactor (approximately 7 liters), a stable operation of the tests can be guaranteed.

The geometry of the hopper ① was designed for pelletized or granulated feedstocks. A paddle placed in the center of the hopper can be moved manually to prevent blockage within the tapered section and to remove adhesions from walls. On the top part of the vessel is the nitrogen connection. The hopper is placed at the beginning of the first screw of the reactor.

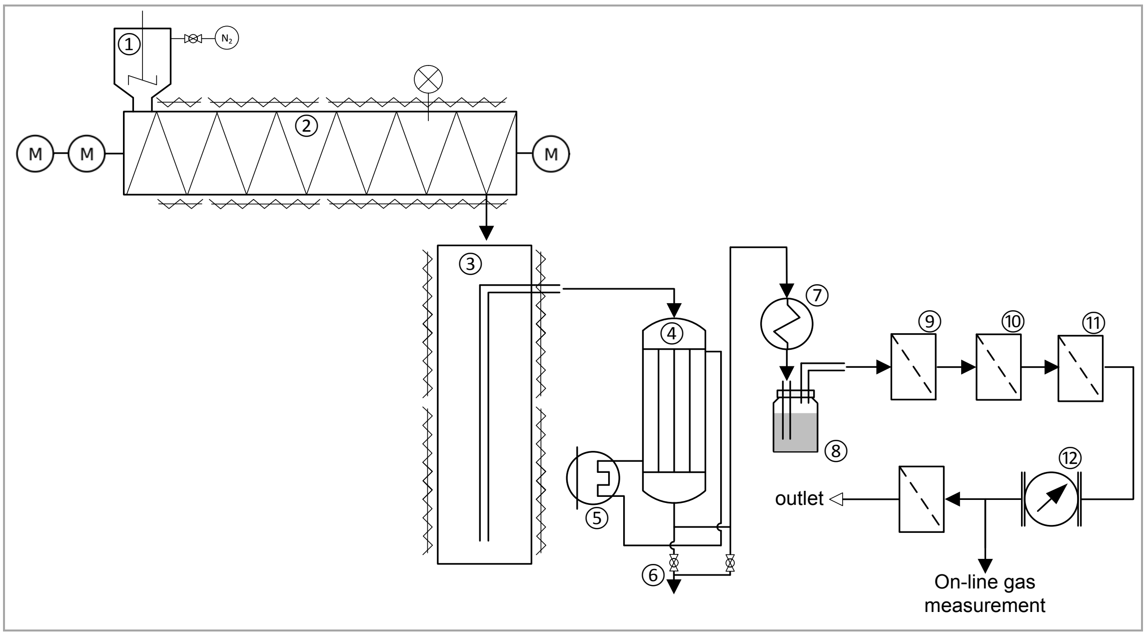

Figure 3: Process flow diagram TCR-2 (①: hopper; ②: horizontal reactor; ③: vertical reactor; ④: countercurrent tubular cooler; ⑤: cryostat; ⑥: condesat container; ⑦: second cooler; ⑧: washing bottle; ⑨: active carbon filter; ⑩: sediment filter; ⑪: silica wool; ⑫: diaphragm gas meter)

The horizontal reactor ② is 1010 mm long and has an inner diameter of 80 mm. The reactor is divided into different zones as described in section 3.2. The three screws are centered in the middle of the reactor on a continuous shaft. The first screw segment has a length of 275 mm, the second screw element 185 mm and the last screw 575 mm. Each screw is separately controllable by an electric motor and frequency inverters from SEVA-tec GmbH with a power of 0.12 kW at 26 rpm. The motors for the first two segments of the screws are placed on the side of the feed inlet. The third segment is controlled by a motor that is placed on the hot side of the reactor. Due to this, the flange sealing must be suitable for temperatures beyond 673 K. Graphite seals with a purity of 99.85 wt% are in use. To reduce the complexity of plant, these seals are also used on the cold side of the reactor.

The horizontal reactor is heated by three electric cylinder heaters with integrated temperature measurement. The lengths of the heaters are 123 mm, 290 mm, and 431 mm. The rated outputs are 1500 W, 3600 W, and 5300 W.

The position of the three heaters does not directly correlate to the three screws zones. The first 140 mm of the first screw element is not heated. The second heater is placed 50 mm before the mixing zone. Also, the last 80 mm of the discharge screw is not heated, primarily due to the connections to the hopper and the vertical reactor ③. Cylinder heaters adapted to the geometry of the connection would need to be custom made for production. This was refrained for economic reasons. Instead, the insulation of the unheated parts was intensified. The stable temperature distribution in the perimeter zones of the reactor proved the success of the insulation.

To control the temperature within the reactor, six temperature elements of type K (chromel–alumel) are installed. Three are placed under the heaters, and the other three are inserted in thermowells. These are positioned within 3 mm of the top of the reactor surface. Additionally, three temperature elements are installed in the heaters by means of fault tolerance components. A process pressure transmitter, JUMO dTRANS p20, is installed in the last third of the reactor.

The transition from the horizontal reactor to the vertical reactor is implemented by two flanges. This enables a quick disassembly of the vertical reactor and easy access to the discharging zone of the horizontal reactor.

The vertical reactor has a height of 950 mm with an inner diameter of 100 mm. Two 375 mm cylinder heaters are installed with a rated output of 5500 W each. Just like the horizontal reactor, four temperature sensors are installed by means of fault-tolerant components. This enables monitoring of the temperatures within the reaction zone, as well as monitoring the heaters to prevent severe damage caused by overheating. All heaters are insulated with sleeves made of 60 mm calcium-silicate wool. The external fabric is made of glass fiber (E-glass). For isolation purposes, a 50 mm calcium silicate slab is lined on the blank flange at the bottom of the vertical reactor. For all flanges, NovaMica Thermex flat gaskets were used.

A riser with a total length of 800 mm is aligned in the middle of the vertical reactor with an outer diameter of 30 mm and a 24 mm inner diameter. The opening is placed 30 mm above the insulation of the blank flange. A fine-pored mesh stops coarse particles at the opening of the riser. It was discovered that poorly pelletized feedstocks or feedstocks with a high percentage of fine particles or due to polymerization of organic carbon compounds this mesh was vulnerable to blockages during operation. Practice has proven that the best results require using TCR carbonisate from previous trials in the vertical reactor to prevent such blockages. Approximately 300 ml is sufficient to submerge the mesh in the carbonisate. The carbonisate acts as a filter and prevents blockages very efficiently. The produced carbonisates of the trial fall in the vertical reactor. Due to the batch-system, the solid pyrolysis products remain within the vertical reactor during the trial, and no carbonisate extraction system is implemented.

The riser exits the vertical reactor with a 90° bend into the countercurrent tubular cooler ④. The cooler has a height of 520 mm and the hot gases flow through eight tubes with a diameter of 10 mm. These tubes are cooled by a glysofor/water mixture using a counter-current principle. The cooling fluid is cooled in a cryostat ⑤ to 267 K. The condensable substances are collected in a collection container ⑥ below the cooler. Adapters with ball valves and a by-pass connection to the scrubber enable the drainage of condensate during plant operation.

The cooled gas stream passes a scrubber that is no longer in operation. Experiments have shown that the efficiency of scrubbing was not sufficient and that it causes contamination of the condensate with the washing fluid and the gas. Due to this, the scrubber is no longer in use. The additional downstream gas cleaning made it possible to dispense washing with biodiesel.

The gas stream enters the second cooler ⑦. After this ice cooled indirect coil exchanger, the gas passes through a washing bottle ⑧ filled with the aqueous pyrolysis phase to remove fine particles and aerosols. Following are a 10-inch active carbon filter ⑨, a 5-inch polypropylene foam 5-µm sediment filter ⑩, and a washing bottle filled with silica wool ⑪. After these gas treatments, the gas passes through a diaphragm gas meter ⑫ to measure the gas volume. Afterwards, a part of the gas stream passes through the online gas measurement (section 5.1.3) systems, and the rest of the gases passes through an additional active carbon filter and is conducted outdoors through a pipe system.

All components that are in contact with the condensate or are active- or passively heated are made of stainless steel. The pipes have a minimum diameter of 5 mm.

The control system is based on the Siemens Simatec S7-1200 and visualized with Siemens WinCC Runtime Advanced. All frequency inverters of the screw motors can be controlled and adjusted through the user interface. The inlet screw is equipped with an automatization and enables feeding rates beyond the capacity of the frequency inverters. This is achieved by a definable pause and run times.

The lab scale plant of the Thermo-Catalytic Reforming technology has also been described in several publications [25,48].

5.1.2 Experimental Procedure

To ensure the same quality standard and the experiments' repeatability, a checklist and several document forms are in use. Plant preparation and post-experiment follow-up are part of the experimental procedure.

The preparation of the experiment can start as the plant is cleaned from previous trial residues and the safety equipment is available. Personal carbon monoxide detectors must be worn during all work at the plant. After a visual inspection of all plant relevant components with a focus on safety-relevant components, a practical verification is carried out. All bolted connections are reviewed and the safety-relevant parts tested. All thermocouples and the pressure sensor are validated, and the electronic components are tested.

If these preliminary tests are successful, a gas tightness test is performed at 50 mbar beyond estimated operation pressure. The plant is flushed with nitrogen, and the gas outlet is closed by a ball valve. As soon as the pressure level is above 90 mbar, the nitrogen flow is stopped, and the ball valve closed to prevent backflow. If the pressure drop is below 5 mbar per minute, the plant can be considered as gas-tight, and the preparations can be continued. The gas measurement system is the next part that must be tested. It is mandatory to know that the plant is oxygen free before any feedstock can be fed into the reactors. The plant is flushed with nitrogen at operating pressure (30–50 mbar) and the gas flow is channeled to the gas measurement device until the amount of oxygen is below 0.5 vol%.

These pre-tests assure that the plant is assembled correctly, gas-tight, and all relevant safety devices are working. Once the preliminary checks succeed, the plant can be heated up to the operating temperatures. As soon as the temperatures are stable in the system, the first cooler can be activated, and the second cooler must be filled with ice. After reaching operating temperatures, the feedstock is filled in the hopper and purged with nitrogen to ensure an oxygen-free environment within the plant. The trial can be started if the gas measurement device detects no oxygen.

All the data is recorded online except for the gas counter (Figure 3 ⑫) that must be read off manually. Every 15 minutes all relevant parameters are recorded manually in the trial documents. Every 45 minutes the condensate is released.

The trial is successfully finished when no more feedstock remains in the hopper and gas is no longer being produced within the system. Following trial completion, the heating units are shut off. When the temperature within the horizontal reactors is below 650 K, the operating screws can be stopped.

The experiment follow-up procedure starts approximately 12 hours after the operating screws are stopped when the temperatures within the vertical reactor are below 300 K. The primary focus of the experiment follow-up is to measure relevant quantities for the mass balance and take homogeneous samples of the products. Therefore, the vertical reactor is disassembled to extract the carbonisate. Residues in the hopper and the horizontal screw reactor are removed and weighed. The condensate is filled in a separation funnel to separate the oil and aqueous phase. For the mass balance, all products, the washing bottle, and the filters are weighed. Additionally, all gas leading parts are cleaned and inspected for deposits or damages.

For proper experiment analysis, all relevant data is collected and evaluated. This includes the results from the laboratory as well the results from the on-line gas measurement. A detailed description of the gas measurements system follows in section 5.1.3. Because the TCR is set up as a batch process, evaluating the data requires an interval determination: only the data from the steady-state-operation of the plant is used to represent the experiment. Therefore, it is essential to utilize the gas composition and property data from this specific steady-state interval. It can be assumed that steady-state-operation has been reached when gas composition and the gas building rate is stable with only small variation over time. Thus, it is possible to utilize the acquired batch scale TCR-2 results for continuous larger scale TCR plants.

5.1.3 Analytical Methods and Measurements

The measurement devices used for the TCR trials can be broken down into on-line and off-line devices.

The gas measurement devices are on-line. This means that the gas is monitored by continuous measurement through a tube connecting the TCR plant with the devices. For the volumetric determination of the produced gas, a residential natural gas diaphragm gas meter (EN 1359:2017) is used [191].

The cooled gas is pumped through a heated tube to the gas detection system. The setpoint temperature of the tube is 453 K to prevent any condensing. The gases are cooled down to 276 K by a GCU gas cooling unit, from Dr. Födisch Umweltmesstechnik AG, and the condensable substances are collected. The detection system, manufactured by Dr. Födisch Umweltmesstechnik AG (Germany), can detect CO, CO_2, CH_4, C_xH_y, O_2, and H_2. Three different measurement devices are integrated into the system. An infrared photometer detects the volumetric amount of CO, CO_2,

CH_4, C_xH_y. An electrochemical cell detects O_2 in the gas stream, and a thermal conductivity sensor detects H_2.

The thermal conductivity sensor and the infrared photometer are affected by side effects of CH_4, CO_2, C_xH_y components, and H_2. To decrease these, Dr. Födisch Umweltmesstechnik AG developed a formula empirically to reduce the impact of the effects. The target was to detect the H_2 content as accurate as possible justifying the composition of TCR gas from biogenic feedstocks. Therefore, CO_2 and CH_4 were identified to have the highest impact on the measuring. To meet the requirements to quantify the volumetric yield of H_2 accurately, the following correlation was developed (Formula 1).

$$H_{2,corr} = H_{2,raw} - (-0.00174 \times (CO_2)^2 - 0.13109 \times CO_2) - (0.00114 \times (CH_4)^2 + 0.12092 \times CH_4)$$

Formula 1: Hydrogen correction term developed by Dr. Födisch Umweltmesstechnik AG

The decision was taken to neglect the influence of C_xH_y due to the expected low quantity of hydrocarbons in the TCR gas. Thus, the influence of C_xH_y on the accuracy of the CH_4 measurement was not taken into consideration.

In most of the experiments, it is not possible to close the balance of the gases. One reason for this is that nitrogen or sulfur components are not detectable with this configuration. Also, the side effects mentioned earlier cause inaccuracies.

The standard deviation of the operated gas detection system is ± 2 vol% [192].

To specify the measured components, a type 7890A gas chromatograph with a flame ionization detector and thermal conductivity detector (GC-FID/TCD) from Agilent Technologies Inc. was used.

A portion of the cooled gas stream is pumped to a gas calorimeter to measure the gas in accordance with DVGW codes of practice G 260 [108]. The CWD 2005 from Union Instruments performs a direct measurement of the density and the Wobbe Index. An acoustic density measurement is used to specify the specific density (d_n). For calculations of $\rho_{n,gas}$, $\rho_{n,air}$ was set regarding DIN 1343 at 1.2931 kg/m as it is simplified at $T_n = 273.15K$ and $p_n = 1013.25\,hPA$ [193]. Due to the likelihood of confusion between the German nomenclature of the DIN norm and the BS EN ISO 13443 standard the index *n* is used [194].

The Wobbe index ($W_{s,n}; W_{i,n}$) is measured by combustion the gas with the aid of a burner. The higher heating value ($HHV_{s,n}$) of the gas is constantly calculated according to Formula 2.

$$HHV_{s,n} = W_{sn} \times \sqrt{d_{rd}}\ ;\ d_n = \frac{\rho_{n,gas}}{\rho_{n,air}}$$

Formula 2: Determination HHV of the gas ($\boldsymbol{W_{sn}}$: superior Wobbe index, $\boldsymbol{d_{rd}}$: relative density at 273.15 K and 1013.25 hPA)

The standard deviation of the operated CWD 2005 is ± 1% [195].

The gas measuring devices are calibrated with synthesis gas on a regular basis. The volumetric composition of the syngas is 20% CO, 20% CO_2, 40% H_2, 12% N_2, and 8% CH_4.

The off-line analytical methods include all feedstock and product analytics. The moisture and ash content of the feedstock and the solid product is determined according to the related ASTM standards [196–203]. For all weight measurements regarding moisture and ash content, a QUINTIX513-1S from Sartorius AG was used. The readability and repeatability is 1 mg.

The water content of the oil is determined by Karl-Fischer titration. The total acid number (TAN) of the oil samples was also determined by titration. 915 KF Ti-Touch and 916 Oil Ti-Touch from Metrohm AG are used for these measurements.

The ash content of the oil was determined in an external laboratory according to DIN 6245 [204]. Several oils from different feedstocks were analyzed, and the ash content for each oil was found to be in the same range. Therefore, it can be assumed that the ash content in the oil is always in the range of <0.1 wt% and no further analysis was carried out.

The elemental composition (CHNS, missing O) of the dried feedstock and products are carried out with a Vario MACRO cube from Elementar Analysensysteme GmbH. The samples were analyzed in triplicate with a sample size of approximately 20 mg.

The higher heating value (HHV) of the samples (feedstock, carbonisate, oil) are measured with a C2000 calorimeter from IKA®-Werke GmbH & Co. KG according to BS EN ISO 18125:2017. The lower heating value is calculated by Formula 3 with the hydrogen content determined by CHNS and the moisture content. [205]

$$LHV = HHV - 2{,}441\left(m_{H_2O} + 9 \times m_H\right) {}^{MJ}/_{kg}$$

Formula 3: LHV calculation by using HHV, moisture content and CHNS analysis ($\boldsymbol{m_{H_2O}}$: mass water, $\boldsymbol{m_H}$: mass hydrogen)

For all weight measurements regarding CHNS, titrations, and calorific value, an ML54 from Mettler-Toledo AG was used. The readability and repeatability are 0.1 mg.

For elemental analysis of chemical elements in the feedstocks and products, an energy dispersive X-ray fluorescence (EDXRF) is in use. This benchtop spectrometer from PANalytical B.V. (Epsilon 3^{XLE}) measures under helium atmosphere qualitative and quantitative elements from sodium to americium.

The oil and water separation is performed by gravity. The condensate is collected for 14 hours in a conical separation funnel.

For all weight measurements regarding the mass balance, a KERN PNJ 12000-1M with automatic internal adjustment was used. The weighing range is 5−12000g with a readout of 0.1 g.

The mass balance is one of the key results of a trial and is calculated by Formula 4.

$$m_{fp} = m_c + m_g + m_a + m_o + m_n$$

Formula 4: Determination of the mass balance ($\boldsymbol{m_{fp}}$: mass of processed feedstock without residues in the hopper, $\boldsymbol{m_c}$: mass carbonisate, $\boldsymbol{m_g}$: mass non-condensable gases, $\boldsymbol{m_a}$: mass aqueous phase, $\boldsymbol{m_o}$: mass oil, $\boldsymbol{m_n}$: non-detectable masses)

The mass balance is the basis of the energy balance and the economic assessment which is crucial for designing up- and downstream processes and for upscaling the technology. Therefore, it is essential to work as accurately as possible to create repeatable results. Consequently, it is critical to follow documentation and the checklists of the trial described in section 5.1.2. The aim is to monitor and assess all material flows within the system, starting with the preparation of the feedstock. The sample must be as homogeneous as possible. However, biogenic feedstocks, such as organic municipal solid waste are very inhomogeneous. Therefore, it is essential to have a representative feedstock sample by means of particle size, composition, density, and water content. A more considerable amount of the biogenic material enables to get feedstock samples as homogeneous as possible. The large capacity of the hopper of the TCR-2 in comparison to other lab scale plants supports the robustness of the results. Moreover, a homogeneous sampling of the feedstock for the analysis of the moisture, ash, and CHNS content as well the measurement of the HHV is crucial.

The exact amount of feedstock that is filled in the hopper needs to be determined before the start of the experiment.

After the trial has concluded, the relevant measurements must be made. These include recording the quantity of carbonisate, condensate, and residues in the hopper, horizontal reactor, and the gas treatment systems. The mass of residues in the hopper is deducted from the feedstock to calculate the processed amount of feedstock. The residues in the horizontal reactor are below 2 wt%. Analysis has shown that most of the residues in the horizontal reactor are not fully carbonized; for this reason, they are not recorded as carbonisates and deducted from the processed feedstock amount. The residues in the gas processing, extend to a large part of condensable hydrocarbons. In an industrial plant, these condensable are fully recovered by an electrostatic precipitator (ESP). These are therefore assigned to the overall oil production.

During the trial, the volumetric gas production is measured as described earlier with a diaphragm gas meter. With the data accomplished by the acoustic measurement of the density by the CWD 2005 the approximate amount of gases can be determined (Formula 5).

$$m_g = \sum_{t=0}^{n} V_{n\,gas} \times \rho_{n\,gas}$$

Formula 5: Gas amount (weight) calculated by measurement ($\boldsymbol{V_{n\,gas}}$: gas volume, $\boldsymbol{\rho_{n\,gas}}$: corresponding density)

Uncertainties are related to the delay of the measurement and the data collection. The delay is due to the different placement of the measurement devices. The volumetric gas counter is placed before the gas stream is divided (Figure 3). The gas measurement systems are placed in the control room, and this causes a delay of approximately 90–150 seconds. The measurement error of the gas stream due to the needed pipe heating, cooling, and condensation related condensation is negligible. The uncertainties are due to the data collection of the gas counter. Contrary to the other measured data that are logged every second, it is not recorded online. Every 15 minutes the volume is recorded manually in the documents. During the steady-state operation of the plant, the delay in data recording is not an issue, however during the start-up and shut-down phases, this delay can cause uncertainties. To account for the mentioned uncertainties, the calculated gas amount is reviewed (Formula 6). The gas amount calculated by difference is compared with the calculated amount of gas.

$$m_g = m_f - m_{fr} - m_{rf} - m_c - m_a - m_o$$

Formula 6: Gas amount calculated by difference ($\boldsymbol{m_f}$: mass feedstock, $\boldsymbol{m_{fr}}$: mass feedstock residues in the hopper, $\boldsymbol{m_{rf}}$: mass filter residues, $\boldsymbol{m_c}$: mass carbonisate, $\boldsymbol{m_a}$: mass aqueous phase, $\boldsymbol{m_o}$: mass oil)

The results have proven that the determination of the gas amount by Formula 5 is very accurate. The amount of non-detectable mass (noted m_n in Formula 4) is correlated with the size of the plant. Due to the dimension of the reactors and the post processing components, as well as uncertainties in the gas measurements, a minor amount of mass is not detectable.

The distribution of the products is an important outcome of the mass balance. The yields of carbonisate, gas, oil, and aqueous phase per processed feedstock are calculated by Formula 7.

$$w_i = \frac{m_i}{m_{fp}}\,;\sum_{i}^{n} w_i = 1$$

Formula 7: Determination of the yields ($\boldsymbol{w_i}$**:** yield, $\boldsymbol{m_i}$: mass of the product, $\boldsymbol{m_{fp}}$: mass of the processed feedstock)

The energy balance is calculated by the energy input of the feedstock and regarding the energy output of the products carbonisates, gas, and oil (Formula 8). In the formula a discrepancy factor (D) is also used. This expresses the difference between the energy content of the feedstock and the energy content of the products. Because the pyrolysis reactions are endo- and exothermic processes, a discrepancy is expected. This factor also includes measuring inaccuracies and deviations especially due to the periods before and after reaching steady-state operation (section 5.1.2).

The energy consumption of the plant is not considered. This is due to the lab scale of the plant and therefore the relatively low energy efficiency of the heating system. The heat losses of small-scale applications are highly disproportional in comparison to industrial scale plants. The surface-area-to-volume ratio is a vivid reason for this.

$$m_{fp} \times LHV_f = m_c \times LHV_c + m_g \times LHV_g + m_o \times LHV_o + D$$

Formula 8: Determination of the energy balance ($\boldsymbol{m_{fp}}$: mass of the processed feedstock, $\boldsymbol{LHV_f}$: lower heating value of the feedstock, $\boldsymbol{c}$: carbonisates, $\boldsymbol{g}$: gas, $\boldsymbol{o}$: oil, $\boldsymbol{D}$: discrepancy)

Nevertheless, several trials have been performed for the determination of the energy consumption for heating. A distinction was made between the following four stages of plant operation: First, the energy demand for heating up the plant to the set temperatures. Second, the energy demand to maintain the desired temperature while the feedstock is loaded into the plant. Third, the energy consumption of the plant during steady-state operation. Lastly, the fourth stage is the energy consumption at the end of the trial, when no gases are built, and the vertical reactor is filled. By subtracting the mean of the second and fourth case from the third case, the real energy demand for processing the feedstock is approximated. The energy demand depends heavily on the moisture content and the composition of the feedstock. To take this into account, the LHV of the feedstock as it processed in the process (moisture) is used. The results are presented in Table 2. Even though the results are approximate estimations, there is a clear trend in the energy demand of the different heating zones in the horizontal and vertical reactor. The bottom section of the vertical reactor has the highest energy demand followed by the middle section of the horizontal reactor. This matches the expectation regarding the temperature and the active reaction zones of the reactors.

Table 2: Energy consumption of the TCR-2 plant (lab scale)

Feedstock	LHV (wet) [MJ/kg]	Proportional energy demand with heat losses [%]	Proportional energy demand without heat losses [%]	Horizontal reactor			Vertical reactor	
				1 [%]	2 [%]	3 [%]	1 [%]	2 [%]
Digestate	13.3	35.5	14	5	31.5	7	23	33
Sewage sludge	10.7	47.2	11.5	6	27	7.5	25	34.5

To approximate the behavior of the feedstock in the TCR regarding degradation in relation to the temperature, TGA and DSC were used. For TGA and DSC a STA 409 PC *Luxx*® thermal analyzer and DSC 204 F1 Phoenix from NETZSCH-Gerätebau GmbH were used. The heating rate was 5 K·min-1 in a nitrogen flow within alumina crucibles.

Statistical Methods

The statistical methods follow the ISO guidance 100:2008 for the evaluation of measurement data. The arithmetic mean $\bar{t}$, experimental standard deviation $s(t_k)$, and standard uncertainty $u(\bar{t})$ of the mean are used to evaluate the robustness of the data. [206] The interpretation of the results are in line with BS 2846:1 [207].

For each trial, the arithmetic mean is the basis for further calculations (LHV, mass balance, energy balance). For the overall data evaluation of a trial series, the data of the trials are averaged. Therefore, the averaged data is not used as a basis for new calculations of the specific data of the average results.

5.2 Trial Setup and Analytics of Feedstock

The trial setups for all biogenic and non-biogenic fuels were similar. Only minor adjustments regarding the feedstock characteristics were necessary. The temperatures within the horizontal reactor were 473 K in the first zone and 673 K in the second zone for all trials. The temperature in the last zone was 673 K but had to be adjusted for the woody biomass feedstocks.

During the pre-trials with woody biomass, severe problems were observed. For example, a blockage between the horizontal and the vertical reactor caused a pressure increase in the system. This led to the screws becoming blocked from the accumulation of solid products within the reactor. This blockage was caused by the solid intermediate product softening temperature. During the disassembly of the plant within the standard follow-up procedure, it was evident that softening occurred in the transition zone. First attempts to avoid the blockage by improving the insulation in the transition zone were not successful. However, a temperature increase by 100 K in the third zone was successful. The aim was to shift the temperature frame where the intermediate solids are softening in the first segment of the discharging zone.

Because of the higher wall temperature, the heat flow is increased, and the adhesive phase is passed faster and earlier. This effect has been described in literature for rotary kilns [208].

The softening phase is the reason for the different temperature settings of woody biomass in comparison to the other feedstocks within the last zone of the horizontal reactor.

The standard temperature in the vertical reactor was for all trials 973 K. The targeted feeding rate was 2 kg/h for all trials. Due to the different densities of the feedstock, the speed of the first screw had to be adjusted for each feedstock. The speed of the mixing and discharging screw as well as the configurations and parameters of the downstream processes were the standard settings described in section 3.2.

In the following section, the processed feedstock samples are described and characterized.

Sewage Sludge

Three different sewage sludge samples were tested within the frame of this work. To represent a large variety, raw and digested sludge samples were used. These samples represent different types of communal sewage sludge from different treatment technologies as described in section 2.1.1. The sludge samples were provided by wastewater treatment plants in Germany and the Netherlands. The digested sewage sludge (DSS) sample was processed in a wastewater plant located in the district of Nuremberg, Germany. The facility has a capacity of 30,000 population equivalents. The raw sewage sludge (RSS) samples were processed in the western portion of the Netherlands. All sludge samples are mechanically dewatered and thermally dried by the companies. The sludge from the German plant is dried with a solar dryer. The pelletization process was done at Fraunhofer UMSICHT.

Woody Biomass

Three different samples of agriculture woody biomass residues (Olive [Olea europaea] (OL), Evergreen Oak [Quercus ilex] (EO), and Vine Shoots [Vitis vinifera] (VS)) were provided by Centro de Investigaciones Científficas y Tecnológicas de Extremadura (Cicytex). The feedstock was collected in 2015 and preconditioned (pelletized).

Seaweed

Eight different samples of seaweed were processed in the lab scale TCR-2. These samples were utilized within a framework of a project with a university in the United Kingdom in 2016. The samples were collected and preconditioned by the University. The seaweed collections are not directed to a specific species. It represents different origins (beach, muscle) and collection times (seasonal). Therefore, the trials are summarized, and the spectrum of the results is indicated by the experimental standard deviation $s(t_k)$, and standard uncertainty $u(\bar{t})$ of the mean. Noticeable is the high content of inert components due to the impurities during the collection process.

Organic Fraction of Municipal Solid Waste

The organic fraction of municipal solid waste (oMSW) was provided by two companies from the United Kingdom and the Netherlands. In section 2.1.4, the separation of the organic load of MSW has already been described and the associated issues regarding the impurities and inhomogeneity of the oMSW. It must be emphasized that the composition of the two samples were very different. The samples were processed without any further pretreatment to evaluate the suitability of the feedstock straight from the industrial processing.

Leather Residues

Three different residues from the leather manufacturing process were tested in the TCR technology. Swarf (SWF), limed leather residues (LLR), and industrial sewage sludge (ISS) are residues from different stages of the leather production (section 2.1.5) and were made available by a leather processing company in Germany. These samples cover a wide range of process waste streams from the leather manufacturing process with the related particularities. As described in section 2.1.5 the contamination with chromium is dependent on the process step. Due to this, limed leather residues are free of any chromium load. By contrast, swarf and sewage sludge are contaminated with chromium (Table 3).

Table 3: Chromium content of the processed feedstocks

		SWF	LLR	ISS
Chromium	[mg/kg]	40,000	0	50,000

The sewage sludge from the wastewater treatment plant of the leather company is very different regarding the composition in comparison to sewage sludge from wastewater treatment plants that handle communal wastewaters with only a small fraction of industrial wastewaters. This is not only in terms of CHNS composition but particularly in the amount of heavy metals. Therefore, the utilization of the products from industrial sludge is even more restricted. For this reason, sewage sludge from the leather industry is an example of an industrial sludge and not categorized in the sewage sludge segment.

Peat

Peat was purchased as a briquette, trademark "Scharreler Gold", from a company in north-western Germany. The peat used for briquetting is a residue from the production of soil and growing medium for professional garden application. Dried peat that is inappropriate for commercial horticulture is sold for energetic utilization. The briquettes have a 150×60×60 mm diameter and were crushed and sieved to a grain size of 1 mm<x <20 mm.

Lignite

Two different lignite feedstocks were selected for the TCR-2 trials. Due to the various qualities of lignite described in section 4.1 the samples were from the two main lignite mining fields in Germany. The unavailability of raw lignite in the market made it necessary to use refined lignite as a backup. Fluidized bed lignite from the Rhenish mining field was used. The pretreatment of the char includes crushing to a fixed particle size of 0–6 mm and subsequently processed in a patented fluidized-bed drying with internal waste heat utilization (WTA) technology at approximately 383 K at 1.1 bar [181]. Fluidized bed lignite is used as an energy source to produce heat and steam in medium-to-large-scale combustion processes. The feedstock has a grain size of 0–4 mm. It was necessary to sieve the lignite to a grain size >1 mm.

The second feedstock sample was briquetted lignite from the Lusatia mining area with the trademark "REKORD". The production of the briquettes requires the same pretreatment as the production of the fluidized bed char. The processed lignite is pressed without binders under high pressure and steam in the briquette form without supplementary substances [139]. The size of the briquettes is 182×59 mm and was crushed to a granulate size <20 mm and sieved to a grain size >1 mm.

The physical and chemical compositions of the feedstocks are shown in Table 4.

Table 4: Feedstock characterization on dry basis (*: calculated by difference)

		Woody biomass [48]			Algae	Sewage sludge			oMSW		Leather residues			Fossil		
		OL	EO	VS		RSS (a)	RSS (b)	DSS	oMSW (a)	oMSW (b)	SWF	LLR	ISS	Peat	Lignite	
															Rhenish lignite	Lusatia lignite
C	[wt%]	44.9	44.2	47.8	34.9	38.2	43.7	32.0	30.9	47.9	45.3	47.7	20.63	50.2	58.7	61.3
H	[wt%]	6.5	6.3	6.2	3.9	5.7	6.7	4.7	4.1	6.1	7.0	7.7	3.4	5.7	5.9	4.6
N	[wt%]	0.4	0.5	0.6	1.4	6.5	6.8	4.8	1.6	1.6	13.1	7.3	1.7	1.2	0.7	0.7
S	[wt%]	0.06	0.04	0.05	1.1	1.4	0.8	0.95	1.3	0.3	2.2	1.9	3.5	0.34	0.26	0.57
H:C		1.73	1.68	1.54	1.33	1.77	1.82	1.73	1.57	1.51	1.84	1.92	1.96	1.35	1.20	0.89
O:C		0.77	0.77	0.65	0.73	0.48	0.4	0.41	0.49	0.24	0.38	0.35	0.58	0.52	0.40	0.33
Ash	[wt%]	2.16	3.60	4.08	24.8	23.8	18.9	39.9	42.1	29.2	9.6	13.2	54.8	7.6	3.5	5.6
O*	[wt%]	46.0	45.4	41.2	33.9	24.4	23.1	17.6	20.1	15.1	22.7	22.2	15.9	35.0	31.0	27.3
HHV	[MJ/kg]	19.3	19.6	19.2	13.6	17.2	20.2	14.6	13.7	19.2	21.5	26.4	8.5	20.5	22.5	24.0
Moisture	[wt%]	8.7	10	7.6	12.1	10.5	21.1	17.4	24.5	5.7	9.7	30.4	14.6	14.0	20.1	16.3
Conditioning		Pellet	Pellet	Pellet	Pellet	Pellet	Pellet	Pellet	Granulate	Pellet	Granulate	Granulate	Granulate	Granulate	Granulate	Granulate

5.3 Co-Pyrolysis Trial Setup

The experimental matrix of the co-pyrolysis trials is shown in Figure 4. Different mixtures of sewage sludge and lignite were examined, and reference trials with each feedstock were performed. The industrial application of the co-pyrolysis of lignite and a biogenic residue was in focus throughout the planning stage of the trials. This is the reason for choosing the mixture rates from 50:50 wt% to 75:25 wt% with the high number relating to lignite. The impact of the catalytic reforming process of the TCR technology was evaluated at three different temperatures in the reforming stage. Four different feedstock mixtures at three temperature levels were investigated. The temperatures in the horizontal reactor, where the intermediate pyrolysis takes place, were constant for each trial. The first evaporating zone had a temperature of 473 K. The second and third zone the temperature was set at 673 K. The targeted feeding rate was 2 kg/h. The speed of the mixing and discharging screw and the settings of the downstream processes were the standard settings described in section 5.1.1.

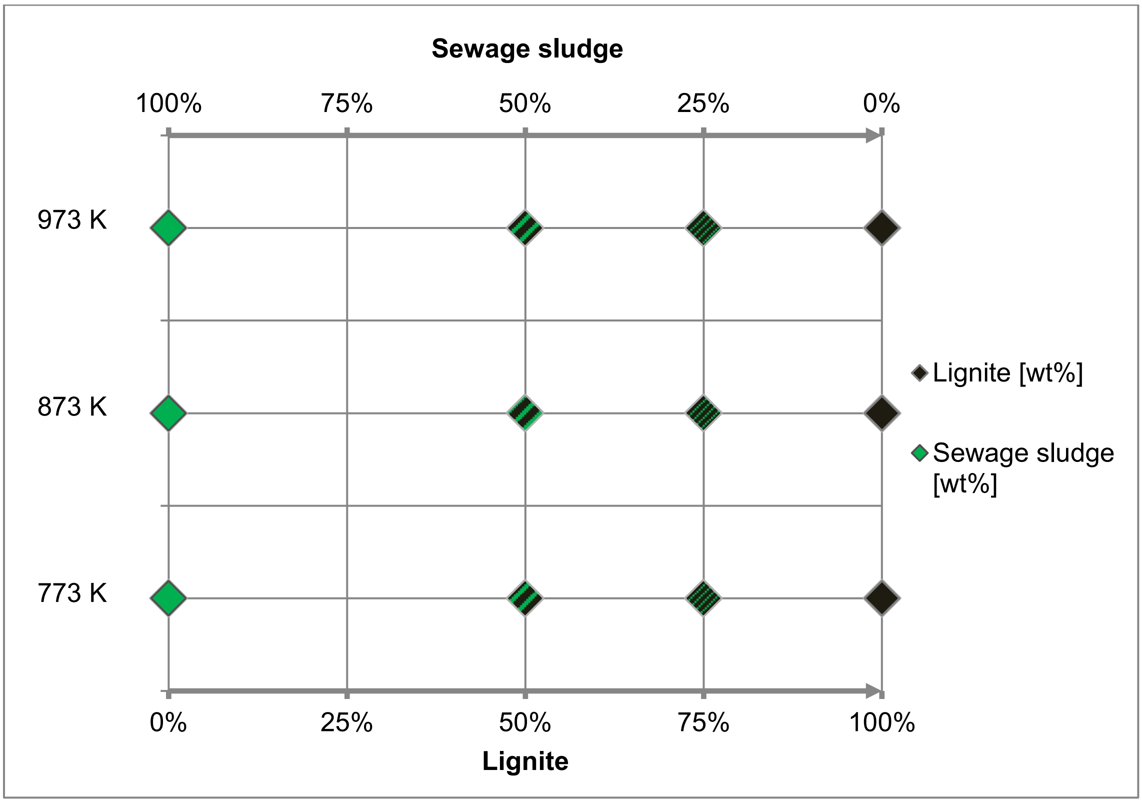

Figure 4: Experimental matrix of mixtures sewage sludge and lignite co-pyrolysis trials in relation to the reforming temperature

The source of the processed lignite was the Lusatia mining area located in western Germany. Lignite briquettes sold under the brand name REKORD were used because no raw lignite was available. The briquettes were crushed into a small granulate with a grinder to achieve an appropriate conditioning of the feedstock to process it in the TCR-2 (as described in section 5.2).

The sewage sludge was provided by a medium-large wastewater treatment plan in Germany. The sludge was digested and solar dried (as described in section 5.2). The batch was received in August 2016.

To distinguish between sewage sludge and lignite carbonisates, different kinds of conditioning of the feedstocks were chosen. This enabled an optical characterization of each carbonisate and eliminated the risk of any impurities. This was critical in evaluating the impact of co-pyrolysis on the solid products. For this purpose, the sewage sludge was pelletized with a KKP300/F Universal from oil press GmbH & Co. KG. Separate tests were conducted to ensure that the preconditioning of the feedstock (pelletized vs. un-pelletized) did not impact the results. No correlation between the preconditioning and the yields were observed.

To exclude the influence of different feedstock moisture levels, it was mandatory to achieve the same water content in both feedstocks. As the water content of lignite granulate is bonded in the interstitial and molecular structure, it was not conducive to adjust the water content of the lignite [182]. Conversely, the water content of the pelletized sewage sludge is difficult to adjust without negatively impacting the stability of the pellets. To compromise, water was added before the pelletizing process. Several tests were needed to achieve the targeted moisture content of approximately 16.5 wt%. The elemental composition, as well as the ash content and the HHV, are shown in Table 5. The composition of the feedstock blends can be derived from a linear transformation of the composition of the feedstocks (Formula 9).

$$x_{mix} = (x_{LG} \times y) + (x_{SS} \times (1 - y))$$

Formula 9: Calculation of the predicted distribution (mass and energy balance) of the mixed trials ($\boldsymbol{LG}$: lignite, $\boldsymbol{SS}$: sewage sludge, $\boldsymbol{y}$: share of lignite in the feedstock mixture)

The elemental composition of the feedstock (Table 5) indicates that two of the three central synergetic mechanisms described in section 4.4 could influence the TCR process reaction. Sewage sludge has a higher value of H:C ratio (1.73) in comparison to lignite (0.89). The ash content of sewage sludge is significantly higher than the ash content of lignite. Bachhiesl et al. had revealed by examples the different composition of the ashes from sewage sludge and lignite [209]. This effect is reinforced by the different amount of ash in the feedstocks.

Table 5: Feedstock characterization of lignite, sewage sludge, and related blendings on dry basis (*: calculated by difference; **: calculated by using Formula 9)

		Lignite	**Sewage sludge**	**LG-DSS 50:50** **	**LG-DSS 75:25** **
C	[wt%]	61.3	32.0	46.65	53.98
H	[wt%]	4.6	4.7	4.65	4.63
N	[wt%]	0.7	4.8	2.75	1.73
S	[wt%]	0.57	0.95	0.76	0.67
H:C		0.89	1.73	1.31	1.1
Ash	[wt%]	5.56	39.88	22.72	14.14
O*	[wt%]	27.3	17.6	22.45	24.88
HHV	[MJ/kg]	24.0	14.6	19.3	21.65
Moisture	[wt%]	16.3	17.4	16.85	16.58
Conditioning		Granulate	Pellet	Granulate/ Pellet	Granulate/ Pellet

Furthermore, TGA and DSC, as well as derivative thermogravimetric analysis (DTG) of the feedstock samples and the mixtures thereof (50:50 wt%), were performed (Figure 5). The thermal analysis was under a nitrogen atmosphere with a heating rate of 5 K/min. The TGA curves indicate that the degradation of lignite and sewage sludge is different. The TGA–DTG curves in Figure 5 reveal that the decomposition of sewage sludge starts at significantly lower temperatures than the decomposition of the lignite sample. The DSC curve indicates that the degradation of lignite is significantly more exothermic than of sewage sludge. The results are in agreement with other studies [210–213]. The final mass change of the mixture sample was not in the expected range. The mass loss of the mixture (53.5 wt%) was lower than for the single feedstock (55.5 wt% sewage sludge, 54.6 wt% lignite). This is strong evidence that the in section 4.4 described central synergetic mechanisms have an impact on the co-pyrolysis of fossil and biogenic fuels.

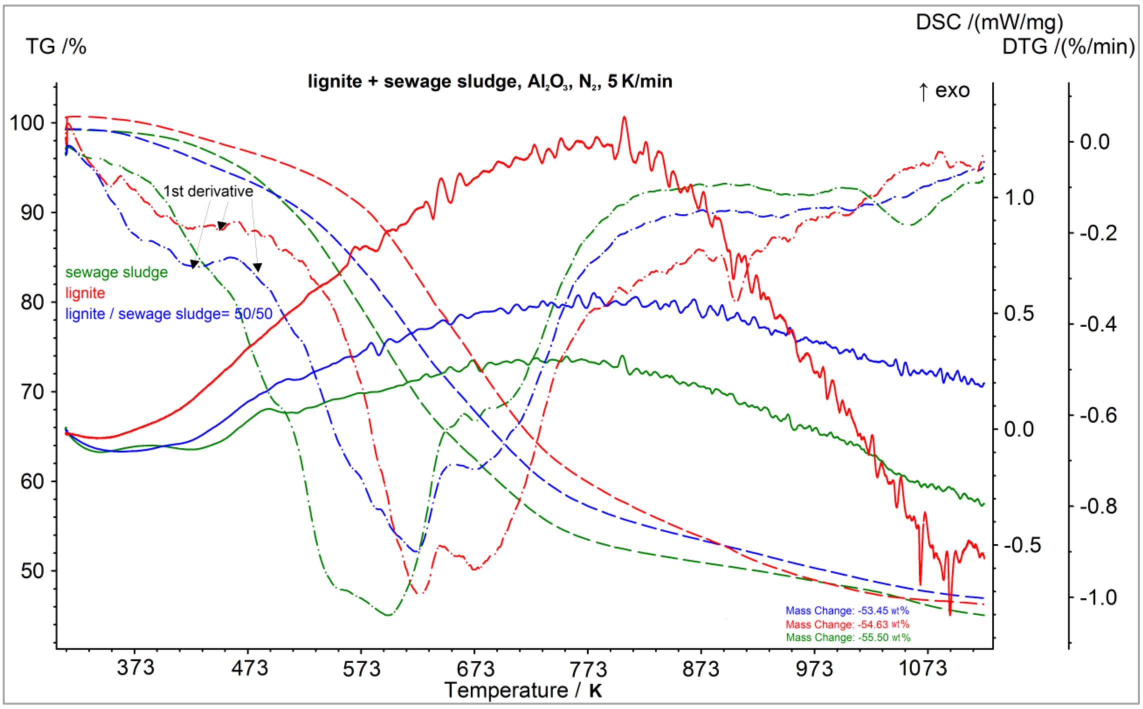

Figure 5: TGA and DSC of sewage sludge, lignite, and mixtures thereof

To verify the results, a series of experiments with a completely different feedstock composition in comparison to sewage sludge were performed. Lignite and birch wood chips with a blending ratio of 50:50 wt% at a temperature of 973 K within the vertical reactor were used. As described in 2.1.2, woody biomass has low ash content and a very different composition than sewage sludge. Therefore, the product distribution and composition are different.

6 BACKGROUND OF THE TECHNO-ECONOMIC EVALUATION OF TECHNOLOGIES

In the following section, the basis of the economic evaluation is elaborated. The theory and advantages of levelized unit costs and levelized unit revenues are presented in section 6.1. The system boundaries and technology configurations are described in section 6.2. Within section 6.3 the economic data basis is presented. The sensitive analysis to validate the robustness of the results is presented in section 6.4.

6.1 Economic Background

Value-oriented investment decisions are often taken on the basis of financial mathematical calculations. The key objective is to evaluate the benefit of an investment under the expected circumstances in the intended lifetime. Uncertainties need to be evaluated and considered in the calculations. The robustness of an investment decision primarily depends on the proper identification of the uncertainties and the corresponding risks.

Investments decisions with a high substantial initial investment are often made with the help of a net present value (NPV) calculation [214]. Cash flows are discounted to the same point in time and summed up to the net present value. If the NPV is positive, the investment is supposed to be profitable.[6]

---

[6] Derivation and further discussion of the NPV see [215–217].

For investment decisions within the energy sector, the NPV approach is not prevalent, because the evaluation is focused on the specific cost of the products [214]. Thus, for a product orientated evaluation the levelized unit costs (LC) approach is more purposeful (Formula 10).

$$\mathrm{LC} = \frac{I_0 + \sum_{t=1}^{t=n} \frac{A_t}{q^t}}{\sum_{t=1}^{t=n} \frac{W_t}{q_a^t}}$$

Formula 10: Levelized unit costs (LC), real ($\boldsymbol{I_0}$: initial investment costs, $\boldsymbol{A_t}$: expenses and operating revenues beyond the main products, $\boldsymbol{W_t}$: amount of produced main products per operational year, $\boldsymbol{q^t}$: discount factor, $\boldsymbol{q_a^t}$: real discount factor, $\boldsymbol{n}$: imputed period under review (planning, construction, and operation)) [214,218]

The estimated initial investment costs (I_0), expenses (e.g. for maintenance, personnel), and fix operating revenues (e.g. gate fees for feedstock) (A_t) of the plant are discounted and divided by the discounted estimated quantity of produced products (W_t). Consequently, the levelized unit costs are the specific real costs of the products produced over the entire considered project period.

The LC approach is based on the research of the Electric Power Research Institute (EPRI), Organisation for Economic Co-operation and Development (OECD), and of the former Verband der Elektrizitätswirtschaft e. V. (VDEW[7]) [219]. This approach is primarily used for the calculation of the specific real costs of electricity. These so-called levelized costs of electricity (LCOE) were used in several publications to compare different technologies for electricity production [219–224]. As LC are specific costs, it is possible to compare the LCs of different processes with

---

[7] German Electricity Association; today Bundesverband der Energie- und Wasserwirtschaft e. V. (BDEW), German Energy and Water Association

the same product. To assess an individual process, it is more conducive to compare the levelized cost with the possible specific levelized unit revenues (LR) on a real basis.

The calculation of LR is depictured in Formula 11.

$$\mathrm{LR} = \frac{\sum_{t=1}^{t=n} \frac{B_t}{q^t}}{\sum_{t=1}^{t=n} \frac{W_t}{q_a^t}}$$

Formula 11: Levelized unit revenues (LR), real ($\boldsymbol{B_t}$: revenues, $\boldsymbol{W_t}$: amount of produced main products per operational year, $\boldsymbol{q^t}$: discount factor, $\boldsymbol{q_a^t}$: real discount factor, $\boldsymbol{n}$: imputed period under review (planning, construction, and operation)) [218]

The possible revenues of a process are related to the commercialization of the related products. Within this assessment, the products are a substitute for fossil fuels sold at market prices.

Based on the assumptions made, the difference between the LC and LR indicates whether the assessed investment is sustainable or not.

As LC/LR approach is designed for processes with a single product like electricity or transport fuels, it is not possible to use it directly to evaluate the TCR process [220,224]. Therefore, within the framework of this work the LC/LR approach is adapted for multi-product processes.

6.2 Development of the System Boundary

The goal of the economic evaluation is to identify sustainable process chains on the basis of the theoretical backgrounds presented in section 6.1. Therefore, the processes from TCR feedstock to final products were evaluated from an economic point of view. Depending on the characteristics of the feedstock, different applications and markets of the final products were investigated. The TCR products can be utilized by various technologies and applications. Thus, the market-proven technologies, like CHP engines and PSA, were included in the analysis as downstream processes. The developed system boundary of the economic evaluation is depictured in Figure 6.

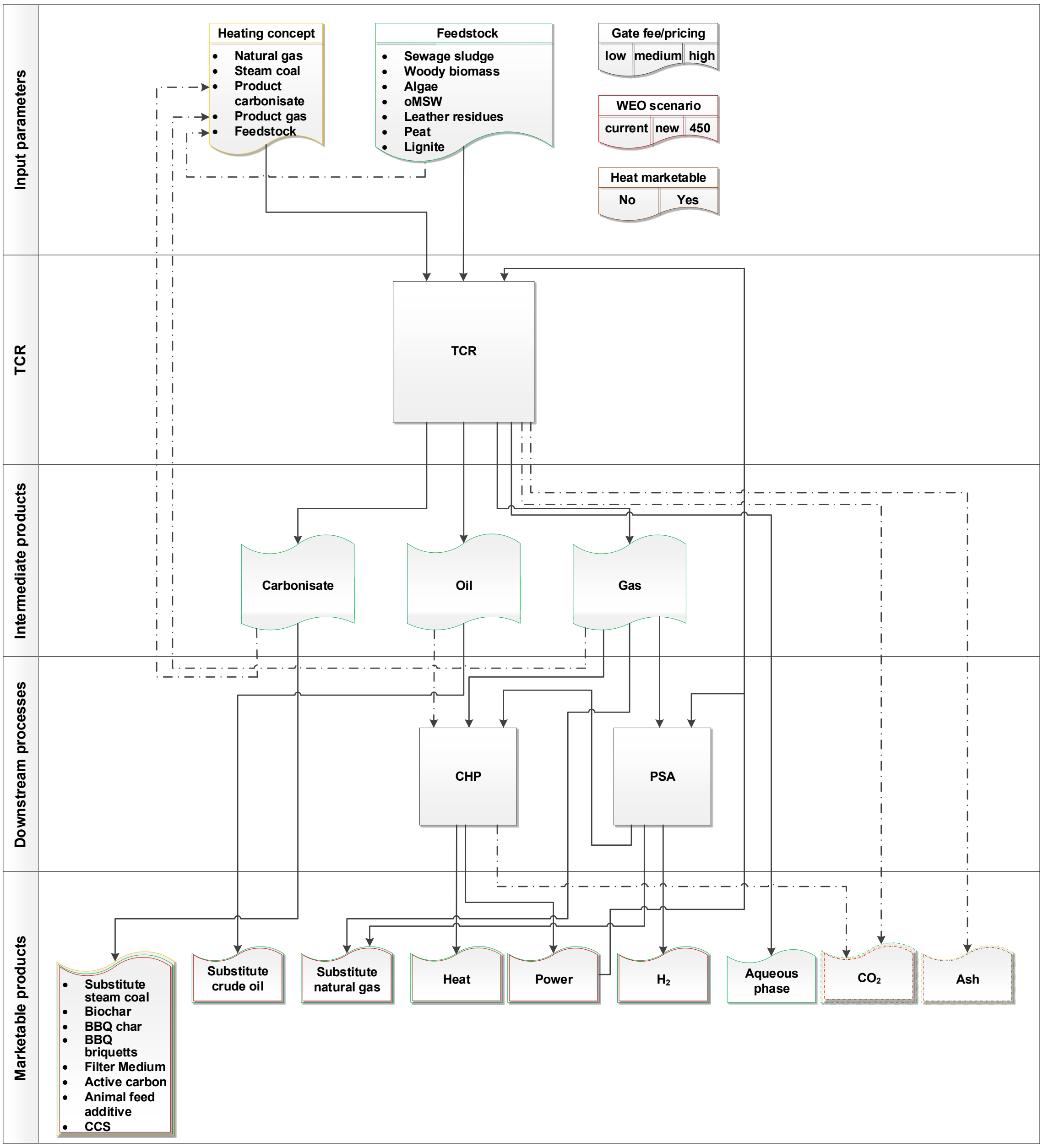

Figure 6: Evaluated process chains and related variables

The first building block is the conversion of biogenic and non-biogenic feedstocks within the TCR technology into three products: carbonisate, gas, and oil. For the heating of the TCR plant, five possible fuels are considered. Besides the fossil fuels, natural gas, and steam coal, the TCR products carbonisate and gas, and the feedstock were investigated. If it is not possible to meet the required energy demand with the products, additional appropriate fossil fuel is used. When using TCR products for heating the plant, the amount of marketable product is reduced accordingly. This has an impact on the LC and mixed levelized revenues (mLR). On the one hand, the decreasing amount of marketable products increases the LC of the products and the mLR. On the other hand, the utilization of TCR products for heating purposes decreases the demand for fossil fuels for heating and thus the variable costs. In addition, this has an impact on the carbon footprint.

PSA and CHP are optional equipment to deepen the value-chain of the products. The base scenario is based on the assumption that the products can be commercialized as substitutes for fossil fuels. TCR carbonisate as a substitute for steam coal and TCR gas for natural gas each, for energy-related use. TCR oil as a substitute for crude oil for a material utilization in a refinery as described in section 2.2. It was assumed that the market values of the substitutes are correlated with the HHV of the substitute in relation to HHV of the fossil fuel. Possible different properties of the products from biogenic sources in comparison to the fossil fuels, as described in section 2.2, are compensated by the sustainable origin. Therefore, no additional price adaptations are needed. This scenario is the benchmark of the following considerations.

First, the solid TCR product pathways are explored. As described earlier, the properties of the TCR carbonisate depend on the characteristics of the feedstock. Thus, each feedstock has different utilization pathways and consequently product values for the carbonisates. In this economic evaluation, a selection of seven possible material usages of the TCR carbonisates is considered. These applications are listed in Figure 6 and described in section 2.2.1.2. The required minimum standards are specified in section 2.2.1.2 and are used to reduce the number of possible utilization pathways. To sell the products directly to the consumer in small quantities is not the core of the business, and thus not considered.

The utilization pathway CCS is limited to carbonisates from biogenic sources. However, when the emission of the TCR heating system exceeds the possible CO_2 saving potential, CCS is not considered as a sustainable utilization pathway of the carbonisates. The product of the CCS pathway is the sequestrated amount of CO_2. It is assumed that existing infrastructure can be used for the sequestration like backfilling the carbonisates in open cast lignite mines. Therefore, no additional costs for the sequestration are included in the calculation.

Each material utilization pathway considered for the carbonisates is compared to the base scenario. The comparison of the different balances of the LC and mLR provides an economic ranking of the utilization pathways for the carbonisate. For the following investigations, the optimum utilization pathway for carbonisates is the new base scenario which is used as a reference in the further investigations.

In the next step, the utilization pathways for the TCR gas are investigated. The energetic utilization pathway of the base scenario is compared with the utilization of the gas in a PSA and/or a CHP. Both alternative utilization pathways are associated with increased investment and operating costs. Also, the quantity of marketable products is reduced.

One essential element of this economic consideration is to assign the additional costs to the cost driving product. The calculated total levelized costs of the process within the base scenario are allocated to products according to their share of the total quantity of products. An increase in the calculated levelized costs of the process is assigned by the difference. The products that are not directly linked to the increased costs keep the value from the base scenario. Therefore, all changes in investment and operating costs are allocated to the products that induce higher costs.

The separation of specific fractions of the TCR gas within a PSA unit is a value-adding process. Within the scope of this work, the separation of hydrogen is investigated. The remaining fractions of the gas as a by-product is marketed as a substitute for natural gas or burned in a CHP engine.

Since CHP plants generate not only electricity but also heat, utilization pathways of both products need to be investigated. Derived from the approach used by the International Energy Agency (IEA), a fixed revenue for the produced heat is used. This heat credit has a value of 44.4 $/MWh_{th}$ for the European market on 2015 basis [224]. Thus, heat is not considered as a separate product, but the income from the heat reduces the variable costs of the process. However, heat as a valuable product is only marketable in a limited range and strongly dependent on long-term customer relationships. For this reason, a second scenario was considered: heat is not marketable and creates, therefore, no additional income.

Each considered utilization pathway is compared to the base scenario. The comparison of mLR and LC enables to identify the most promising value chain for the product gas under the framework conditions.

Besides the commercialization of the TCR oil within a standard refinery process, the oil can alternatively be burned in a CHP engine. As mentioned earlier, for long-term operation the TCR oil is blended with biodiesel in the ratio 3:1. Thus, the considered CHP system is expanded for the combustion of the TCR oil biodiesel blends. This utilization pathway is also compared with the previous optimum scenarios to identify the most sustainable utilization pathway for the TCR oil.

The CO_2 emissions of the TCR plant are related to the heating concept of the plant. If the plant is heated with fossil fuels like natural gas, steam coal or TCR coal from fossil feedstocks, the emissions are calculated from the stoichiometric reaction. If the plant is heated with TCR gas from non-renewable sources, the carbon footprint is calculated by difference (Formula 12) and the related stoichiometric reaction.

$$\mathrm{C_{gas}} = \mathrm{C_{feedstock}} - \mathrm{C_{oil}} - \mathrm{C_{char}} - \mathrm{C_{aqueous\ phase}}$$

Formula 12: Carbon footprint of TCR gas calculated by difference

In addition, if the TCR products from a fossil source are burned in a CHP, the emissions are also calculated.

It is targeted to implement this considered system in a tool with a simple user interface. Excel was chosen for a smooth integration of the tool within existing workflows and to lower entry barriers for users.

6.3 Economic Data

The basis of the economic calculation is the implemented data. The database is as important as the accurate modeling of the system boundaries. The data can be divided into three different sets.

Within the first data set, the key parameters for the determination of the system boundaries and basic investment parameters are defined (Table 6). It is assumed that the plant is in Germany. Therefore, legal framework and associated parameters are set accordingly. The considered model is based on the capacity of the TCR plant. The downstream processes are designed accordingly. The plant capacity was specified after an intense exchange of information with Susteen Technologies GmbH[8]. The plant capacity of 0.5 t/h was assessed as the minimum capacity for a commercial-size plant. The targeted full load hours of 7000 h/a are derived from biogas plants [225].

The project launch as the starting point for the economic calculation is set to the beginning of 2018. The planning and construction period is estimated to be one year each. The allocation of the costs was set to 50% at the beginning of the first year and 50% at the end of the construction period. All cash flows are made at the end of a calendar year. The operating period of the plant was defined to 20 years including 12 years of depreciation time.

The nominal hurdle rate was estimated at 8% [226]. The tax rate of 29.83% is derived from the German legal regulations [227].

The inflation rate is set at 1.5% per year. This rate corresponds to the average inflation rate of the last 20 years [228].

---

[8] Susteen Technologies GmbH is a Fraunhofer spin-off founded in 2014. Susteen Technologies focuses on the worldwide commercial exploitation of the TCR technology.

Table 6: Basic TCR parameters and framework condition of the economic calculation

Country		Germany
Plant capacity	[t/h]	0.5
Full load hours	[h/a]	7000
Project launch	[year]	2018
Planning period	[year]	1
Construction period	[year]	1
Investment costs payment at the beginning of the project	[%]	50
Investment costs payment at the end of construction phase	[%]	50
Operating period	[year]	20
Depreciation time	[year]	12
Hurdle rate after tax (nominal)	[%]	8
Tax rate	[%]	29.83
Inflation rate	[%]	1.50

The second data set refers investment (Table 7) and operational (Table 8) cost data. The costs of the TCR-plant were compiled in close cooperation with Susteen Technologies GmbH. The TCR investment costs consisted of 1,250,000 euros for the reactors, 425,000 euros for additional equipment, 80,000 euros for the combustion chamber for gaseous fuels, 325,000 euros for the site development and estimated 292,500 euros for planning expenses.

The costs to adapt the combustion chamber to solid fuels were estimated with additional 80,000 euros.

The cost of the CHP is dependent on the capacity and is, therefore, route specific. The available amount of gas is reliant on the processed feedstock and whether an additional

PSA is integrated into the downstream processing. Derived from experimental results published by Apfelbacher et al., a CHP engine for digested biogas is selected [149]. The investment costs of the CHP are based on the data of the IEA [224].

The investment costs of the PSA for a TCR-500 with a capacity of 120 kg TCR gas per hour were investigated in cooperation with HyGear Technology and Services BV. The costs of the PSA include the main components of the PSA and periphery components like compressors.

Table 7: TCR-500 and downstream processing investment costs (basis Q3/2017)

Core TCR equipment	[€]	1,250,000
Additional equipment	[€]	425,000
Combustion chamber gaseous fuels	[€]	80,000
Combustion chamber solid fuels	[€]	160,000
Site development	[€]	325,000
Planning	[€]	292,500
CHP	[€/kW_{el}]	1913
PSA	[€/$t_{TCR\ gas}$]	450

The operational costs are summarized in Table 8. The fix operational expenditures (Opex), such as maintenance and assurance, are derived as a fixed percentage of 1.5% of the investment costs [229]. The staffing requirement is estimated with three persons with overall costs of 60,000 €/a per person.

The heat demand for plant operation was approximated with 1983.3 MWh_{th}/a. The power demand of the TCR was estimated at 280 MWh/a for a TCR under the considered framework conditions. The power demand of the PSA depends on the quantity of gas and was set to 0.25 kWh/kg gas. Further operating costs are related to the disposal of residues. If the process is heated with solid fuels, ash disposal costs were set to 30 €/t [230]. The costs for the disposal of aqueous phase were set to 70 €/t. These costs presuppose that the aqueous phase cannot be declared as municipal wastewater.

Table 8: TCR-500 and downstream processing operational costs (basis Q3/2017)

Fix Opex: share of nominal investment costs	[%]	1.50
Personnel	[persons]	3
Personnel costs	[€/a]	60,000
Heat demand	[MWh_{th}/a]	1983.3
Fresh water demand	[t/a]	5000
Freshwater price	[€/t]	1
Power demand TCR	[MWh/a]	280
Power demand PSA	[kWh/kg]	0.25
Disposal ash	[€/t]	30
Disposal aqueous phase	[€/t]	70

The third set of data is regarding the route specific TCR related data. This includes the mass and energy balance, the composition of the feedstocks and products, the properties of the products and consumables. These data are generated by lab-scale trials, as described in section 5.1.2 and are presented in section 7.1.4. Within the data set, also specific data from the downstream processing of the intermediate and final products are included.

The fuel input needed to provide the heat is calculated by the efficiencies listed in Table 9. The efficiencies include the conversion losses of the combustion chamber, tubing, radiation, and temperature gradient and are conservative assumptions.

Table 9: Efficiencies of the heating system

Heating the plant with:	Efficiency [%]
Natural gas	40
Steam coal	35
Feedstock	35
Product carbonisate	35
Product gas	40

The associated CO_2 emissions resulting from heating the plant with fossil fuels are calculated with the values depictured in Table 10. The lowest CO_2 emissions of the considered fossil fuels have natural gas with 0.22 kg CO_2/kWh. Lignite has the highest CO_2 emissions with 0.492 kg CO_2/kWh.

Table 10: CO_2 emissions of fossil fuels [231]

Natural gas	[kg CO_2/kWh]	0.22
Steam coal	[kg CO_2/kWh]	0.3465
Lignite	[kg CO_2/kWh]	0.492

For the operation of a CHP engine, the TCR oil is blended with biodiesel at a ratio of 3:1 [149]. The costs of biodiesel were approximated with 1555.9 €/t for the year 2017 [232]. A price correlation between biodiesel and crude oil would enable to estimate the price of biodiesel over the whole project time frame. This correlation was investigated in several publications. Bakhat and Würzburg give a good overview [233]. Even though there is no general statement about the correlation of biodiesel and crude oil, for this work, a correlation between crude oil and biodiesel was assumed. This is in line with the results published by Amna and Fatimah [234]. For that reason, the biodiesel price was linked to the crude oil price of the different scenarios and further specified in section 6.4.

The capacities of the CHP and the related efficiencies are shown in Table 11. Dimensions from 100 kW_{el} up to 2000 kW_{el} were considered.

Table 11: Basic CHP data [235]

Electric capacity	[kW_{el}]	100	334	500	633	1121	2000
Feed input	[kW]	370.4	1128.4	1430.3	1834.8	3046.2	5563.9
Power to heat ratio		0.51	0.57	0.79	0.78	0.89	0.97
Electric efficiency	[%]	27.0	29.6	35.0	34.5	36.8	35.9

Two different power prices must be considered: buy and sell prices. The power buy price was derived from the World Energy Outlook (WEO) New policy scenario for the European market and adapted for all scenarios [236]. The power price for industrial customers includes taxes, subsidies, sales and network costs.

The selling price for generating power in the German power market can be subdivided into two categories: power generated from renewable sources and non-renewable sources (Table 12).

Table 12: Power price classifications (buy: nominal prices 2020; sell: levelized revenues)

Power price (buy)	[€/MWh]	136.45	[236]
Power price (sell) ≤ 150 kW installed capacity	[€/MWh]	91.75	[237]
Power price (sell) ≤ 500 kW installed capacity	[€/MWh]	79.68	
Power price (sell) ≤ 5000 kW installed capacity	[€/MWh]	71.21	
Power price (sell) ≤ 20,000 kW installed capacity	[€/MWh]	38.89	
Power price (sell) non-renewable	[€/MWh]	58.99	[236]

The definition in the German legislation of renewable sources to produce power is different to the scientific definition. The organic fraction of MSW, sewage sludge, and residues from the leather industry are not included in the definition of the German legislation [10]. Also, the German Renewable Energy Sources Act (EEG) classifies the value according to the rated capacities. The power sell price of non-renewable sources as a wholesale price was adapted from the World Energy Outlook (WEO) scenarios 2016. Due to the difference between the sell and buy price, produced power is self-consumed and only surplus power is sold to the market. The self-consumed power reduces the costs of the overall process and is not a product of the LC calculation.

The prices for natural gas, steam coal, crude oil, carbon dioxide, biodiesel, and hydrogen are presented in section 6.4. The prices for the final products were levelized as described in section 6.1.

The performance figures of the PSA are depictured in Table 13.

Table 13: Basic PSA data

Recovery rate	[%]	90	[238]

The levelized prices for the final solid products are shown in Table 14 and are derived from a review of the German, Switzerland, and Austrian market based on the database of BUND [92]. It was investigated that the prices of active carbon and animal feed additive were in a similar range of the biochar prices.

Table 14: Levelized prices of solid pyrolysis substitutes

Biochar	[€/t]	609.00	[239]
BBQ char	[€/t]	82.41	[240]
BBQ briquettes	[€/t]	82.41	

6.4 Sensitivity Analysis

To validate the robustness of the results of the economic evaluation, a sensitivity analysis is needed. Three different pillars were elaborated to ensure the robustness of the economic evaluation and to identify potential risks and improvements.

One pillar is based on the 2016 WEO scenarios. The IEA publishes on a yearly basis an outlook on the world energy markets. Based on three different policy scenarios, the future price developments of energy market related key data are forecasted. The Current policy scenario is based on the impact of the policy decisions implemented until mid-2016. The New policy scenario is a more progressive scenario based on implemented policy decisions and defined targets. Therefore, it depictures the impact of the policy trends expected by the IEA. The 450 scenario is a goal-oriented scenario and fundamentally different from the Current and New policy scenario. This top-down scenario is based on the target to limit the amount of climate-relevant gases in the atmosphere to 450 ppm in the year 2100 with a likelihood of 50%. [236]

The 2016 WEO provides forecasts of natural gas, crude oil, steam coal, and carbon dioxide prices of the years 2020, 2030, and 2040. Based on this data, yearly price assumptions were extrapolated. Thus, the needed pricing of the feedstocks and substitutes were investigated for the next two decades based on different policy scenarios.

Figure 7 depictures the range of the possible crude oil pricing within the three scenarios for the next decades extrapolated from the 2016 WEO.

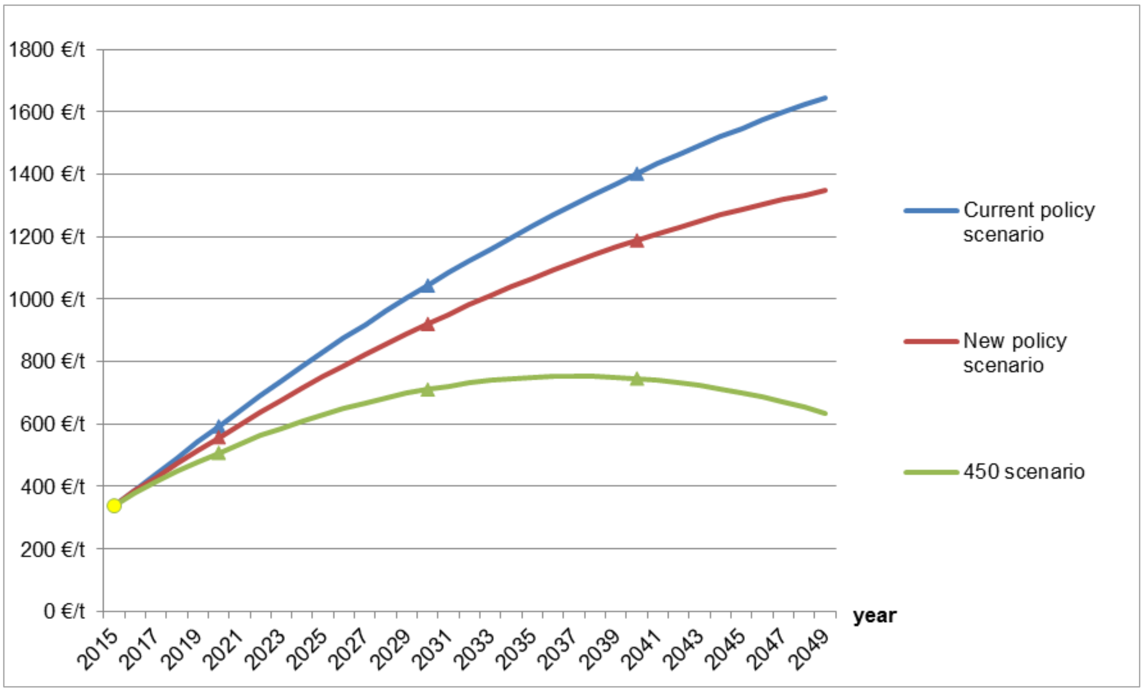

Figure 7: Extrapolated crude oil price scenarios based on the 2016 World Energy Outlook (WEO) on a nominal basis; colored triangles are the values given in the scenarios

Thus, a wide range of possible price developments caused by different policy frameworks are addressed by this sensitivity analysis. The natural gas, steam coal, and carbon dioxide price forecasts based on the 2016 WEO are depictured in the appendix (Figure 48, Figure 49, Figure 50).

The price development of biodiesel (appendix Figure 51) for the operation of the CHP was correlated with the price development of fossil crude oil as mentioned earlier in section 6.3.

The market structure of hydrogen is strongly dependent on the characteristics and properties of hydrogen and is therefore different to the natural gas market [241,242]. Thus, within the considered scenarios no price trends are given. For this reason, hydrogen levelized revenues were used based on calculations of previous work [155]. The values are based on a reference plant of a large-scale natural gas reformer. This is in line with the previous assumptions that the TCR products must be competitive against state of the art technologies.

The second pillar of the sensitivity analysis is the variation of the gate fee. Initial calculations confirmed the impact of the gate fee/pricing of the feedstock on the calculation. Therefore, three different gate fee cases were implemented: low, medium, and high (Table 15).

Table 15: Three different feedstock price/gate fee cases of the seven considered feedstocks

Gate fee/ pricing case [€/t] Feedstock	low	medium	high
Sewage sludge	-20	-80 [243]	-130 [243]
Woody biomass	53 [244]	75 [245]	160
Algae	-15	-37.5	-60
oMSW	-15 [245]	-37.5	-60 [245]
Leather residues	-20	-40	-100 [243]
Peat	20	65	140 [246]
Lignite	7.5 [247]	15 [248]	30

For the feedstocks generating a gate fee like sewage sludge or oMSW, low means a low gate fee. Feedstocks that do not generate a gate fee like woody biomass or lignite, the considered low case means the lowest considered price for the feedstock.

The last pillar, to guarantee the robustness of the economic evaluation, is the breakdown of the levelized costs by the individual costs centers. The distribution of the specific costs is a straightforward way to identify the most significant cost drivers and therefore the cost centers with the highest proportional saving potentials.

The three approaches create individually valuable data and ensure the needed robustness of the economic evaluation holistically.

7 RESULTS AND DISCUSSION

In the following chapter, the results from the TCR-2 trials (section 7.1) and the economic evaluation (section 7.2) are presented. The selected feedstocks described in section 2.1 and 4.1 were processed in the TCR-2 plant as described in section 5.1.1. The products of the TCR process were analyzed, and mass and energy balances of the trials were created (as described in section 5.1.3). The economic calculations are based on the fundamentals and assumptions as described in section 6.

7.1 Results from the TCR Trials

The number of conducted trials in the lab scale TCR plant is shown in Table 16. Additionally, several other feedstocks were tested within the framework of this work. These results are integrated within the discussion in section 7.1.4.

Table 16: Number of conducted TCR-2 trials

Feedstock	Total number of trials	Reactor temperature	Reformer temperature
Sewage sludge	8	673 K	773 K, 873 K, 973 K
Woody biomass	9	773 K	973 K
Seaweed	16	673 K	973 K
oMSW	20	673 K	723 K, 873 K, 973 K
Leather residues	8	673 K	973 K
Peat	4	673 K	773 K, 873 K, 973 K
Lignite	8	673 K	773 K, 873 K, 973 K
Co-Pyrolysis trials	8	673 K	773 K, 873 K, 973 K

7.1.1 Biomass and biogenic Residues

Within the following section, the results of the TCR trials of five different biogenic feedstocks are presented. For each feedstock, several samples were tested to build a robust database. The aim was to gain a detailed understanding of the TCR process for a broad spectrum of feedstocks. The level of detail is in line with the requirements of the economic assessment (section 7.2).

7.1.1.1 Sewage Sludge

As described in section 5.2, three different sewage sludge samples were processed in the TCR-2: raw sludge samples (RSS) and digested sludge samples (DSS). Results of digested sewage sludge utilized within the TCR technology have been presented already in several publications [25,138,148,149,249].

Mass and Energy Balance

The mass balances of the three different sludge samples (raw sewage sludge sample one: RSS(a), raw sewage sludge sample two: RSS(b), and digested sewage sludge DSS) are shown in Figure 8.

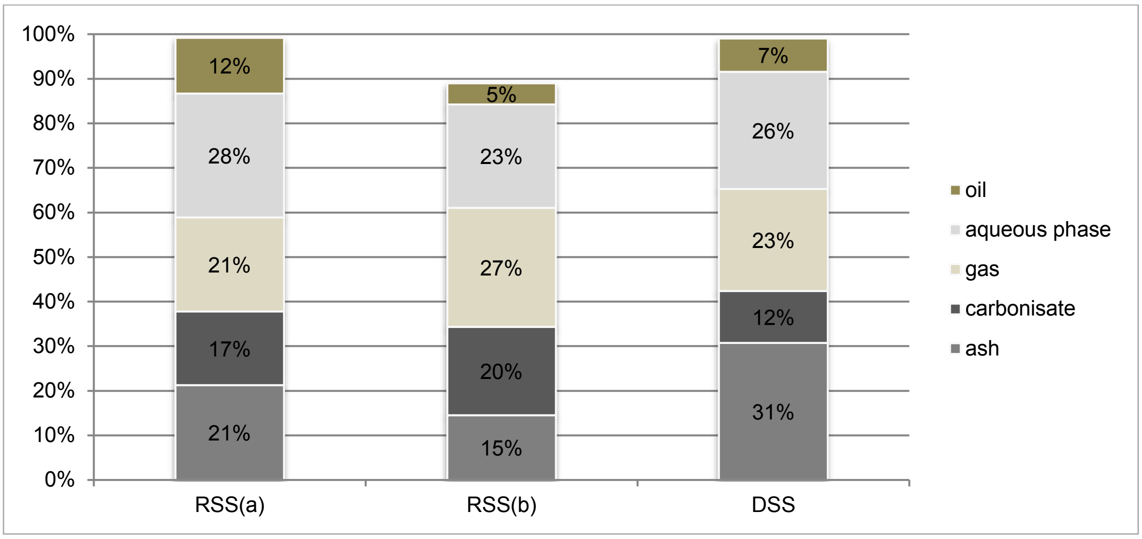

Figure 8: Mass balance of three different sewage sludge streams

The conditioning of the feedstock RSS(b) was not stable. A significant amount of the feedstock got stuck and degraded in the hopper. Due to this, the mass balance could not be completed properly. Therefore, the amount of undetected mass was on average 11 wt%.

The ash content of the samples is a good indicator of the pretreatment of the sludge. For the two raw sludge samples, the ash content was below 21 wt%; DSS had an ash content of 31 wt%. These numbers are based on the ash content of the feedstock in the condition they were fed into the process. A general assumption was made that the ash content in the feedstock was transferred to the solid pyrolysis product. The two processed raw sludge samples had a carbonisate content on water and ash-free (waf) basis of 17–20 wt%. In comparison, the digested sludge had a carbon content of 12 wt% that is strongly related to the higher ash content of the feedstock. Interestingly, the gas content of the samples was not correlating to the pre-processing of the sludge. The trials of the RSS(a) samples had the lowest gas yields (21 wt%) and RSS(b) the highest with 27 wt%. The digested sludge sample had a gas content of 23 wt%. Previous studies of digested sewage sludge showed even lower gas yields, ranging from 17–18.5 wt%

[25,149]. The yield of aqueous phase varies from 23–28 wt%. In relation to the high moisture content of the feedstock RSS(b), the low yield of the aqueous phase is remarkable. A possible explanation for this could be the residue of feedstock in the hopper. It was observed that an increased amount of condensing water was apparent within the hopper after the trial and the feedstock residues had absorbed additional moisture. The oil yield varied from 5–12 wt%. No trend regarding oil yield and the pretreatment of the sludge was observed. The highest and lowest oil yields were achieved with the raw sludge. Apfelbacher et al. reported 12 wt% of oil from digested sludge [149]. From these results, it can be concluded that no reliable predictions concerning the yields of the products can be made, even if elemental composition, HHV, moisture content, and ash content are known or if the sludge has received pretreatment.

The energy balance pictured in Figure 9 supports the results of the mass balance. No identifiable relationship between the characteristics of the sludge and the related energy distribution is observed. The balances for all three test series were nearly closed. Even RSS(b) with a high amount of mass that couldn’t be balanced duly. Therefore, it can be concluded that the missing part of the balance was mainly process water with a low heating value.

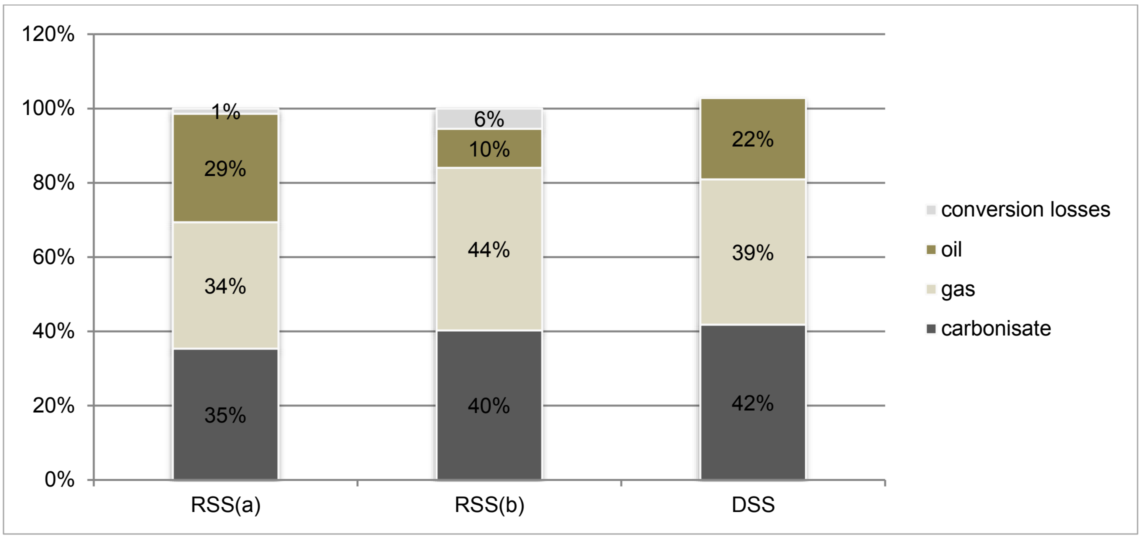

Figure 9: Energy balance of three different sewage sludge streams

The energy content of the solid product varies between 35–42%. Interestingly, the feedstock with the highest ash content, DSS, had the highest energy content of the carbonisates with a value of 42%. RSS(b) followed closely with 40%, although it had the lowest ash content.

For the feedstock RSS(b), 44% of the energy from the feedstock was converted to the gaseous product, whereas the gaseous energy content for RSS(a) was only 34%. In between these values, DSS had a transfer rate from feedstock to gas of 39%. These results are in line with the work published in 2016 [25,149]. The contribution of the liquid products to the energy balance varies from 10–29%. Both extremes were based on raw sewage sludge.

Gas Composition and Characterization

The characteristics of the TCR gases from sewage sludge were diverse. As seen in Table 17, the heating value of the gases was 20.2 MJ/kg for DSS, 27.4 MJ/kg for RSS(b), and 24.9 MJ/kg for RSS(a). The density also varied between 0.97 (DSS) and

1.14 kg/m (RSS(b)). This variation in the density and HHV is evidence of a diverse gas composition of the three feedstocks.

Table 17: Characteristics of TCR-2 gas from different municipal sewage sludge samples

		RSS(a)	**RSS(b)**	**DSS**
Density	[kg/m³]	1.10	1.14	0.97
Wobbe s	[MJ/m³]	28.3	32.8	22.5
HHV	[MJ/kg]	24.9	27.4	20.2

Figure 10 reaffirmed the first conclusions of the mass and energy balance. Both raw sludge samples have a different gas composition. This tendency is exacerbated by the high volumetric content of C_xH_y and the associated inaccuracies of the gas measurement system (section 5.1.3). Due to this reason, only 50 vol% of the gases from RSS(b) were identified. Based on deductions from the preceding characterization of the gases, the share of higher hydrocarbons within the gas stream was expected to be significantly higher than the detection limit of 5 vol%. The impact of C_xH_y on the accuracy of the CH_4 measurement has led to the fact that no methane was measured. However, GC control measurements of gases with a similar composition proved the presence of methane (section 7.1.1.4).

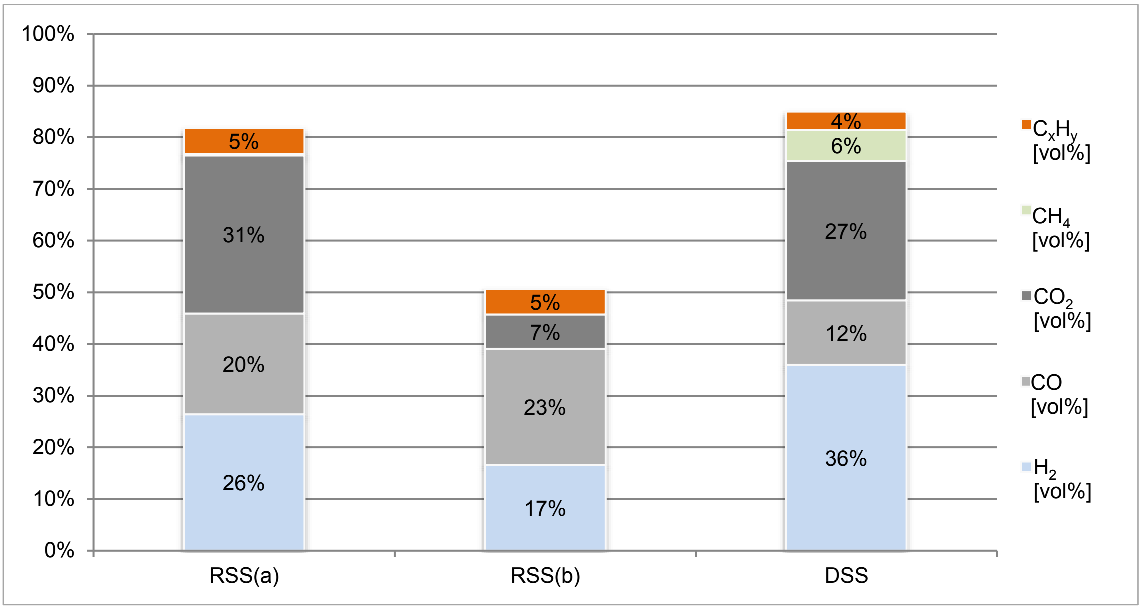

Figure 10: Composition of TCR-2 gas from different sewage sludge streams

From Figure 10, it is evident that all gases had a high amount of C_xH_y components. This opposes the results reported by Conti et al., in which the hydrocarbon concentration was below 3 vol% [25].

The hydrogen content varied for the three samples between 17 vol% for RSS(b) and 36 vol% for DSS. For digested sludge samples, similar numbers have been presented in a related patent [138].

Carbonisate Characterization

The composition of the TCR carbonisates from the sewage sludge trials is presented in Table 18.

Table 18: Properties of TCR-2 carbonisate from different sewage sludge streams (*: calculated by difference)

		RSS(a)	RSS(b)	DSS
C	[wt%]	34.4	44.8	28.2
H	[wt%]	0.2	3.0	0.3
N	[wt%]	3.0	6.1	2.1
S	[wt%]	0.7	0.4	1.1
Ash	[wt%]	59.7	52.4	71.7
O*	[wt%]	<2	<2	<2
HHV	[MJ/kg]	13.0	16.5	10.2
H_2O	[wt%]	<0.5	<0.5	<0.5

The results indicate that from the characteristics of the feedstock, only limited information is gained regarding the final product composition and quality. The carbonisate showed a negative correlation between the ash content of the feedstock and the HHV of the carbonisate, which confirms previous data [48]. The feedstock with the lowest ash content (RSS(b)) had the highest carbon content in the carbonisate among all three samples. On the other hand, the digested sludge sample's carbonisate had the lowest carbon content (28.2 wt%) and the highest ash content (71.7 wt%). The mass balances were not possible to close due to the high ash content.

The HHVs are in line with the ash and carbon content. In general, as the ash content in carbonisate increases, the carbon content and HHV decreases. Interestingly, there is variation between the hydrogen and nitrogen content of the carbonisate. The high nitrogen (6.1 wt%) and hydrogen (3.0 wt%) content had not been observed in previous trials [25,72,148]. With regard to the gas composition, it must be concluded that dehydrogenation and denitrification of the carbonisate within the vertical reactor did not occur. Due to the results of the temperature variations of the vertical reactor, it can be concluded that the 973 K reforming temperature is not high enough for this feedstock. This might be an interesting topic for further studies to confirm the reaction mechanism behind this.

Bio-Oil Characterization

The properties of the TCR oil from the three sewage sludge streams depictured in Table 19 are comparatively close to the data that has been already published.

Table 19: Properties of TCR-2 oil from three different sewage sludge streams (*: calculated by difference)

		RSS(a)	RSS(b)	DSS
C	[wt%]	70.7	72.0	74.6
H	[wt%]	8.5	7.3	8.8
N	[wt%]	9.3	7.6	7.2
S	[wt%]	1.3	0.7	0.9
Ash	[wt%]	<0.1	<0.1	<0.1
O*	[wt%]	10.1	12.3	8.5
HHV	[MJ/kg]	34.3	31.4	32.1
H_2O	[wt%]	5.1	4.2	3.6
TAN	[mg KOH/g]	20.7	32.5	7.3

The oils had high nitrogen content, ranging from 7.2–9.3 wt%. The distribution of the nitrogen yield is in line with the nitrogen content of the feedstock. The HHVs of the oils varied between 31.4–34.3 MJ/kg. The oil from the feedstock RSS(a) had the highest HHV of 34.3 MJ/kg with a moisture content of 5.1 wt%. RSS(b) had the lowest HHV (31.4 MJ/kg) with a measured moisture content of 4.2 wt%. Significant differences were found in the acidity of the oils. Oils from the raw sludge samples had a TAN of 20.7 and 32.5 mg KOH/g. In comparison, oil from the digested sludge had a TAN of only

7.3 mg KOH/g. This is in line with the results of other digested sludge TCR oil samples reported elsewhere [25,138,148,149].

The oil from DSS was distilled by VTA Verfahrenstechnische Anlagen GmbH & Co. KG, Germany. It was the objective to prove the thermal stability of the TCR oils from sewage sludge and evaluate the distribution of the fractions. These results are listed in Table 20.

Table 20: Distilled TCR-2 oil fractions from DSS (*: calculated by difference; **: two phases were apparent in the naphtha fraction; ×: not measured)

Fraction				Elemental composition					Properties		
		T_{dist}	Yield	C	H	N	S	O*	H_2O	TAN	HHV
		[K]	[wt%]	[wt%]					[wt%]	[mg KOH/g]	[MJ/kg]
Naphtha	heavy**	<454	17.5	6.9	13.0	4.9	0.1	75.1	76.6	18.5	×
	light**			81.4	10.4	7.8	0.4	<0.5	1.0	0.8	39.2
Diesel		454–508	24.3	80.8	9.8	7.3	0.5	1.6	1.7	3.2	35.8
Gas oil		508–644	26.6	79.5	9.2	7.4	0.7	3.3	0.2	4.0	37.1
Heavy oil		>644	31.6	78.0	10.1	7.0	1.0	4.0	<0.05	1.6	43.5

The fraction of heavy oil in DSS is with over 30 wt% larger than previous distillations of TCR oils from digested sludge (15 wt% at 649 K and 20 wt% at 623 K, respectively) [138,149]. The yields are similar to the distillation of the liquids from water gas production reported by Volkmann [250].

To conclude, the results of the experiment on raw and digested sludge have demonstrated that there are only minor correlations between the pre-processing of the sludge and the composition and characteristics of the products. A reliable forecast for the mass and energy distribution based on the pre-processing and elemental composition of the sludge is not possible. However, a correlation between the acidity of the TCR oils and pretreatment of the sewage sludge was detected. Raw sludge had a higher TAN than digested sludge. The correlation between ash content and carbonisate properties is inherent for sewage sludge.

7.1.1.2 Woody Residues

In the following section, the results of the TCR-2 trials with three different woody biomass residues are presented. These results were part of a publication in Energy and Fuels in 2016 [48].

Mass and Energy Balance

As described in section 5.2, three different agricultural woody residues have been investigated. The trials were carried out under the process conditions described in section 5.1.2. When performing experiments with woody biomass, the temperature in the last zone of the horizontal reactor is increased, as described in section 5.2. The product yields are presented in Figure 11.

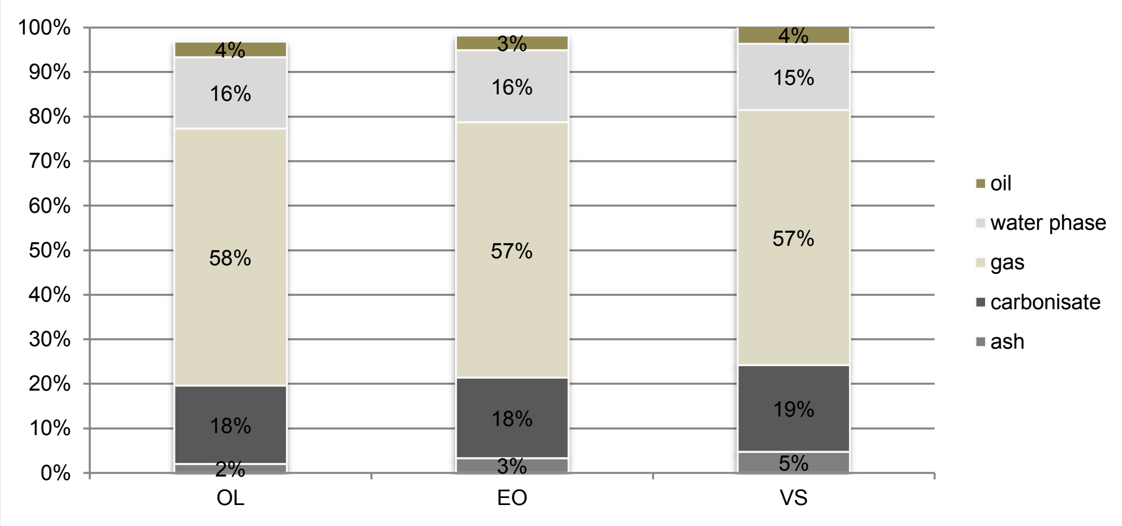

Figure 11: Product allocation from TCR-2 trials woody biomass

The distribution of the product fractions for OL (olive pruning residues), EO (evergreen oak pruning residues), and VS (vine shoots) are very similar**.** The amount of carbonisates is between 19.5–24.2 wt% on average. Considering the ash content of the feedstocks, the carbon yields (water and ash free) are even closer together. It can be noted that the utilization of woody biomass in the TCR technology produces a high amount of gas, generally over 55 wt%. Due to the low moisture content of the feedstock, the amount of aqueous phase is reasonable at 15.0–16.5 wt%. Moreover, woody biomass as feedstock results in low bio-oil yields of 3.3–4.0 wt%.

From the product allocation (Figure 11) and the lower heating values of the feedstock and products (carbonisate, gas, and oil), the energy balance was calculated as explained earlier in section 5.1.3.

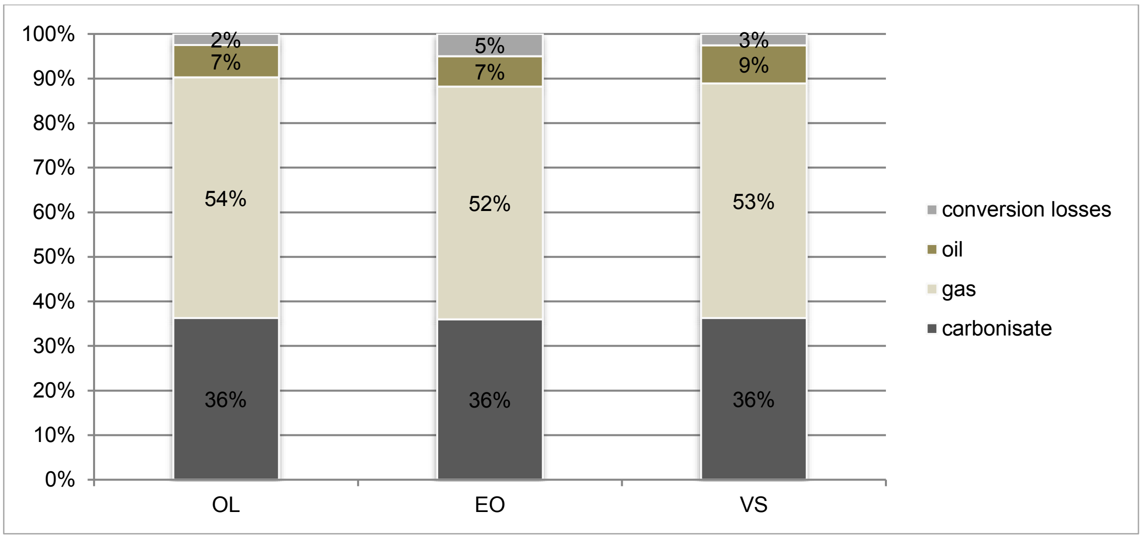

Figure 12: Energy balance of products from three different woody feedstocks

The energy balances of the three feedstocks are consistent with the results of the mass balance. The most substantial fraction of the bound energy of the feedstock is converted to the gaseous fraction (Figure 12). The relative fractions of the energy content are as follows: 53% of the energy is in the gas phase, 36% in the carbonisate, and 7% in the oil. It is also apparent that there is only a small variation in the distribution of the energy balances. The discrepancy is within a narrow range between 2.5–5%.

Gas Composition and Characterization

The compositions of the gases are shown in Figure 13.

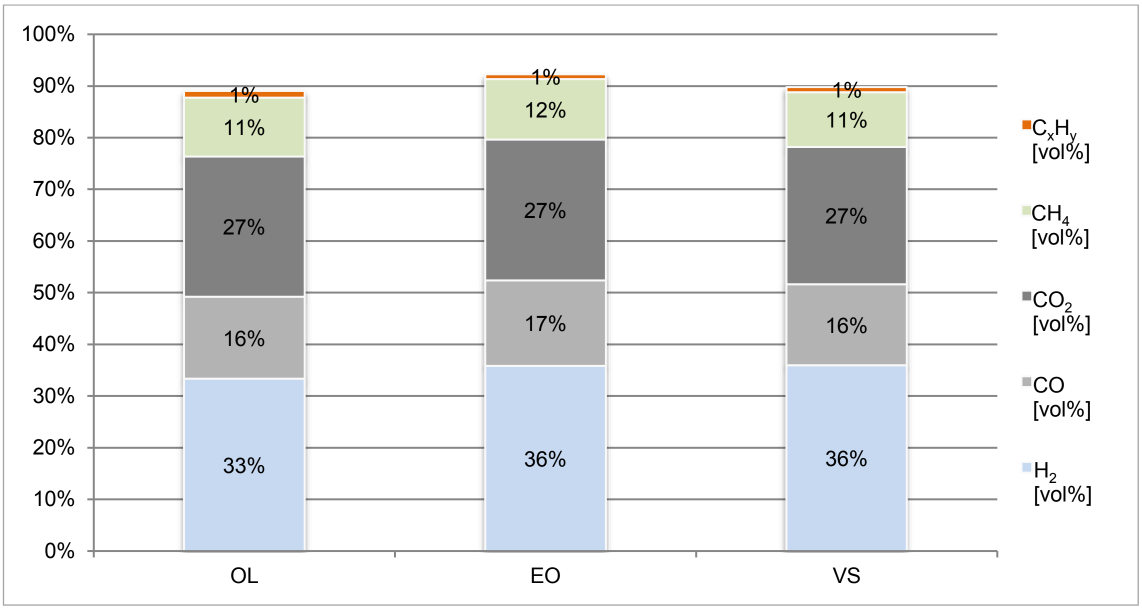

Figure 13: Quality of TCR-2 gases from three different woody feedstocks

The hydrogen content varies between 33–36 vol% of the detected components. The second highest share is CO_2 (26.5–27.5 vol%), followed by CO (15.5–16.5 vol%) and CH_4 (10.5–11.5 vol%). The share of C_xH_y components is approximately 1 vol%. Due to the low amount of C_xH_y, the gap to close the balance is small. It can be assumed that the missing 8–11 vol% is made up of nitrogen compounds and light boiling compounds. The density of the gases was around 0.9 kg/m . The HHV varied between 16.2–16.5 MJ/kg. The superior Wobbe index is in the range of 17.7–18.5 MJ/m (Table 21).

Table 21: Characteristics of TCR-2 gas from three different woody biomass residues

		OL	EO	VS
Density	[kg/m³]	0.97	0.93	0.94
Wobbe s	[MJ/m³]	18.5	17.8	17.7
HHV	[MJ/kg]	16.5	16.2	16.2

Therefore, it can be concluded that the composition and characteristics of TCR gas from different sources of woody biomass are very similar.

Carbonisate Characterization

Table 22 lists the elemental analysis, together with the calorific values, and moisture and ash contents of the carbonisate.

Table 22: Properties of TCR-2 carbonisates from woody residues (*: calculated by difference)

		OL	EO	VS
C	[wt%]	84.2	78.1	74.4
H	[wt%]	1.2	1.2	1.0
N	[wt%]	0.8	0.9	0.9
S	[wt%]	0.1	0.1	0.1
Ash	[wt%]	12.2	18.1	23.1
O*	[wt%]	1.5	1.6	0.7
HHV	[MJ/kg]	30.3	27.3	25.5
H_2O	[wt%]	<0.5	<0.5	<0.5

The carbonisate from the feedstock OL had the highest carbon content (84.2 wt%), followed by EO (78.1 wt%) and VS (74.4 wt%). The carbon content is directly related to the ash content of the feedstock. A high ash content leads to a low carbon content and vice versa. On an ash-free basis, the carbon contents are very similar. The hydrogen, nitrogen, oxygen, and sulfur contents were not correlated to the ash content. These values were comparable to each other. All three samples had an oxygen content below 1.2 wt%, a nitrogen content below 0.9 wt% and a sulfur content close to the detection limit (0.1 wt%). These results are slightly different from data presented in 2017 by Conti et al. in which birch wood chips with a low ash content of 0.6 wt% have been processed in the TCR-2. The carbonisate had an oxygen content of 9.8 wt%. [25] Therefore it can be assumed that the deoxygenation of the solid pyrolysis products is favored by high ash contents.

The correlation of the carbon and ash content is notably reflected in the HHVs of the carbonisates. The HHV of the carbonisate from the feedstock OL was found to be 30.3 MJ/kg. This result is in line with HHV from birch wood chips, even if the ash content of the carbonisates is 9 wt% lower than from OL. The heating values from EO and VS were lower, with values of 27.3 and 25.2 MJ/kg, respectively. As expected, the percentage of ash among the three carbonisates increased in the order of OL (12.2 wt%), EO (18.1 wt%), and VS (23.1 wt%). This is the same trend observed among the ash content of the feedstocks as the mineral content of the feedstock is transferred to the carbonisate.

Bio-Oil Characterization

The bio-oils had a high carbon content of over 72 wt% (Table 23). The bio-oil from the feedstock VS had the highest carbon content with 78.6 wt%, followed by OL (75.2 wt%) and EO (72.2 wt%). The oils showed similar elemental compositions for hydrogen, nitrogen, and sulfur. The oxygen contents of the bio-oils from OL, EO, and VS were in the range of 11.4–17.9 wt% because of the higher water content. In correlation with this, the TAN of the bio-oil was in the range of 9–30 mg KOH/g. OL had the lowest TAN with 9.3 mg KOH/g, on average. The bio-oil from VS had the highest HHV with 35.5 MJ/kg. The feedstock OL and EO, obtained TCR oil with lower HHVs of 33.6 and 32.8 MJ/kg.

Table 23: Properties of TCR-2 bio-oil from woody residues (*: calculated by difference)

		OL	EO	VS
C	[wt%]	75.2	72.2	78.6
H	[wt%]	7.4	7.0	7.2
N	[wt%]	2.2	2.6	2.5
S	[wt%]	0.3	0.3	0.3
Ash	[wt%]	<0.1	<0.1	<0.1
O*	[wt%]	14.9	17.9	11.4
HHV	[MJ/kg]	33.6	32.8	35.5
H_2O	[wt%]	8.2	6.0	8.4
TAN	[mg KOH/g]	9.3	14.6	30.1

Distribution of C, H, and O from Feedstock to Products

Table 24 shows the yield distribution of the elemental compositions of C, H, and O in the products based on the elemental analysis of the feedstocks and products.

Table 24: Elemental distribution of TCR-2 products from woody residues

Gas		C	H	O
OL	[wt%]	56.7	56.1	62.0
EO	[wt%]	55.6	59.3	63.0
VS	[wt%]	57.8	55.0	55.8

Carbonisate		C	H	O
OL	[wt%]	36.3	3.6	0.6
EO	[wt%]	37.7	4.2	0.8
VS	[wt%]	34.4	3.7	2.3

Oil		C	H	O
OL	[wt%]	6.1	4.2	1.2
EO	[wt%]	5.4	3.7	1.3
VS	[wt%]	6.7	4.7	1.1

Aqueous phase		C	H	O
OL	[wt%]	1.0	36.2	36.2
EO	[wt%]	1.4	33.4	34.8
VS	[wt%]	1.1	36.6	40.8

On the basis of the elemental compositions of the feedstock, carbonisate, bio-oil, and aqueous phase, the composition of the non-condensable gaseous products were calculated by difference. In correlation with the mass and energy balance, carbon was mainly distributed in the gas and the carbonisate. Only a minimal amount of carbon was found in the aqueous phase.

Over 98.5 wt% of carbon was transferred to the fuels. On the other hand, over 90 wt% of hydrogen and 96.5 wt% of oxygen were distributed in the gas and aqueous phase. This contrasts with other pyrolysis technologies, where the bio-oil products have higher oxygen contents than the original biomass feedstock. Mohan et al. reported an oxygen content of 46 wt% in the bio-oil versus 42 wt% oxygen in the woody feedstock [251].

In conclusion, it was found that the characteristics and yields of the products from woody biomass are in a tight range. The correlation between the ash content of the feedstock and the oxygen content of the solid product was apparent. This leads to the correlation that high ash content of the feedstock decreases the HHV. Within the frame of this work, the required ash content for the deoxygenation of the solid pyrolysis products was not investigated. This is an interesting parameter for feedstock blending and could be considered in future projects.

7.1.1.3 Seaweed

Eight different samples of seaweed were processed in the TCR-2 unit. As described earlier in section 5.2, the samples were mixtures of different seaweed algae which were gathered at different times throughout the year. To generate general knowledge of the conversion of algae in the TCR technology, the results were averaged and the standard deviation specified.

Mass and Energy Balance

The average product allocation of the seaweed TCR-2 trials is given in Figure 14.

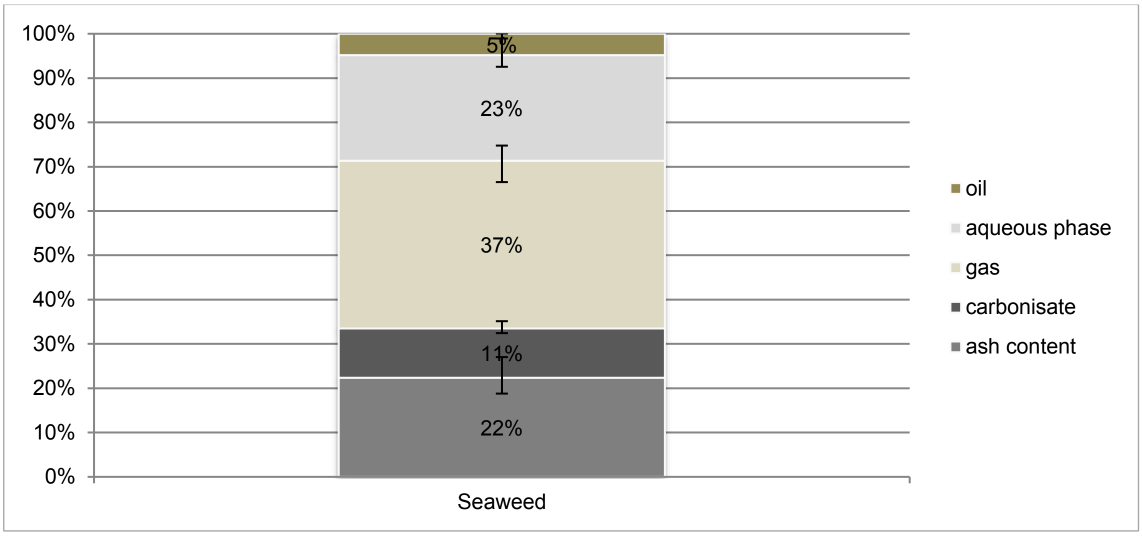

Figure 14: Average product allocation from eight different seaweed collections

The carbonisate content was on average 33 wt%. On a waf basis, the carbonisate content was only 11 wt% due to the high ash content. This is in line with the high amount of inert material described in section 5.2. The waf carbonisate content shows an experimental standard deviation $s(t_k)$ of only 0.91 wt% and standard uncertainty $u(\bar{t})$

of 0.32 wt%. Therefore, it can be concluded that the solid pyrolysis product from the TCR process has only negligible variation in respect to the waf composition.

The gas yield was approximately 37 wt% ($s(t_k)$ of 2.63 wt%; $u(\bar{t})$ of 0.93 wt%). The aqueous phase yield was 23 wt% ($s(t_k)$ of 2.24 wt%; $u(\bar{t})$ of 0.79 wt%), and the oil yield 5 wt% ($s(t_k)$ of 0.74 wt%; $u(\bar{t})$ of 0.26 wt%).

Figure 15 shows the average energy balance of the TCR-2 trials with seaweed samples. On average, 50% of the feedstock energy is converted to the gas fraction ($s(t_k)$ of 3.08 %; $u(\bar{t})$ of 1.09 %) while only 15% of the energy of the feedstock is converted into the bio-oil fraction ($s(t_k)$ of 2.84 %; $u(\bar{t})$ of 1.00 %). In contrast, the solid product fraction was approximately 29% ($s(t_k)$ of 3.17 %; $u(\bar{t})$ of 1.12 %); almost double the bio-oil fraction. As depicted in Figure 15, the energy losses are limited to 6% on average ($s(t_k)$ of 4.75 %; $u(\bar{t})$ of 1.68 %).

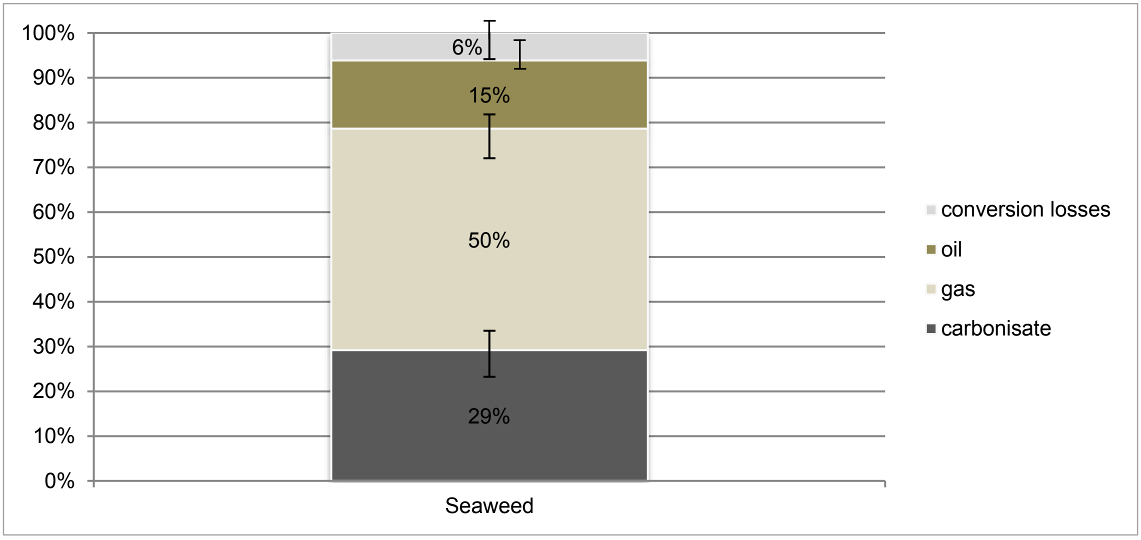

Figure 15: Average energy balance of products from eight different seaweed collections

Gas Composition and Characterization

The composition regarding H_2, CO, CO_2, CH_4, and C_xH_y components of the TCR gases from seaweed is shown in Figure 16.

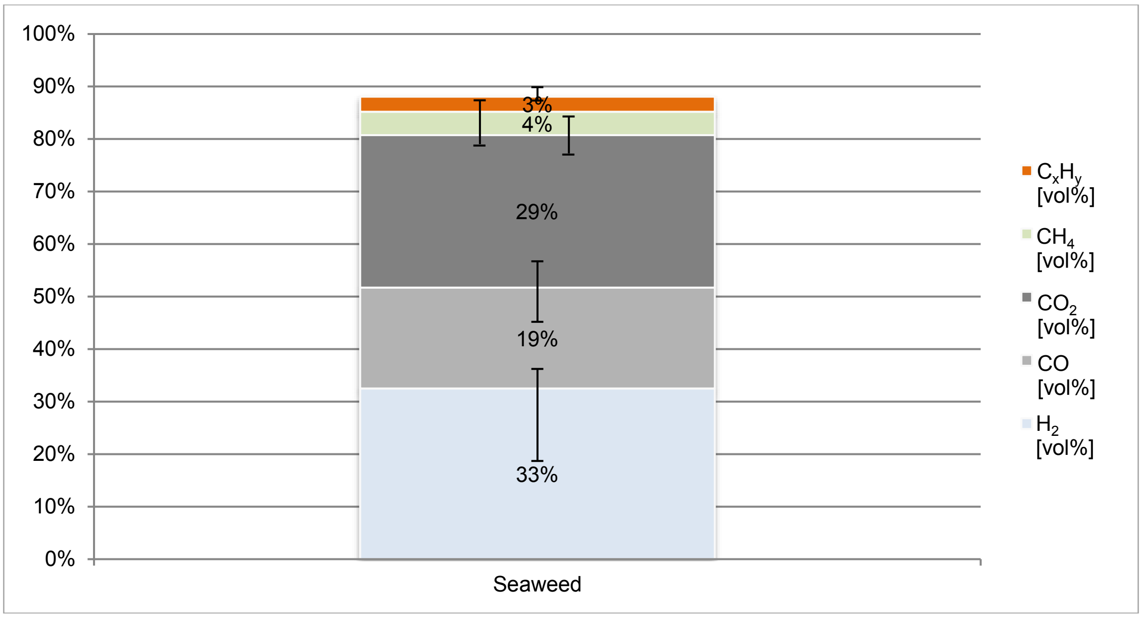

Figure 16: Composition of TCR-2 gases from seaweed samples

Over 80 vol% of the gas from the seaweed was divided into three components (Figure 16). The most substantial volumetric proportion was H_2 (33 vol%; $s(t_k)$ of 5.80 vol%; $u(\bar{t})$ of 2.05 vol%), followed by CO_2 (29 vol%; $s(t_k)$ of 2.49 vol%; $u(\bar{t})$ of 0.88 vol%) and CO (19 vol%; $s(t_k)$ of 4.07 vol%; $u(\bar{t})$ of 1.44 vol%). Only a small fraction of CH_4 and C_xH_y (4 and 3 vol%, respectively) components were measured ($s(t_k)$ of 2.96 vol%; $u(\bar{t})$ of 1.05 vol%; $s(t_k)$ of 0.94 vol%; $u(\bar{t})$ of 0.33 vol%). As described earlier, the balance does not close. The missing 12 vol% was most likely nitrogen and higher hydrocarbon compounds that are not detectable with the used devices (section 5.1.3). The HHVs of the gases were approximately 16.6 MJ/kg ($s(t_k)$ of 1.10 MJ/kg; $u(\bar{t})$ of 0.39 MJ/kg) with a density of about 1.0 kg/m ($s(t_k)$ of 0.06 kg/m; $u(\bar{t})$ of

0.02 kg/m). The superior Wobbe index (Wobbe s) of the gases were 18.7 MJ/m on average ($s(t_k)$ of 0.94 MJ/m ; $u(\bar{t})$ of 0.33 MJ/m).

Carbonisate Characterization

The composition of the carbonisate is stringent to the feedstock analysis (Table 25).

Table 25: Properties of carbonisates from seaweed samples (*: calculated by difference; ×**:** not calculated)

Seaweed			**Experimental standard deviation** $s(t_k)$	**Standard uncertainty** $u(\bar{t})$
C	[wt%]	28.3	5.00	1.77
H	[wt%]	0.09	0.03	0.01
N	[wt%]	0.94	0.15	0.05
S	[wt%]	2.50	0.58	0.20
Ash	[wt%]	71.3	3.21	1.14
O*	[wt%]	<2	3.72	1.31
HHV	[MJ/kg]	9.7	1.37	0.48
H_2O	[wt%]	<0.5	×	×

The high ash content (>70 wt%) and the related low carbon content (28.3 wt%) resemble the feedstock. Due to the high ash content, it was not possible to close the balance and calculate the oxygen content of the carbonisates. Successive measurements of the ash contents revealed that the measured ash content of the carbonisates was not in line with the measured content of the determination of the elemental composition. The samples increased instead of losing weight during the incineration of the char. Two possible solid-gas reactions are described in literature:

I. Oxygen can be absorbed by metals under incineration conditions. The oxygenated metallic elements are therefore heavier than the not oxygenated compounds [252].

II. Carbon dioxide can react with inorganic components during incineration [253,254]. These carbonation reactions are causing weight increase of the components. McLaughlin et al. investigated that sodium hydroxide is carbonated under incineration conditions to sodium carbonate. [253]

Therefore, EDXRF analysis of the carbonisates from seaweed was performed (appendix Table 50). The composition revealed that the described solid-gas reaction could occur during the ash determination and therefore cause the uncertainties.

The hydrogen content was below 0.1 wt% and the nitrogen content approximately 1.0 wt%. The proportion of sulfur (2.5 wt%) is in correlation with the measured content of sulfur in the feedstock. Due to the high amount of inert material (>60 wt%) within the carbonisate, the HHV of the carbonisate from seaweed was around 9.7 MJ/kg.

Bio-Oil Characterization

The properties of bio-oils from the seaweed trials are summarized in Table 26.

Table 26: Properties of bio-oil from seaweed samples (*: calculated by difference; ×: not calculated)

Seaweed			**Experimental standard deviation** $s(t_k)$	**Standard uncertainty** $u(\bar{t})$
C	[wt%]	78.2	2.05	0.72
H	[wt%]	8.0	0.35	0.12
N	[wt%]	5.0	0.58	0.21
S	[wt%]	1.0	0.14	0.05
Ash	[wt%]	<0.1	×	×
O*	[wt%]	<8	2.39	0.85
HHV	[MJ/kg]	36.2	0.53	0.19
H_2O	[wt%]	1.8	0.15	0.05
TAN	[mg KOH/g]	7.5	2.61	0.92

The carbon content of the oils was around 78.2 wt%. The hydrogen, nitrogen, and sulfur content of the oils were for all oils in close range. On average, the content of hydrogen was 8.0 wt%, nitrogen was 5.0 wt%, and sulfur was around 1.0 wt%. The oxygen content, calculated by difference, was approximately 8 wt% in average. The water content for the bio-oil from seaweed was determined to an average of 1.8 wt%. The maximum moisture content of an oil sample from seaweed was 2.0 wt%. Therefore, the properties of the oils regarding moisture content were very similar for all trials. Thus, the HHVs of the oils were approximately 36.2 MJ/kg with also only minor variations (34.98–36.75 MJ/kg). The total acid number of the oil was approximately 7.5 mg KOH/g.

To summarize, although the composition of the feedstock in terms of CHNS and ash content varied, the properties of the TCR oil from each seaweed trial were similar.

7.1.1.4 Organic Fraction of Municipal Solid Waste (oMSW)

Samples of the organic fraction of MSW (oMSW) from two different suppliers (section 5.2) were processed in the TCR-2 plant. Due to the highly inhomogeneous feedstock, over 65 kg of oMSW were utilized in twenty trials. Feedstock oMSW(a) was used for a parameter variation. The temperature in the vertical reactor was variated between three temperatures to evaluate the influence on the yields and the quality of the products. The temperatures in the vertical reactor were 973 K, 873 K, and 723 K. Thus, similar temperature intervals were used for bagasse [26]. The temperature in the horizontal reactor was not varied.

Because of the preliminary trials with oMSW(a), the reforming temperature was lowered to 873 K to maximize the oil yield for the second series of experiments with oMSW(b). The preliminary tests assured that the quality of the carbonisates and the syngas was in a similar range to the products with a 100 K lower reforming temperature. Within the experiment, refilling the hopper during the operation of the plant was also investigated. Before the hopper was empty, the feeding screw was stopped. Once gas production stopped, the system was purged with nitrogen. The refilling of the feeding system was performed with a suction system to prevent uncontrolled emissions. Attention was paid to the limited capacity of the vertical reactor. This procedure caused the inconsistencies of the mass balance.

Organic Fraction of Municipal Solid Waste(a)

In the following segment, the results from the experimental trials of the feedstock oMSW(a) are presented. As described earlier, the influence of the temperature in the vertical reactor on the products was investigated within this series of experiments. Previous results were part of a publication in Energy Procedia in 2017 [255].

Mass and Energy Balance

The mass balance of the oMSW(a) trials is shown in Figure 17.

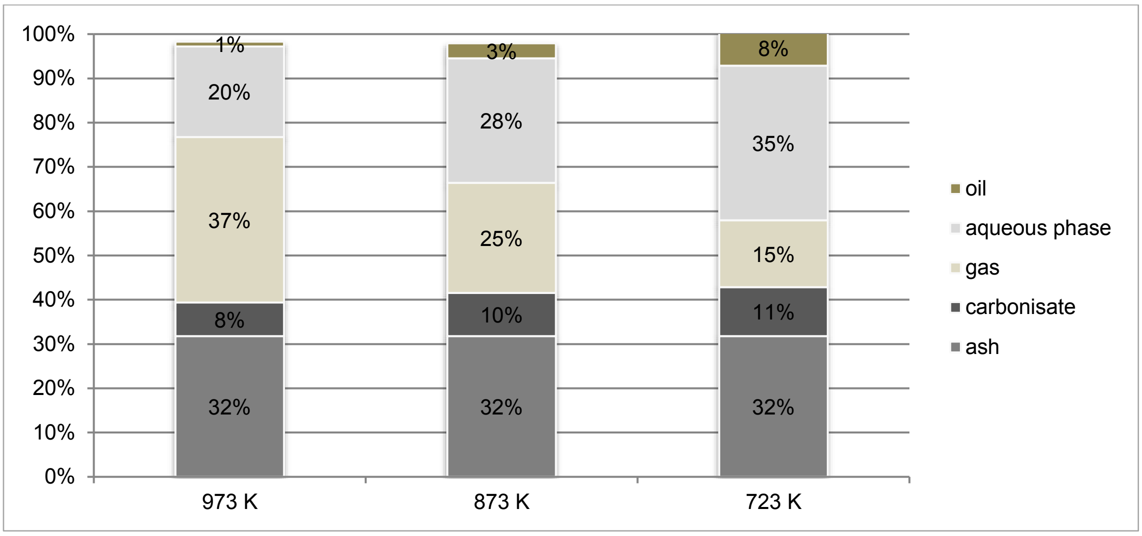

Figure 17: Mass balance of products from oMSW(a) at different temperature levels in the vertical reactor

The influence of the temperature within the vertical reactor on the product yields is apparent. A decrease in reactor temperature causes an increase of carbonisates (waf) and liquid products. Consequently, the gas distribution decreases with a decrease in temperature. At 723 K the carbonisate content (waf) is 11 wt% and an increase to 973 K results in a reduction of the yield to 8 wt%. The variation of the temperature in the vertical reactor had the most significant impact on the gas yield. At 723 K, only 15 wt% of the products are gaseous. With an increase of 150 K, the gas amount raised up to 25 wt%. Interestingly, an additional 100 K increase in reactor temperature causes an increase in the gas yield of 12 wt% to 35 wt%. The yield of aqueous phase varied between 37 wt% at 723 K and 20 wt% at 973 K. The TCR oil yield varied from 8 wt%

at the lowest reactor temperature to only 1 wt% at 973 K. Therefore, the relation of temperature to product-distribution followed no linear curve for all fractions.

The mass balance of the 973 K trial is different from an oMSW sample that was processed in the TCR previously. The carbon yield of MSW(a) was higher by 9 wt% and gas content 7 wt% lower. Interestingly, the oil content was 5 wt% lower, and there was a similar content of aqueous phase. It must be mentioned here that the earlier processed MSW sample had substantially higher carbon and lower hydrogen content at similar ash content. [72]

Figure 18 shows the energy balances from oMSW(a) at the three temperature levels.

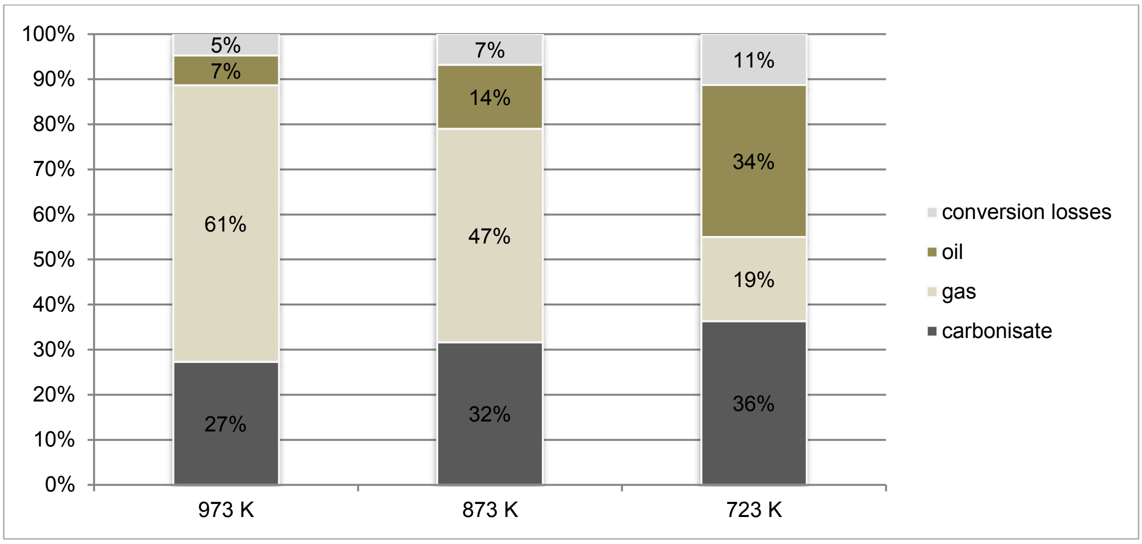

Figure 18: Energy balance of products from oMSW(a) at different temperature levels in the vertical reactor

The results are in line with the results presented regarding the mass balance. High temperatures in the vertical reactor favor the transformation of the energy content of the feedstock in the gaseous products (61% at 973 K). This was more than three times higher than at 723 K reactor temperature (19%). An increase of the temperature by 150 K leads to an increase in the energy content bound in the gas phase to 47%. On the contrary, the energy content of the oil phase at 723 K was nearly five times higher than with 973 K reactor temperature. The overall energy losses were in the range of 5−11% with low energy losses at the high reactor temperature, high losses at 723 K respectively.

The results of the mass and energy balance are in line with the results reported elsewhere related to digestate and bagasse [23,26].

Gas Composition and Characterization

The density, Wobbe s index, and higher heating value of the TCR gases from oMSW(a) are presented in Table 27.

Table 27: Properties of TCR-2 gases in correlation to the temperature in the vertical reactor from oMSW(a)

		973 K	**873 K**	**723 K**
Density	[kg/m³]	0.94	1.03	1.37
Wobbe s	[MJ/m³]	19.9	21.8	14.6
HHV	[MJ/kg]	18.73	18.85	11.03

The properties of the gases are dependent on the temperature of the vertical reactor. At 973 K reactor temperature, the density is in the range of 0.94 kg/m . With a decrease in temperature, the measured density increases. The trial series with the lowest reforming temperature had a density of 1.37 kg/m on average. Interestingly, the Wobbe index and therefore also the HHV are not linearly correlated to the temperature of the vertical reactor. The highest Wobbe s index was measured at 873 K (21.8 MJ/m). A further increase of the temperature to 973 K leads to a lower Wobbe index of 19.9 MJ/m . A significantly lower Wobbe index of 14.6 MJ/m was measured at a temperature of 723 K. Therefore, an increase of the temperature was followed by a decrease of

1.9 MJ/m and a decrease of 150 K to a reduction of 7.2 MJ/m . The impact of the temperatures on the composition of the gases is depicted in Figure 19.

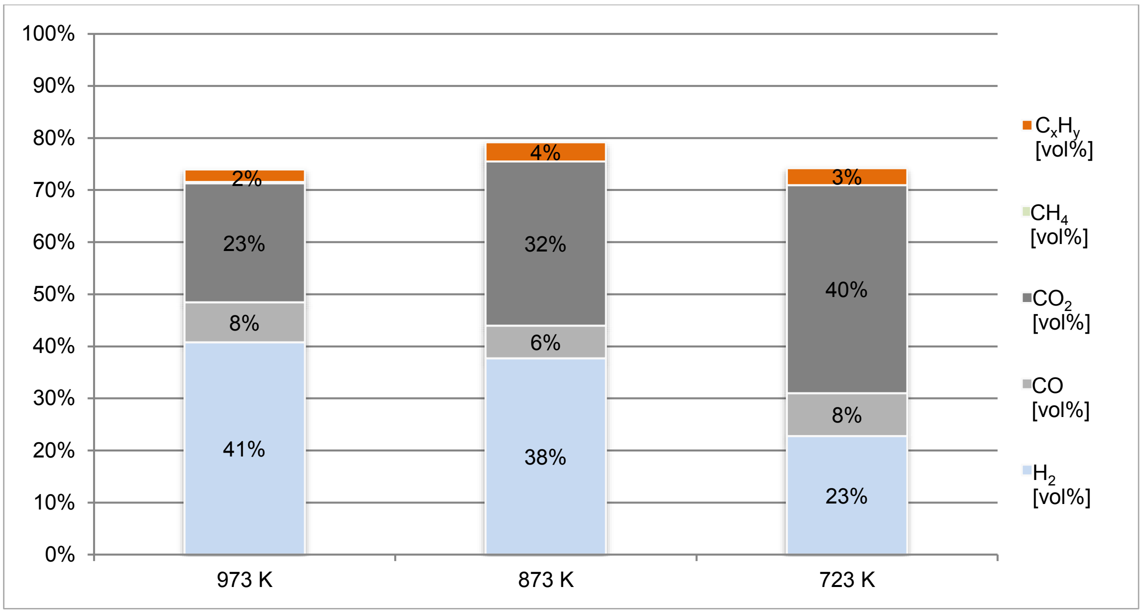

Figure 19: Quality of TCR-2 gases from oMSW(a) samples at three different vertical reactor temperatures

For all three experiments, over 25 vol% of the gases could not be identified. This was due to the large quantity of hydrocarbons, which inhibited the gas analysis system from measuring methane as described in section 5.1.3. Due to the high heating value and density of the non-identifiable gases, it is reasonable to assume that they include CH_4 and C_xH_y.

High temperatures in the vertical reactor promoted the release of H_2 (23, 38, and 41 vol%). On the contrary, higher temperatures caused lower CO_2 content in the gases (40, 32, and 23 vol%, respectively). The volumetric content of CO_2 at the lowest tested vertical reactor temperature even exceeded the detectable limit of 40%. This is in line with the measured density of the gases. The content of CO was stable for the three tested temperatures. These results are in line with the TCR of digestate reported in Journal of Analytical and Applied Pyrolysis in 2015 [23]. Regarding the relation of the hydrogen content and the reforming temperature, similar results were also achieved by the utilization of bagasse in the TCR. Interestingly, the effect of the increased CO_2 was not observed by Ahmad and co-workers [26]. For the patent DE102015108552A1, a different oMSW sample was tested, but the composition of the gases was very similar. At 973 K, the H_2 content was 36 vol%, and the CO content was 12 vol% [138]. Ouadi and coworkers described a similar gas composition at 973 K to the data presented here. In contrast to results from the gas composition of MSW(a), 14 vol% of methane was measured by an increased CO content. [72]

Regarding the properties and the composition of the gases, the optimum reforming temperature was 873 K. The increase of 100 K resulted in a slight decrease in the HHV and only an increase of 3 vol% of hydrogen in the gas stream. It must be considered that over 25% of the gases were not identified. Therefore, the composition of the C_xH_y components and the remaining undetected 20 vol% were not determinable.

Carbonisate Characterization

The elemental composition of the carbonisate of MSW(a) at three different reforming temperatures is shown in Table 28.

Table 28: Properties of char from oMSW(a) in correlation to the temperature in the vertical reactor (*: calculated by difference)

		973 K	873 K	723 K
C	[wt%]	17.9	21.2	20.6
H	[wt%]	0.3	0.2	0.3
N	[wt%]	0.4	0.6	0.6
S	[wt%]	0.2	0.3	0.4
Ash	[wt%]	84.7	81.9	80.3
O*	[wt%]	<1	<1	<1
HHV	[MJ/kg]	6.4	6.8	7.5
H_2O	[wt%]	<0.5	<0.5	<0.5

The carbon content decreased from 21.2 wt% to 17.9 wt% with an increase in temperature from 873 K to 973 K. This is in line with the results from bagasse [26]. The carbon content at 723 K (20.6 wt%) was contrary to this. Inhomogeneous sampling might explain these results.

The yields of the elemental composition of H, N, and S do not differ between all three samples significantly. The yields of H, N, and S were only different by 0.2 wt% for all temperatures. This is not consistent with the reported bagasse results. Ahmad and his coworkers observed a decreased hydrogen and sulfur content at higher reforming temperatures [26]. Since the compositions of the feedstock on a dry basis were very similar regarding the hydrogen content (4.0 wt% for bagasse, 4.1 wt% for oMSW(a)), polymeric composition of the feedstocks is of vital importance. This is because the degradation mechanisms of the components are different [256].

It is worth to highlight that the hydrogen content of the gases is not from reactions of the carbonisate in the vertical reactor. This contrasts the findings of Ahmad and coworkers. This leads to the conclusion that the oil and steam are reformed in the vertical reactor and provide the hydrogen of the TCR gas. Calculations have shown that the moisture of the feedstock provided the most significant source of hydrogen within the reaction and therefore also in the TCR gas.

Additional calculations based on the data from bagasse, digestate, and woody biomass confirmed these initial results.

The observed correlation of ash content, HHV, and temperature in the vertical reactor is stringent with previous work [26]. At a high reforming temperature, the ash content of the carbonisate is relatively high, and the HHV is low. For the oMSW(a) TCR trials at 973 K, the HHV was on average 6.4 MJ/kg with an ash content of 84.7 wt%. Thus, at 723 K the HHV was on average 7.5 MJ/kg and therefore 17% higher than at 973 K and 10% higher than the HHV of the 873 K trials. The ash content was 81.9 wt% of the 873 K trials, and approximately 80 wt% of the 723 K trials.

To consolidate, the impact of the temperature within the vertical reactor on the properties of the TCR carbonisates from oMSW(a), was minimal. No advantage of higher temperatures was observed regarding deoxygenation and denitrification of the carbonisates. Therefore, regarding the HHV and the quality of the carbonisate, high reforming temperatures did not make a difference.

Bio-Oil Characterization

The elemental composition, HHV, moisture content, and TAN are depicted in Table 29.

Table 29: Properties of bio-oil from oMSW(a) in correlation to the temperature in the vertical reactor (*: calculated by difference)

		973 K	873 K	723 K
C	[wt%]	82.2	82.0	76.7
H	[wt%]	8.3	9.0	10.9
N	[wt%]	4.0	5.0	3.1
S	[wt%]	0.6	0.8	0.5
Ash	[wt%]	<0.1	<0.1	<0.1
O*	[wt%]	4.8	3.1	8.7
HHV	[MJ/kg]	38.6	39.0	40.2
H_2O	[wt%]	4.0	0.9	4.8
TAN	[mg KOH/g]	7.5	4.8	8.1

The composition of the oils from each trial was similar. The carbon content of the oils at 723 K was 76.7 wt%, only slightly lower in comparison to 873 K (82.0 wt%) and 973 K (82.2 wt%). This is in line with results of MSW reported elsewhere [138]. The hydrogen content of the oils from oMSW(a) decreased by an increase of the reforming temperature. The same trend was detected for the bagasse trials [26]. Interestingly, the trials with 873 K in the vertical reactor had the highest nitrogen and sulfur content in the oil. The lowest nitrogen and sulfur content was apparent at 723 K. This can be explained with the higher oil yield and the assumption that the sulfur and nitrogen compounds of the oils are not transferring into the gaseous or solid products but remain in the oil fraction. The HHVs of the three different oils were 39.4 MJ/kg (±1 MJ/kg). A slight decrease of the HHV was observed with an increase of the reforming temperature. Water quantity and the TAN varied only slightly. Therefore, the impact of the vertical reactor temperature on the oil properties of the feedstock oMSW in the TCR can be considered negligible. This is in complete contrast to the results published for bagasse by Ahmad et al. [26]. The oil compositions at 773 K and 873 K had significantly lower carbon content than the oil at 973 K reforming temperature (53.7 wt%, 71.4 wt%, 80.0 wt%). In addition, the HHV and the moisture content of the oils were substantially different.

It was demonstrated that the optimum reforming temperature for the utilization of oMSW in the TCR technology is below 973 K regarding the quality of the products. However, it must be emphasized that the temperature of the vertical reactor is the most important parameter for the product distribution. A high temperature produces an increased gas yield regarding the mass and energy balance. In addition, the hydrogen content of the gases increased with an increased reforming temperature. On the contrary, a lower reforming temperature favors higher carbonisates and oil yields. Thus, the final utilization purpose of the products determines the needed reforming temperature.

Organic Fraction of Municipal Solid Waste(b)

The results of the series of experiments with the feedstock oMSW(b) in the TCR-2 plant are described in the following section. It must be stressed that the temperature in the vertical reactor was reduced to 873 K because of the performed trials with oMSW(a). This should be considered when interpreting the results.

Mass and Energy Balance

The mass balances of the seven performed TCR-2 trials with the feedstock oMSW(b), and the calculated average thereof is depictured in Figure 20.

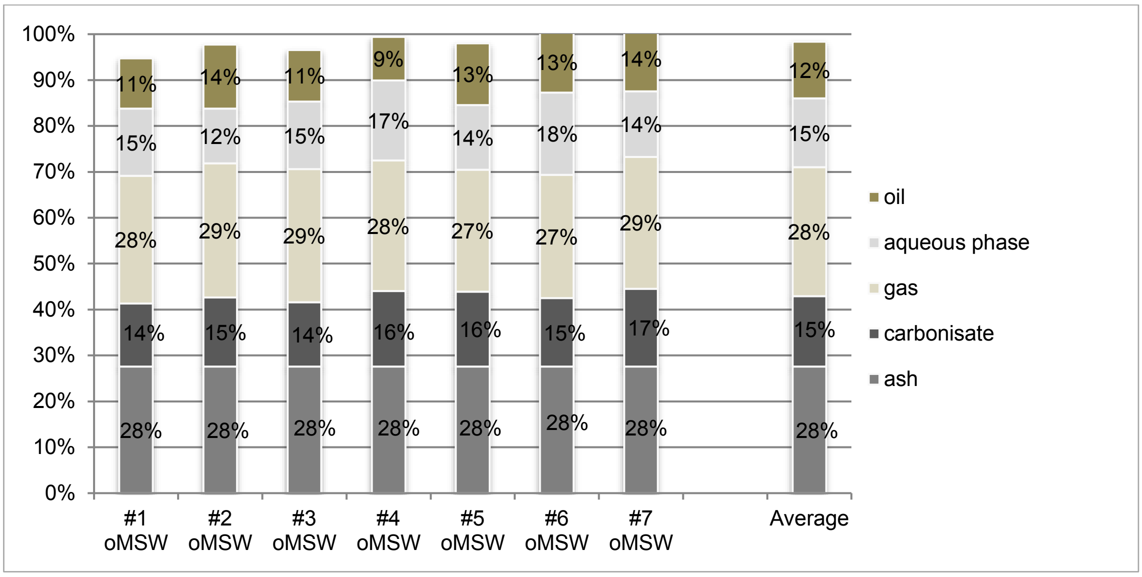

Figure 20: Mass balance of products from oMSW(b) collections

The variations in the yields of the solid and gaseous products were less than 2 wt%. The spectrum of results for the liquid TCR products ranges from 26–31 wt%. As described earlier, a small percentage of the masses could not be identified due to the size of the plant and the measurement of the gases.

The results of the mass balance of the feedstock oMSW(b) were different from the results presented earlier for the feedstock oMSW(a). This can be attributed to the different feedstocks composition. The differences in the ash and aqueous phase yields of the two mass balances can be traced back to the ash and moisture contents. The feedstock sample oMSW(a) had a significantly higher ash (42.1 to 29.2 wt%) and moisture content (24.5 to 5.7 wt%). The higher carbon content of the feedstock oMSW(b) favored the production of oil (12 to 13 wt%). Interestingly, on a dry basis of the feedstock, there are no substantial differences in the carbonisate and gas yield.

The energy balances of the TCR oMSW(b) trials are presented in Figure 21.

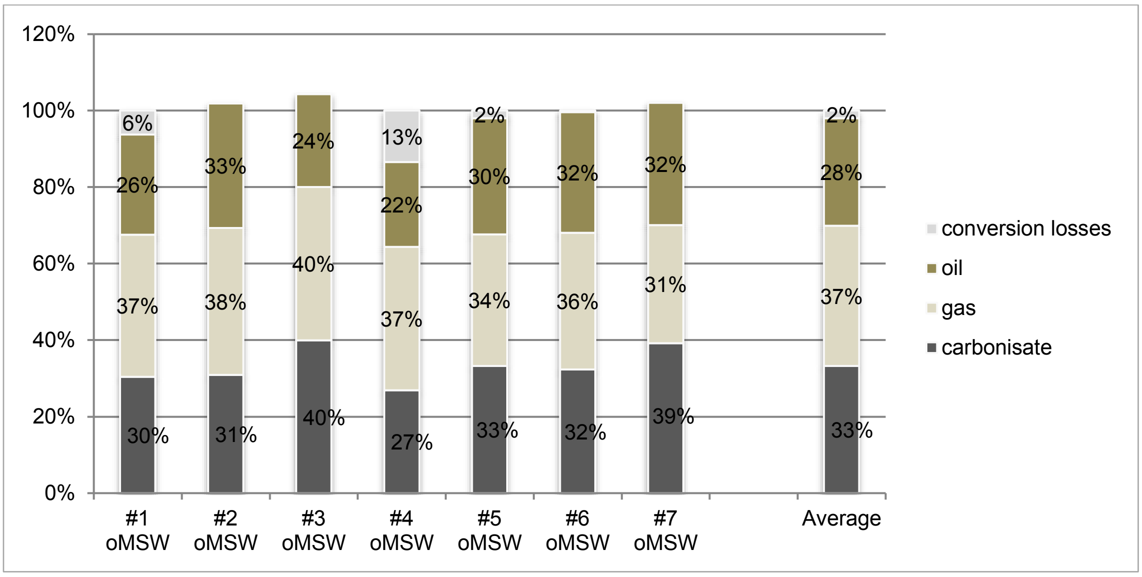

Figure 21: Energy balance of products from oMSW(b) collections

In comparison to the mass balances, the energy balances showed higher variations within the seven different trials. Of the energy in the feedstock, 27–40% was chemically bounded within the carbonisate. This is in line with the energy balance of oMSW(a). Compared to the energy content of the gaseous products, the feedstock oMSW(b) showed a significantly lower amount of energy bounded in the gas than the feedstock oMSW(a). On average, only 37% of the feedstock energy was found in the gas phase. The significantly higher energy content of the oil is in line with the results of the mass balance from oMSW(b). On average, no significant energy loss for the feedstock oMSW(b) was observed. Overall, the differences in the energy balances from oMSW(a) and oMSW(b) are in accordance with the related mass balances.

Gas Composition and Characterization

The compositions of the TCR gases from oMSW(b) are depicted in Figure 22.

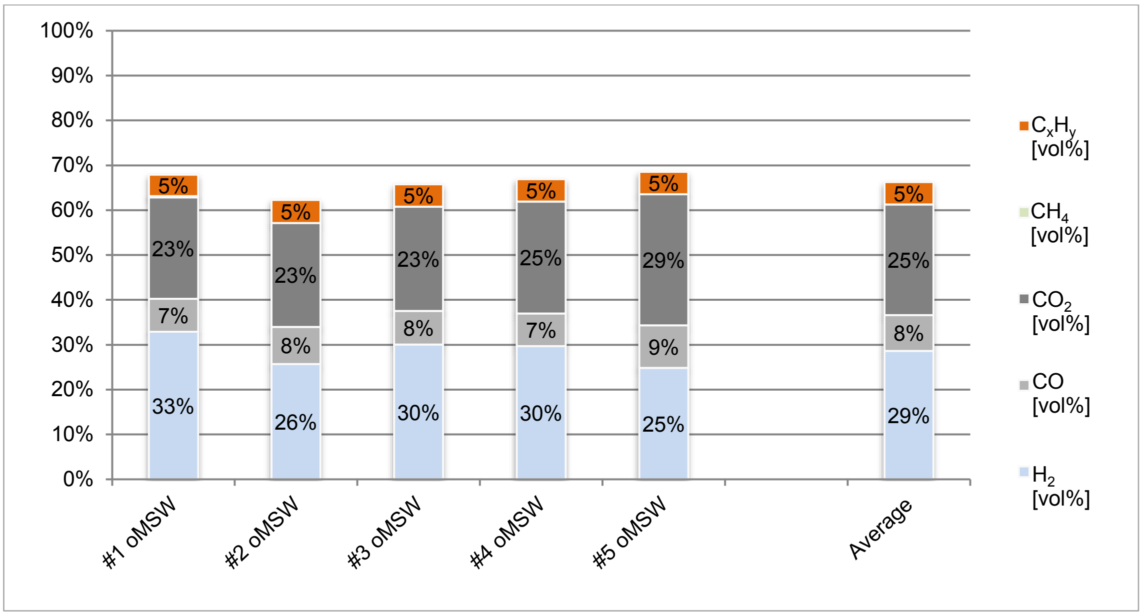

Figure 22: Quality of TCR-2 gases from oMSW(b) samples

The compositions of trial #6 and #7 were not determined due to maintenance work on the gas analyzer.

Due to the high content of C_xH_y (beyond the 5 vol% detection limit), the gas balance could not be adequately closed (section 5.1.3). Therefore, gas samples from trial #3 were analyzed by GC-FID/TCD to determine if CH_4 was in the gas. The measurements revealed significant CH_4 content of 13.5 vol%. The GC-FID/TCD measurement was in line with the results of the on-line gas measurement device regarding H_2 and CO content. Interestingly, less CO_2 was measured with GC-FID/TCD in comparison to the on-line gas measurement device (17 to 25 vol%). Unfortunately, the analyzer was not calibrated for the detection of C_xH_y components. Therefore, no detailed information about the exact composition could be provided. This is an interesting topic for further studies.

Thus, the density and HHV of the gases played a leading role in determining the missing 20 vol% and the composition of the 5 vol% of C_xH_y components.

The density of the TCR gas from oMSW(b) was 1.1 kg/m on average. The Wobbe s index was approximately 29.25 MJ/m , which indicates the presence of gases with a high density and HHV like butane or propane.

The HHV was 24.5 MJ/kg on average, which is significantly higher in comparison to the gas from oMSW(a). This is due to the more significant amount of C_xH_y (>4 vol%) and the lower hydrogen content (29 to 38 vol%).

Undoubtedly, the compositions of the gases from the two oMSW samples at 873 K reforming temperature were different. This indicates the impact of the higher carbon content of the feedstock oMSW(b) on the quality of the product gas.

Carbonisate Characterization

The properties of the solid products regarding CHNS-O, ash and moisture content, as well as the HHV, are shown in Table 30.

Table 30: Properties of carbonisate from oMSW(b) (*: calculated by difference; trial #1 and #3 not taken into account due to inconsistent values)

		oMSW(b)							
		#1	#2	#3	#4	#5	#6	#7	Average
C	[wt%]	(35.4)	29.7	(43.9)	20.9	25.5	31.2	29.1	27.2
H	[wt%]	(0.9)	0.6	(0.7)	0.4	0.5	0.6	0.4	0.5
N	[wt%]	(1.0)	0.9	(1.4)	0.6	0.8	0.8	0.7	0.74
S	[wt%]	(0.9)	0.7	(0.4)	0.4	0.9	0.8	0.8	0.72
Ash	[wt%]	(71.1)	67.3	(62.8)	70.0	69.7	67.6	65.2	67.9
O*	[wt%]	(<2)	0.8	(<2)	8.2	2.6	<2	3.8	2.9
HHV	[MJ/kg]	(12.4)	12.2	(16.1)	10.2	12.7	12.7	14.7	12.5
H_2O	[wt%]	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5

The carbon content of the carbonisate from oMSW(b) is on average 27.2 wt%, and thus higher than the carbon content of the carbonisate from oMSW(a). This is in line with the differences in the carbon content of the feedstock. The inhomogeneous feedstock could explain the high deviations of the carbon content. The hydrogen content within the carbonisate is also higher in comparison to the oMSW(a) trials. This could also be traced back to the different feedstock composition. Thus, the consistent nitrogen content is reasonable.

The sulfur content in the carbonisates from oMSW(b) is significantly higher than the sulfur content of oMSW(a) under the same reforming conditions. Thus, the sulfur content of the feedstock oMSW(a) was lower than of oMSW(b) (1.3 to 0.3 wt%). This could be explained by different sulfuric components and the degradation thereof. Consequently, a lower ash content (67.9 to 81.9 wt%) and HHV of the carbonisate from oMSW(b) was observed.

Bio-Oil Characterization

The results of the CHNS analysis of the oils are in line with the other pyrolysis products of oMSW(b). From Table 31, it is evident that the increased carbon content of the feedstock also had an impact on the elemental composition of the oils.

Table 31: Properties of bio-oil from oMSW(a) (*: calculated by difference)

		oMSW(b)							
		#1	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**Average**
C	[wt%]	88.4	88.3	79.4	88.7	87.3	89.2	84.0	86.5
H	[wt%]	9.7	10.1	9.1	10.4	10.3	10.1	9.3	9.9
N	[wt%]	2.0	2.0	2.8	1.7	2.0	1.9	3.8	2.3
S	[wt%]	0.3	0.3	0.5	0.2	0.3	0.2	0.4	0.3
Ash	[wt%]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
O*	[wt%]	<2	<2	<2	<2	<2	<2	<2	<2
HHV	[MJ/kg]	41.6	40.9	37.81	40.9	39.7	41.6	39.2	40.2
H_2O	[wt%]	0.4	0.5	0.6	0.6	0.6	0.5	1.3	0.6
TAN	[mg KOH/g]	2.5	3.7	2.3	2.1	3.7	2.6	(22.4)	2.8

The high carbon content of 86.5 wt% is one of several indicators of the improved oil properties. It is worth emphasizing the low nitrogen content of the oils from oMSW(b) in comparison to the oMSW(a) oils. Interestingly, the nitrogen contents of the feedstocks from both oMSW samples were the same (on dry basis), and due to the higher moisture content, even lower for the feedstock oMSW(a). The improved HHV and lower moisture content of the oil from oMSW(b) rounded the picture of the positive correlation between a high carbon content and the quality of the TCR products.

7.1.1.5 Leather Residues

Mass and Energy Balance

The mass balances of the three different residues from leather manufacturing are shown in Figure 23.

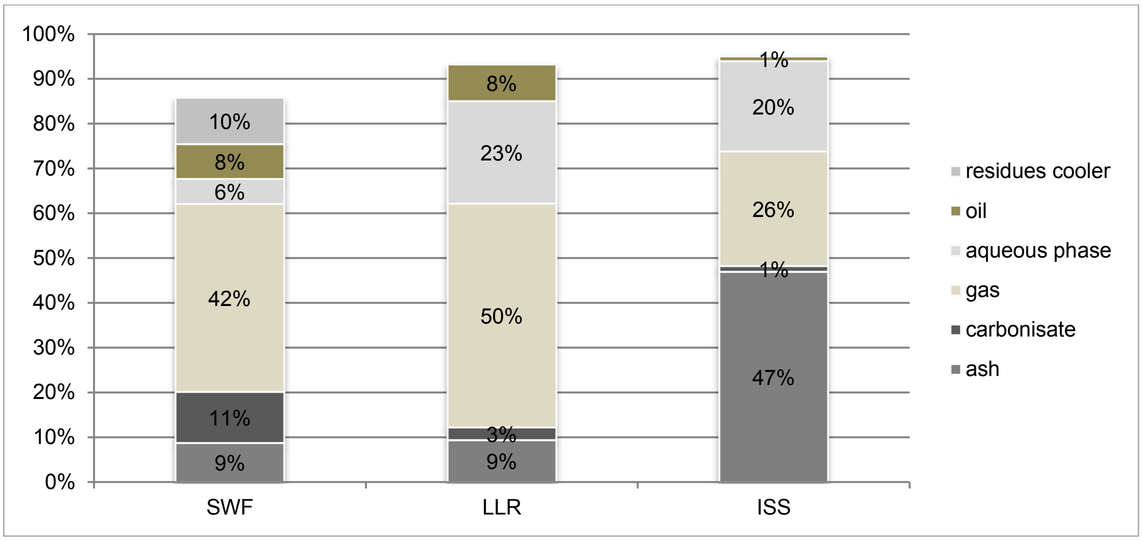

Figure 23: Mass balance of products from three different leather industry waste streams

The trials of the SWF samples revealed a fourth product fraction that was agglomerated within the condensing unit. The gap in the mass balance can be attributed to this fraction. During the cleaning of the condenser, it was not possible to account for the entire amount of residue.

The elemental composition of the product in the cooler revealed a low calorific value. The carbon content was 13.1 wt%, hydrogen 9.1 wt%, nitrogen 23.1 wt%, and sulfur 1.2 wt%. Therefore, the mass in the condenser is more comparable to the aqueous phase than to the oil fraction. For this experiment, a GC analysis of the fraction was not completed. Due to this, this fraction was not considered as a valuable product for the economic investigation (section 7.2). For further investigations of the feedstock SWF, a more detailed analysis of this fraction would be mandatory.

The impact of the different characteristics regarding elemental composition and ash content is revealed in the mass balances. Interestingly, even though the elemental compositions of the feedstocks SWF and LLR were very similar, the mass balances revealed severe differences for the solid product distribution. The carbonisates content (waf) of SWF was significantly higher than the content of the feedstock LLR (11 to 3 wt%). If the residues from the cooler of the feedstock SWF are accounted to the aqueous phase, the volume of liquid products was in a similar range for both feedstocks. The oil yield of both feedstocks was 8 wt%. Consequently, the lower detected carbon content of LLR was apparent in a higher gaseous content. The mass balance of the feedstock ISS was completely different from the mass balances of the other two feedstocks. Significantly higher ash content of feedstock (55 wt%) can be identified as the main reason for this. Therefore, over 48 percent of the mass was related to the solid products. It must be emphasized that a significant amount of the carbonisate was the ash contained in the feedstock. Interestingly, only a minor amount of oil was observed (1 wt%).

Figure 24 shows the energy balances of the three feedstocks SWF, LLR, and ISS.

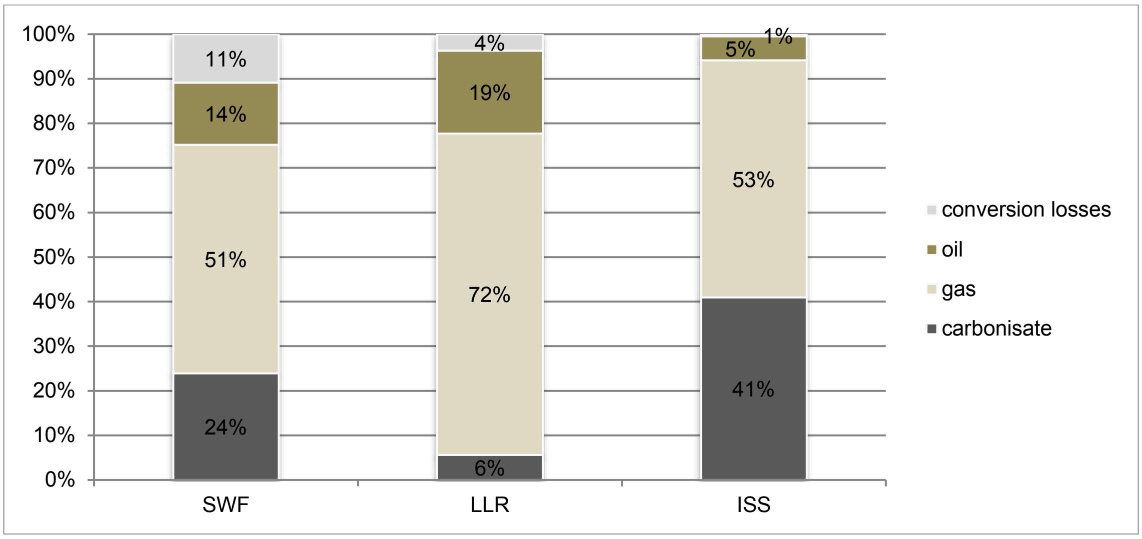

Figure 24: Energy balance of products from three different leather industry waste streams

It was observed that over 50% of the energy from the feedstock was transferred into the gaseous product fraction for each leather sample. The feedstock LLR had its energy share of 72%. The low carbonisate yields (waf) that are depicted in Figure 23 were in line with the low energy content within the energy balance. The same trend was observed for the oil yields.

Gas Composition and Characterization

The measured Wobbe s indexes of the gases from the three feedstocks (SWF, LLR, and ISS) were in correlation to the carbon contents of the feedstocks. LLR had the highest carbon content (47.7 wt%) and the highest Wobbe s index of all three feedstocks (28.7 MJ/m). From the measured densities of the gases depicted in Table 32, no correlation regarding the analyzed feedstock composition could be observed.

Table 32: Properties of TCR-2 gases of leather residues

		SWF	LLR	ISS
Density	[kg/m³]	0.81	0.98	0.91
Wobbe s	[MJ/m³]	24.2	28.7	16.8
HHV	[MJ/kg]	24.0	26.1	15.9

The gas composition of the feedstock SWF, LLR, and ISS is shown in Figure 25.

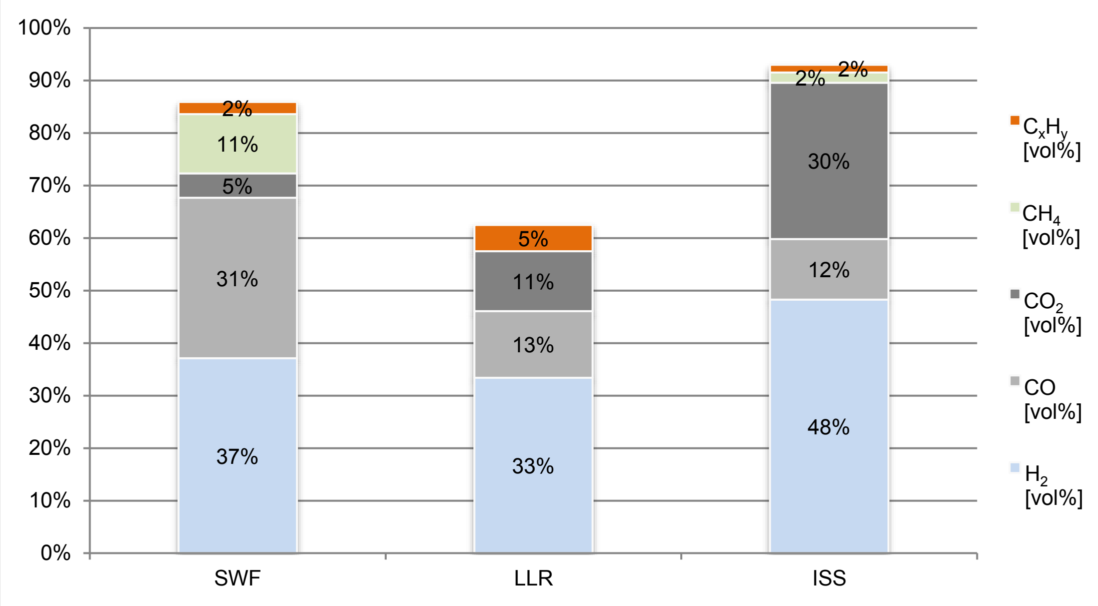

Figure 25: Gas composition of three different leather industry waste streams

As described earlier in section 5.1.3, due to the high amount of C_xH_y components beyond the detection limit (5 vol%) in the gas from LLR, the accuracy of the gas analyzer is negatively affected. Therefore, only 62 vol% of the gases were detected. The hydrogen contents of the gases were over one-third of all tested feedstocks. The hydrogen content of ISS was 48 vol%. The CO contents of the gases were varying, 12 vol% for ISS, 13 vol% for LLR, and 31 vol% for the feedstock SWF. Interestingly, the TCR gases from SWF had a high CO and a low CO_2 content (31 vol% and 5 vol%, respectively). On the contrary, the gases from ISS had a low CO and high CO_2 content (12 vol% and 30 vol%, respectively). Considering the properties and the composition of the gas from LLR, it is reasonable to assume a certain amount of CH_4 was present in the gas stream.

Carbonisate Characterization

The properties of the solid pyrolysis products from the three leather residues SWF, LLR, and ISS are presented in Table 33.

Table 33: Properties of TCR-2 carbonisates from three different waste streams (*: calculated by difference)

		SWF	LLR	ISS
C	[wt%]	56.1	25.8	13.3
H	[wt%]	1.2	0.2	0.2
N	[wt%]	5.9	2.1	0.6
S	[wt%]	3.1	3.7	5.0
Ash	[wt%]	31.8	68.5	94.6
O*	[wt%]	<2	<4	<1
HHV	[MJ/kg]	21.1	8.2	6.9
H_2O	[wt%]	<0.5	<0.5	<0.5

The carbon content within the carbonisate is very different for all three samples. This is remarkable because of the similar carbon content of the feedstocks SWF and LLR. The carbon content of SWF increased from 45.3 to 56.1 wt% (dry matter). In contrast, the carbon content of the LLR was reduced from 47.7 to 25.8 wt% (dry matter). On the one hand, an enrichment of carbon in the carbonisate was observed and, on the other hand, a depletion. The H, N, and S content did not follow these two opposing trends. The dehydrogenation and denitrogenation of the carbonisates were observed for all three feedstocks. The sulfur content for all three samples increased. Thus, it seems reasonable to suppose that the sulfur content only increased because of the proportionally higher decreasing of the elements H and N. The ash contents of the carbonisates were in line with the earlier described relation to the ash content of the feedstocks and the carbonisates (section 7.1.1.3). The balance regarding the CHNS and ash content of ISS could not be closed.

Bio-Oil Characterization

The properties of the oils from the three leather industry waste streams are presented in Table 34.

Table 34: Properties of TCR-2 oil from three different waste streams (*: calculated by difference)

		SWF	LLR	ISS
C	[wt%]	73.3	82.4	83.2
H	[wt%]	6.7	7.1	7.6
N	[wt%]	10.7	8.4	4.3
S	[wt%]	1.3	1.3	1.0
Ash	[wt%]	<0.1	<0.1	<0.1
O*	[wt%]	8.0	0.8	3.8
HHV	[MJ/kg]	33.5	37.3	38.4
H_2O	[wt%]	2.6	1.4	0.1
TAN	[mg KOH/g]	12.3	12.5	12.5

The oil from the feedstock SWF had the lowest carbon content with 73.3 wt%. The feedstocks LLR and ISS had a carbon content of 82.1 and 83.2 wt%. Therefore, no correlation between the elemental composition regarding carbon content of the feedstocks and the related oil was observed. This was also the case for the hydrogen content of the oils. All three samples had similar hydrogen content (6.7–7.6 wt%). Interestingly, ISS had the lowest hydrogen content in the feedstock, and in contrast, the highest hydrogen content in the oil. However, it must be taken into consideration that the oil yield of the feedstock ISS was only 1 wt%, which was significantly lower than the yield from the other samples (Figure 23).

A countervailing effect was observed regarding the sulfur content of the oils from ISS. The high sulfur content of the feedstock did not result in a high sulfur content in the oil. Due to this, it is reasonable to assume that the sulfur content of the feedstock ISS was mainly bound to the solid pyrolysis products.

An interdependence of the nitrogen content of the feedstock and the nitrogen content within the related oil was observed. The feedstock SWF had the highest nitrogen content of the three samples (Table 4) and, in accordance to this, also the highest nitrogen content in the oil (10.7 wt%). Interestingly, the oils from LLR and ISS had a higher nitrogen content in the oil than within the feedstock. The nitrogen content increased from 7.3 to 8.6 wt% for LLR and 1.7 to 4.3 wt% of the feedstock ISS.

Due to the calculation of the oxygen content by difference, the average oxygen content of the oils is in correlation with the measured carbon and nitrogen content. SWF had the highest oxygen content of the oils with approximately 8 wt% on average. The oil from the feedstock ISS had a content of 3.8 wt%, and LLR had the lowest oxygen content with only 0.8 wt% on average. The HHVs of the oils are in line with the carbon content. Thus, the feedstock ISS obtained oils with an HHV of 38.4 MJ/kg, and LLR oils with a similar HHV of 37.3 MJ/kg. SWF oils had the lowest HHV of all three collections at 33.5 MJ/kg. All three TCR oils showed a similar TAN, ranging from 12.3–12.5 mg KOH/g.

Distribution of C, H, and S from Feedstock to Products

Table 35 shows the different elemental distribution of C, H, and S in the products based on the elemental analysis of the feedstocks and main products. Because elemental distribution data was unobtainable for the gas phase, it was calculated by difference.

Table 35: Elemental distribution of pyrolysis products from three different waste streams

Gas		C	H	S
SWF	[wt%]	62.2	78.3	67.5
LLR	[wt%]	77.1	59.8	59.9
ISS	[wt%]	74.64	25.9	43.7

Carbonisate		C	H	S
SWF	[wt%]	28.8	3.9	28.1
LLR	[wt%]	7.2	0.3	27.6
ISS	[wt%]	19.5	1.3	52.1

Oil		C	H	S
SWF	[wt%]	7.7	4.6	2.4
LLR	[wt%]	12.9	6.8	5.6
ISS	[wt%]	2.1	2.3	0.8

Aqueous phase		C	H	S
SWF	[wt%]	1.3	13.1	2.1
LLR	[wt%]	2.8	33.2	6.9
ISS	[wt%]	3.7	70.1	3.4

The utilization of the three feedstocks by the TCR process transferred over 96 wt% of the carbon to the fuels. Over 60 wt% of the carbon content was transferred to the gaseous product. The feedstocks LLR and ISS had a remarkable transfer rate of over 77 and 74 wt% to the gas. The hydrogen distribution can be distinguished into three types. SWF had a high hydrogen transfer rate into the gaseous product and only a small transfer rate into the aqueous phase. In contrast, the distribution of ISS was the opposite: low hydrogen transformation into the gas phase (25.9 wt%) and high transfer into the aqueous phase (70.1 wt%). LLR can be assigned to the third group: the transfer rate of hydrogen to the pyrolysis products gas and aqueous phase is in-between the other types.

Particularly noticeable was the distribution of the sulfur. As the characterization of the oils and carbonisates indicated, the distribution of the sulfur for the feedstock ISS is unique. Over 52 wt% of the sulfur from the feedstock is bounded in the carbonisate.

Therefore, it can be concluded that the three samples from the leather making process behave differently. No relation of the elemental composition to the resulting product yields or syngas and oil qualities could be derived.

Overall, it can be concluded that the utilization of five different classifications of biogenic feedstocks with the TCR technology was successful. The twelve different samples were converted into the storable products oil, gas, and carbonisates. From the evaluation of the trials, the following conclusions can be drawn:
The compositions and therefore the properties of the carbonisates were strongly related to the ash content and, therefore, to the elemental composition of the feedstocks. Additionally, the oil yield was dependent on the feedstocks; not regarding elemental composition, but for the composition of organic compounds. Thus, it is not possible to approximate the oil yield based on the elemental composition of the feedstock. The composition of the gaseous product was dependent on the feedstocks and varied strongly in terms of composition and characteristics.

7.1.2 Fossil Feedstocks

Three different fossil feedstocks have been tested in the TCR-2 plant. The target was to upgrade low-rank coals to higher quality products. Therefore, peat and two different lignite chars were processed. In the following section, the results of these experiments are presented and discussed.

7.1.2.1 Peat

The granulated feedstock peat was processed in the TCR technology at three different reforming temperatures. To be able to compare the results, the same temperature ranges were used as for oMSW and in previous studies [23,26].

Mass and Energy Balance

The mass balance of the conversion of peat at three different vertical reactor temperatures is shown in Figure 26.

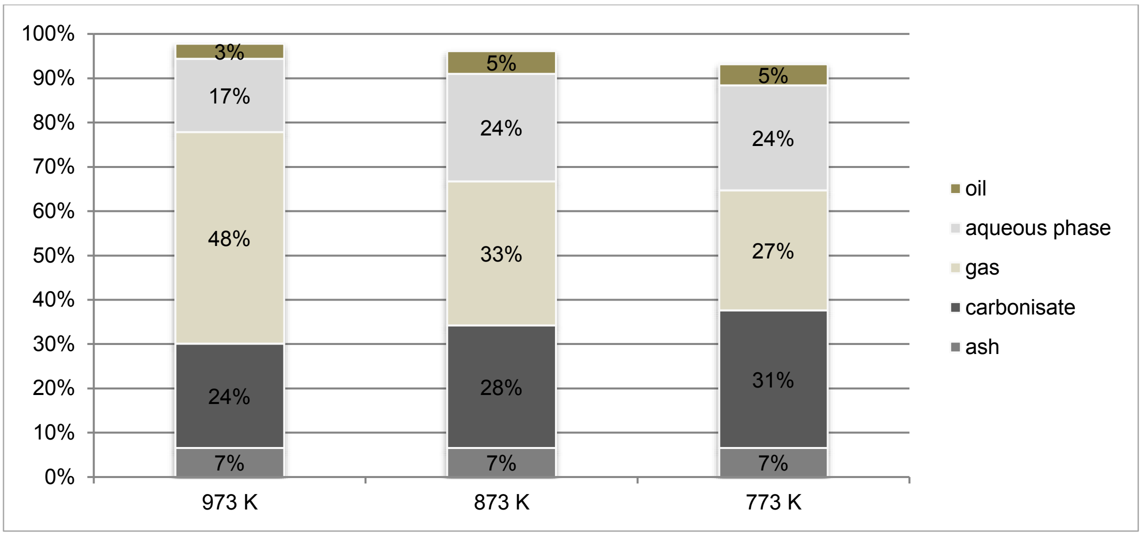

Figure 26: Mass balance of products from peat at three different vertical reactor temperatures

The results were in line with earlier related work for oMSW, bagasse, and digestate [23,26]. With an increase in temperature, the carbonisate content decreased, and the syngas content increased. Conversely, the amount of condensate remained stable for 773 K and 873 K and decreased with an increase of temperature by 9 wt%. The increase of undetected mass, previously described in section 7.1.1.4, was also confirmed by Ahmad et al. [26].

The carbonisate yield (waf) varied between 24–31 wt%. At 973 K nearly 50 wt% of the pyrolysis products was gas. This share was reduced at 773 K to only 27 wt%. The liquid products of the trials at 873 and 773 K were in the range of 24 wt% for the aqueous phase and 5 wt% for the oil. At 973 K the percentage of liquid products was reduced to 20 wt%, with an oil yield of only 3 wt%.

Regarding the mass balance, the same trends were found for biogenic feedstocks. The energy balance of the three peat trials is presented in Figure 27.

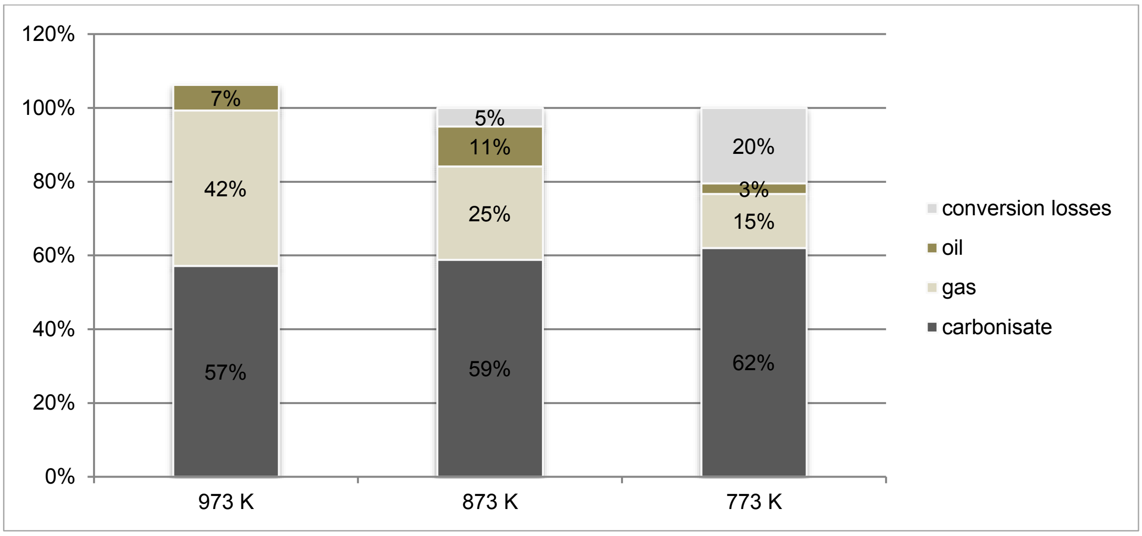

Figure 27: Energy balance of products from peat at three different vertical reactor temperatures

Regarding energy distribution, the energy balance for the fossil-based feedstock contradicts the mass balance. Over 57 wt% of the energy from the feedstock was transferred into the solid pyrolysis product. At 773 K, 62% of the energy of the feedstock was identified in the carbonisate. At 973 K, the share was still 57%. The energy of the gases was strongly varying with the temperatures in the vertical reactor; from 15% at 773 K to 42% at 973 K reforming temperature. Interestingly, the energy content of the oil from the 773 K and 873 K trials were different by more than a factor of 3.5. The amount of oil as depicted in the mass balance was the same; therefore, the properties and composition of the oils must be different. It was noted that the energy balance for the experiments at 973 K exceeded 100%. This can be explained by the overall tolerances of the measurements and the analytics. It is also apparent that the process at 973 K seems to be very energy efficient.

Gas Composition and Characterization

The density, Wobbe s index, and the related HHV of the TCR gases from peat at 973 K, 873 K, and 773 K are presented in Table 36.

Table 36: Properties of TCR-2 gas from peat at three different vertical reactor temperatures

		973 K	873 K	773 K
Density	[kg/m^3]	0.91	1.12	1.48
Wobbe s	[MJ/m^3]	17.5	16.7	13.3
HHV	[MJ/kg]	15.8	13.9	9.6

The results are in line with the findings of the oMSW(a) and the bagasse trials [26]. With an increase of the temperature within the vertical reactor, the density decreased while both the Wobbe index and HHV increased. The density varied from 1.48 kg/m at 773 K to 1.12 kg/m at 873 K, and ultimately to 0.91 kg/m at 973 K. The HHVs of the gases increased significantly, ranging from 9.6–15.8 MJ/kg.

The compositions of the gases from peat are shown in Figure 28.

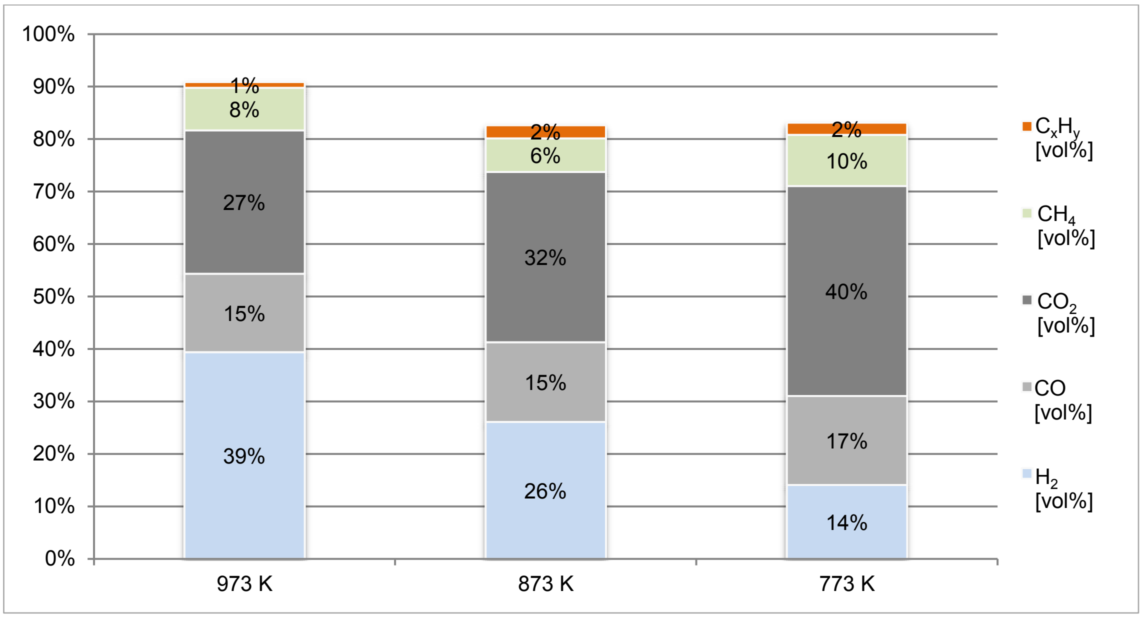

Figure 28: Gas composition of products from peat at three different vertical reactor temperatures

The effect of vertical reactor temperature on the relationship between H_2 and CO_2 was previously described in 7.1.1.4. The fossil-based feedstocks followed similar patterns. At 993 K the hydrogen content was 39 vol%, and the volumetric carbon dioxide was reduced to 27 wt%. On the contrary, the minimum hydrogen content was measured at the lowest reactor temperature (14 vol%). As predicted, the minimum hydrogen goes along with an increased CO_2 content beyond the detectable limit (>40 vol%). In contrast to results presented by Ahmad et al., the CO content does not vary in the same ratio as the hydrogen share did. Only a slight decrease from 17.0 to 15.2 to 15 vol% was detected. The share of higher hydrocarbons was only slightly above 2 vol% and therefore within the detectable limit of the measurement system.

Carbonisate Characterization

The results of the CHNS elemental analysis, ash and moisture content as well as the HHV of the three carbonisates from peat, are presented in Table 37.

Table 37: Properties of TCR-2 carbonisate from peat at three different vertical reactor temperatures (*: calculated by difference)

		973 K	873 K	773 K
C	[wt%]	78.8	73.9	75.5
H	[wt%]	1.1	1.7	2.8
N	[wt%]	1.4	1.6	1.9
S	[wt%]	0.34	0.31	0.40
Ash	[wt%]	18.3	16.6	11.8
O*	[wt%]	0.1	5.9	7.5
HHV	[MJ/kg]	30.7	28.1	28.3
H_2O	[wt%]	<0.5	<0.5	<0.5

The direct comparison of the three carbonisates generated at 973 K, 873 K, and 773 K reveals a strong relationship between temperature in the vertical reactor and the properties of the carbonisate. The impact of an increasing reforming temperature was a decrease of hydrogen, nitrogen, and sulfur content in the carbonisate. This is in line with the results discussed earlier (section 7.1.1.4). The carbon content of the carbonisate did not follow a clear trend. At 773 K the carbon content was on average 75.5 wt% and decreased by 1.6 wt% with an increase of 100 K. Contrary to the previously observed trend, the carbon content increased by 4.9 wt% with further temperature increase.

Interestingly, the oxygen content of the carbonisates decreased significantly with an increase of reforming temperature. Consequently, the HHV at 773 and 873 K is constant at 28.1 to 28.3 MJ/kg and increases at 973 K to 30.7 MJ/kg. The increasing reforming temperature of the fossil feedstock peat had a different impact than it was the case for biogenic feedstocks. In contrast to biogenic feedstocks, like bagasse or oMSW, the HHV of the carbonisates from fossil feedstocks increased with an increase in reforming temperature. One explanation for this could be secondary coking reactions on the carbonisates that lead to an increase of carbon content in the carbonisates. Scanning Electron Microscope (SEM) images could prove this assumption. This phenomenon will be investigated in future work.

Oil Characterization

The properties of the TCR oils from peat regarding the CHNS-O composition, ash content, HHV, TAN as well as moisture content are depicted in Table 38.

Table 38: Properties of TCR-2 oil from peat at three different vertical reactor temperatures (*: calculated by difference)

		973 K	873 K	773 K
C	[wt%]	69.4	71.2	26.3
H	[wt%]	8.4	9.4	11.1
N	[wt%]	2.7	2.5	1.7
S	[wt%]	0.7	0.8	0.3
Ash	[wt%]	<0.1	<0.1	<0.1
O*	[wt%]	18.9	16.1	60.6
HHV	[MJ/kg]	35.3	36.0	11.8
H_2O	[wt%]	3.4	3.3	52.3
TAN	[mg KOH/g]	13.9	16.2	16.2

Significant differences in the properties of the oils at 773, 873, and 973 K were observed. At a low vertical reactor temperature, the water content of the oil is above 50 wt%. Consequently, the carbon content and the HHV are low (26.3 wt% and 11.8 MJ/kg, respectively). After the experiments, there was no clear phase separation between the aqueous and the oil phase. The only separation that occurred was an emulsion of oil drops within the aqueous phase.

At higher reforming temperatures, the oil had a carbon content of 69.4–71.2 wt%. The nitrogen and sulfur share was stable at both investigated temperatures. The hydrogen content of the oil decreased by 1 wt% at temperature increase of 100 K. The HHVs of the TCR oils from peat at 873 and 973 K were in the range of 36–35.3 MJ/kg. This contrasts with the results observed from oMSW and bagasse. The elemental composition of the carbonisates indicated that this is due to the increase of oxygenated compounds.

The study using peat with the TCR technology at three different vertical reforming temperatures demonstrated a correlation between temperature and product yields and qualities. However the achieved results at lower reforming temperatures indicated that there are differences between the utilization of biomass and fossil feedstocks.

7.1.2.2 Peat and Lignite

In the following section, the results of the TCR trials of three different fossil feedstocks at 973 K vertical reactor temperature are presented. The results of peat were individually discussed in section 7.1.2.1 but were also included here for a more straightforward comparison of the results.

Mass and Energy Balance

The mass balances of the three tested fossil feedstocks are shown in Figure 29.

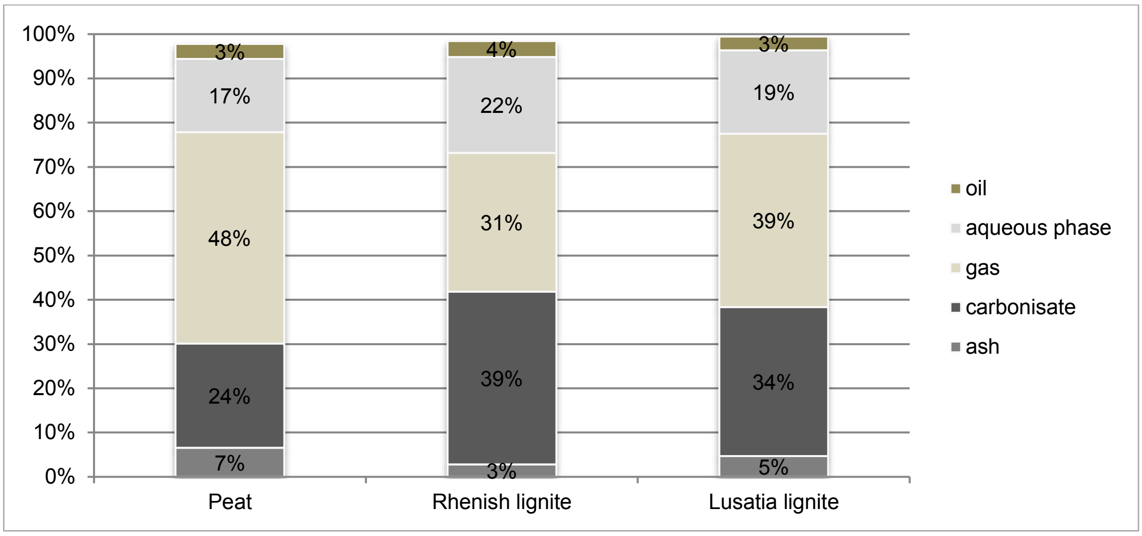

Figure 29: Mass balance of products from peat, Rhenish and Lusatia lignite at 973 K vertical reactor temperature

The ash content of the feedstocks varied between 3–7 wt%. Rhenish lignite had the lowest and peat had the highest content of inert material. The share of carbonisate correlated with this. Rhenish lignite had the highest content of carbonisate with 39 wt% (waf) in the mass balance, and peat the lowest share with 24 wt% (waf). Lusatia lignite had a carbonisate content of 34 wt%, which indicates that the higher carbon content of the feedstock Lusatia lignite in comparison to Rhenish lignite does not translate to a higher carbonisate share in the mass balance.

The distribution of gaseous products varied between 31–48 wt%. The subbituminous coals had the lower shares with 31 wt% for Rhenish and 39 wt% for Lusatia lignite. According to the differences in feedstock moisture content, the mass distribution in the aqueous phase for each feedstock was in a similar range. Only minor differences were detected regarding the oil yields: at 973 K reforming temperature, the share of oil within the mass balance was between 3–4 wt%.

The related energy balances of the fossil feedstocks are presented in Figure 30.

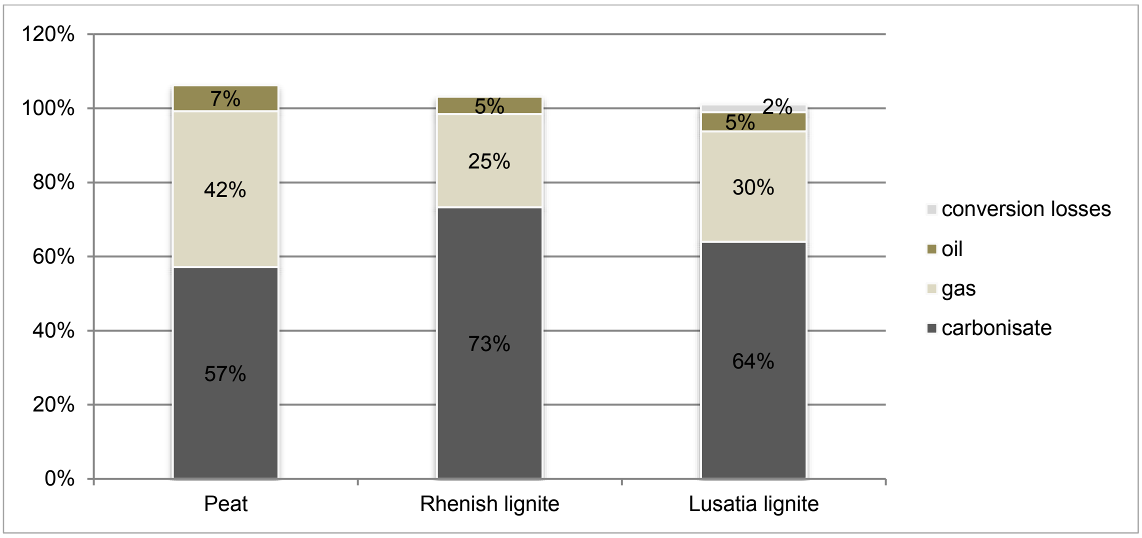

Figure 30: Energy balance of products from peat, Rhenish and Lusatia lignite at 973 K vertical reactor temperature

It is apparent that most of the energy from each feedstock is transferred into the solid pyrolysis product. Over 73% of the energy from Rhenish lignite was recovered in the carbonisate, 64% for Lusatia lignite, and 57% for peat. Approximately 25–30% of energy was recovered in the gaseous products for the lignite feedstocks. Corresponding to the results of the mass balance, the feedstock peat had the highest share of energy converted into the gas. At 973 K reforming temperature, only 5–7% of the feedstock energy was transferred into the oil. The observed transformation of the bounded energy from the feedstock to the products was highly efficient for fossil fuels. As previously described in this section, there is no indication that the energy required for heating the process is transferred into the products. In fact, it is more likely that measuring tolerances, analytics, and the differences between heat-up/shut-down and steady state operation were the reason for the surplus in the energy balance.

Gas Composition and Characterization

The characteristics of the gases regarding density, Wobbe s index, and HHV are listed in Table 39.

Table 39: Characteristics of TCR-2 gas from peat, Rhenish and Lusatia lignite at 973 K vertical reactor temperature

		Peat	Rhenish lignite	Lusatia lignite
Density	[kg/m³]	0.91	0.94	0.96
Wobbe s	[MJ/m³]	17.2	16.6	17.1
HHV	[MJ/kg]	15.8	15.5	15.1

The results were measured in a narrow range of values. The density varied between 0.91 kg/m for peat, 0.94 kg/m for Rhenish lignite, and 0.96 kg/m for Lusatia lignite. The highest Wobbe s index was achieved by the feedstock peat (17.2 MJ/m), followed by Lusatia lignite (17.1 MJ/m), and Rhenish lignite (16.6 MJ/m).

The compositions of the gases are presented in Figure 31 and confirm the previous results.

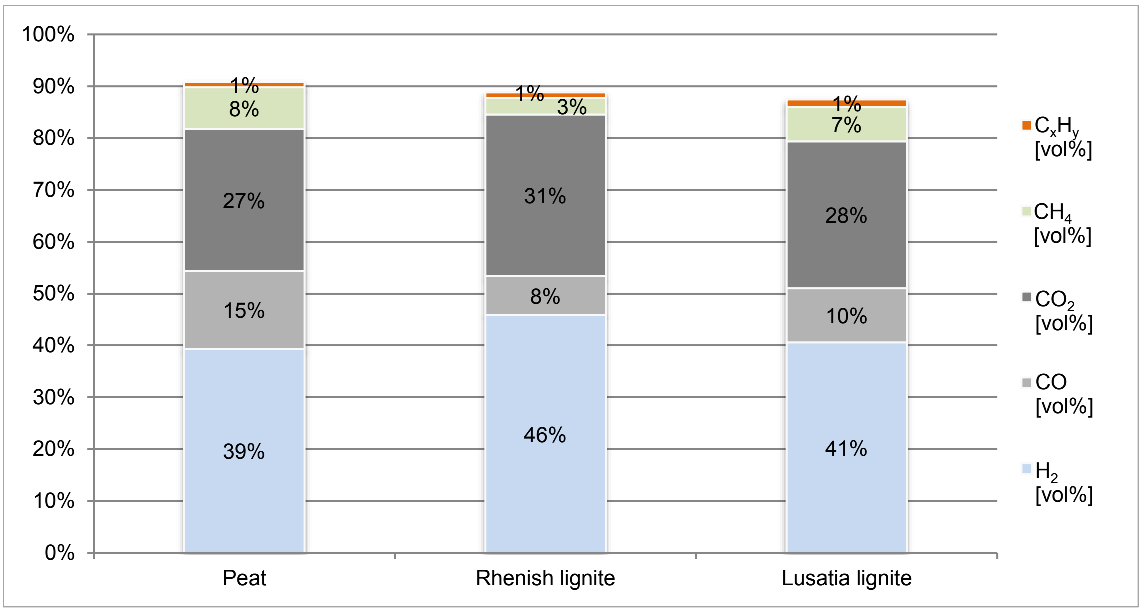

Figure 31: Gas composition of products from peat, Rhenish and Lusatia lignite at 973 K vertical reactor temperature

The hydrogen content varied between 39–46 wt%. The lignite feedstocks tended to have higher hydrogen content. Countervailing the distribution of hydrogen was the volumetric share of CO in the gases. Ahmad et al. observed a similar trend for the TCR of bagasse [26].

The content of CO_2 was for all three trials within the close range of 27–31 wt%. For peat and Lusatia lignite, methane contents of 8 and 7 vol% were detected. In contrast, only 3 vol% of methane was detected in the gaseous products from Rhenish lignite. Interestingly, only 1 vol% of C_xH_y components were detected.

Carbonisate Characterization

The properties of the TCR carbonisates from the three tested fossil feedstocks peat, Rhenish and Lusatia lignite are listed in Table 40.

Table 40: Properties of TCR-2 carbonisate from fossil feedstocks at 973 K vertical reactor temperature (*: calculated by difference)

		Peat	**Rhenish lignite**	**Lusatia lignite**
C	[wt%]	78.8	86.8	86.3
H	[wt%]	1.1	2.2	1.1
N	[wt%]	1.4	1.0	0.8
S	[wt%]	0.34	0.36	0.79
Ash	[wt%]	18.3	7.4	11.5
O*	[wt%]	0.1	2.4	0.2
HHV	[MJ/kg]	30.7	30.8	31.1
H_2O	[wt%]	<0.5	<0.5	<0.5

The carbon content of both lignite related carbonisates was around 86.5 wt% and thereby 8 wt% higher than the carbon content of carbonisate from peat. Only minor differences regarding the hydrogen, nitrogen and sulfur content were observed. The higher hydrogen content of the Rhenish lignite carbonisate is in line with the higher hydrogen content of the feedstock. The same applies to the higher sulfur content of the carbonisate from Lusatia lignite. Rhenish lignite had the highest oxygen content in the oil with 2.4 wt%. Peat had an oxygen content of only 0.1 wt% and Lusatia lignite of 0.2 wt%, respectively. The HHVs of all three carbonisates are in a close range of 38.5 ± 1.5 MJ/kg.

Oil Characterization

The properties of the oils from three tested fossil feedstocks are presented in Table 41.

Table 41: Properties of TCR-2 oil from three different fossil feedstocks at 973 K vertical reactor temperature (*: calculated by difference)

		Peat	**Rhenish lignite**	**Lusatia lignite**
C	[wt%]	69.4	59.3	78.7
H	[wt%]	8.4	10.2	8.5
N	[wt%]	2.7	1.0	1.5
S	[wt%]	0.65	0.16	0.62
Ash	[wt%]	<0.1	<0.1	<0.1
O*	[wt%]	18.9	29.3	10.7
HHV	[MJ/kg]	35.3	24.6	33.3
H_2O	[wt%]	3.4	30.0	14.7
TAN	[mg KOH/g]	13.9	14.8	12.5

The composition of the oils regarding the carbon content varied widely. A significant difference between the Lusatia lignite oil and the Rhenish lignite oil was observed. Lusatia TCR oil had a high carbon content of over 78.7 wt%. In contrast, Rhenish oil had a carbon content of only 59.3 wt%. This was explained by the high water content (30 wt%) of the oil.

Therefore, it can be assumed that the gravimetric separation of the oil and aqueous phase was not completely developed. Exemplary for this is the variating water content of the Lusatia lignite TCR oil, noticeable through the experimental standard deviation $s(t_k)$ 10.53 wt%, and standard uncertainty $u(\bar{t})$ of 5.27 wt%. Due to this fact, experiments to centrifuge the oil were performed with a positive result. It was possible to reduce the water content of the oil below 3.5 wt% with a correlating increase of carbon content and HHV. The differences in the nitrogen content of the oils can be derived from the nitrogen content of the feedstocks. Consequently, peat had the highest nitrogen content of the oils with 2.7 wt%. Both oils from lignite were in the range of 1.0–1.5 wt%. Except for the oils from the feedstock Rhenish lignite, the HHVs of the oils were in the range of 33–35 MJ/kg.

In addition, the oil from Rhenish lignite was distilled to prove the thermal stability and to clarify if the water content of the oils could be reduced by a stepped condensing unit (Table 42).

Table 42: Distilled fraction of TCR-2 Rhenish lignite oil (*: calculated by difference; ×: not measured)

Fraction			**Elemental composition**					**Properties**		
	T_{dist}	**Yield**	**C**	**H**	**N**	**S**	**O***	**H_2O**	**TAN**	**HHV**
	[K]	[wt%]	[wt%]					[wt%]	[mg KOH/g]	[MJ/kg]
Aqueous phase	<323	34.2	×	×	×	×	×	×	×	×
Product	323–593	48.1	80.6	10.9	0.6	0.2	7.8	1.4	2.3	39.3
Heavy oil	>593	10.7	×	×	×	×	×	×	×	×

The distillation trial was successful. The oil proved to be stable, and the water content was reduced to below 1.5 wt%. This was also reflected in the elemental composition of the oils and the heating value. The carbon content increased to 80 wt%. The HHV increased to 39 MJ/kg. The nitrogen content was slightly reduced to 0.6 wt%. The overall distillable yield of 89 wt% can be attributed to the high water content of the crude oil.

It can be concluded that the utilization of fossil feedstock in the TCR has been proved successful for three different feedstocks. The unique characteristics of the products that were known from the TCR conversion of biomass feedstocks were also achieved for fossil feedstocks when using optimum parameters. All three processed fossil feedstocks had a significant share of solid pyrolysis products. The quality of the solid products was, regarding carbon content and HHV, significantly refined. The gas had high hydrogen content with an HHV in the range of 15.4 MJ/kg. It has been shown that the process conditions to produce high-quality oil from fossil feedstocks with the TCR technology are of greater importance than for the utilization of biomass. This is essential, not only regarding elemental composition but also in terms of the separation of the oils and the aqueous phase. As a result of this study, the temperature in the vertical reactor must be increased for fossil feedstocks in comparison to biogenic feedstocks. This is especially important for the possible utilization of the oils. Whether these correlations are also apparent for mixtures of biomass and fossil feedstock will be investigated in the following section 7.1.3.

7.1.3 Co-Pyrolysis of Biomass and Lignite

The trials aimed to determine possible interactions between the co-pyrolysis of lignite and biomass in the TCR technology. As set out in section 4.4, the impact of the synergetic mechanisms as described in literature, have not been investigated within the TCR technology. For an industrial application of mixtures of biogenic and fossil feedstocks as described in section 4.4, it is mandatory to know the impact of those mixtures on the yields and product composition.

As described in section 5.3, lignite was blended with sewage sludge at a ratio of 50:50 wt% and 75:25 wt%, and for each mixture, trials were performed at three different temperatures in the vertical reactor (973 K, 873 K, 773 K). To verify the results, an additional experiment series was performed with a different biogenic feedstock. A feedstock with antipode characteristics was chosen: high-quality wood chips with a low ash content (<1 wt%). Lignite was blended with wood chips at the ratio 50:50 wt% and processed at 973 K reforming temperature to ensure that the achieved lignite/sewage sludge results would be in line with the lignite/wood results and can, therefore, be adopted for different feedstock blends.

To interpret the results of the mixed feedstock trials, it is necessary to compare them with calculated distributions based on the results of reference trials with unblended feedstocks. This makes it possible to evaluate the impact of the synergy effects described in section 4.4 on the product yields and the quality of the products. If the co-pyrolysis of biomass and lignite in the TCR technology has a significant impact, the results of the mixed trials would be different from the results derived from the reference trials. Accordingly, if the mechanisms of heat and hydrogen transfer, as well as the catalytic effect of the inert material among each other, are not dominant within the TCR, it would be possible to calculate the expected distribution by a linear function based on the reference trials. The mass and energy balance can be derived from a linear transformation of the results from the reference trials described earlier in section 5.3 (Formula 9).

For the calculation of the composition of the products, a linear transformation of the relative blending ratio is not expedient. It must be considered that the product distributions of the feedstocks are different. Therefore, the properties of the carbonisate, oil, and gas are dependent on the blending ratio as well as the product distribution of the feedstock derived from the reference trials. Formula 13 is applied for the calculation of the properties of the products. (ash, moisture, TAN, C, O, H, N, S, H_2, CO, CO_2, CH_2, C_xH_y, HHV)

$$x_{mix} = \frac{(x_{LG} \times m_{LG} \times y) + (x_{BM} \times m_{BM} \times (1 - y))}{(m_{LG} \times y + m_{BM} \times (1 - y))}$$

Formula 13: Calculation of the predicted distribution of the carbonisate, oil, and syngas of the mixed trials (ash, moisture, TAN, C, O, H, N, S, H_2, CO, CO_2, CH_2, C_xH_y, HHV) ($\boldsymbol{mix}$: mixture, $\boldsymbol{LG}$: lignite, $\boldsymbol{BM}$: biomass, $\boldsymbol{y}$: share of lignite in the feedstock mixture)

Due to the defined structure of the feedstocks, it is possible to identify each carbonisate within the carbonisate from the mixture trials. For that reason, it is possible to compare the carbonisate from the mixture trials directly with the carbonisates from the reference trials. A disadvantage is that it is not possible to take the impact of the specific carbonisate yield into consideration. As this is the case for all products, the yields are extrapolated from the reference trials.

Mass and Energy Balance

Figure 32 shows the mass balance of the four different experimental setups. For each temperature and feedstock mixture, lignite (LG) and sewage sludge (DSS) as well as lignite and wood chips (WC), the results of the reference trials (100 wt%), the calculated (as described earlier), and the real results are presented.

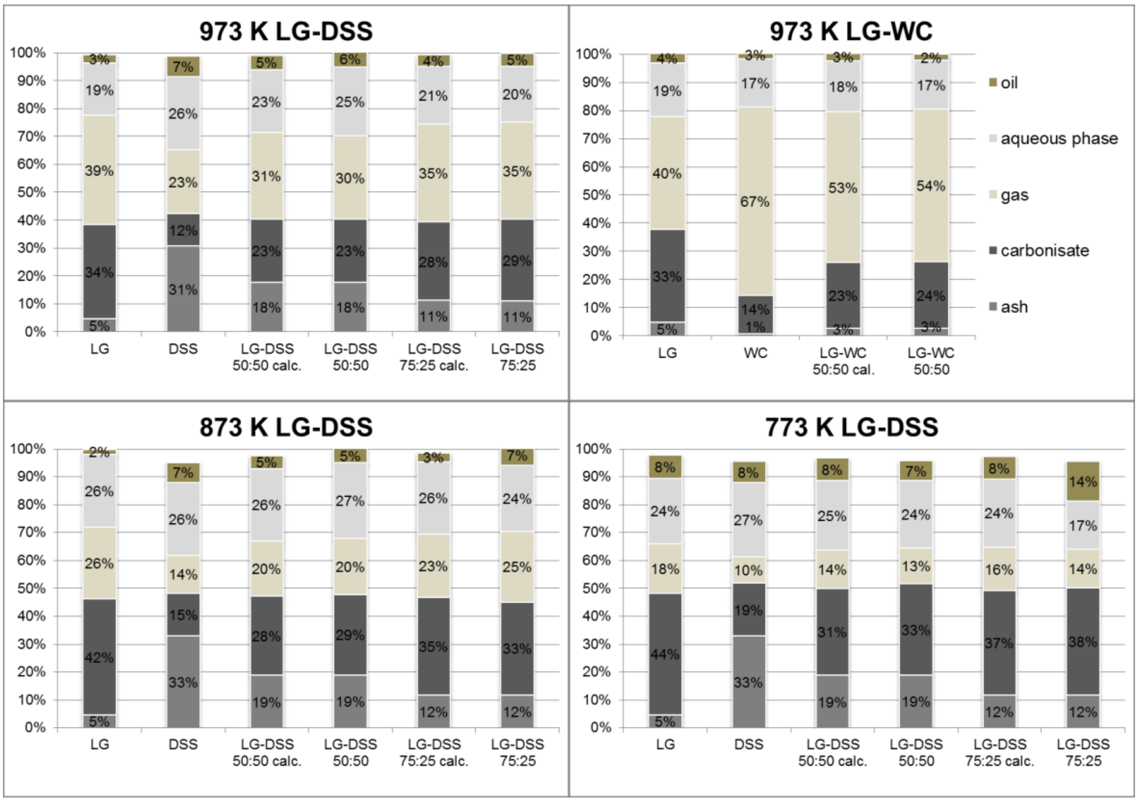

Figure 32: Mass balance of reference and co-pyrolysis trials at 973 K, 873 K, and 773 K reforming temperature

The differences in the yields of the three feedstocks are clearly apparent. Sewage sludge has the highest ash content (31 wt%), lignite has only 5 wt% ash, and wood chips have a very low content of inert material (1 wt%). The carbonisate yields of the reference trials also revealed differences. For all setups, lignite had the highest carbonisate yield (waf). The decreased carbon content with an increase of the temperature in the vertical reactor is in line with the results previously published [26]. The syngas, aqueous phase, and oil content of the reference trials confirmed the results presented earlier in section 7.1.1.1, 7.1.1.2, and 7.1.2.2. The slight differences between the yields were among other things attributable to the different water content of the feedstocks. In addition, the sources of the woody biomass were different. Instead of pruning residues with high ash content, high-grade birch wood chips were used for a high contrast to the sewage sludge. Therefore, sewage sludge can be assumed as an antipode of high-quality wood chips.

For the interpretation of the results, it is important to highlight that the temperature variation of lignite trials confirmed the results of the peat trials. At a low vertical reactor temperature of 773 K, there is no clear phase separation of the liquid phase. As mentioned in section 7.1.2.1, the condensable components were an emulsion of aqueous phase and oil. Consequently, it was difficult to separate both fractions in a separation funnel. This must be considered in the interpretation of the yields of the liquid phase and later in the composition of the fractions.

The comparison of the calculated and measured yields shows stringent results for all temperature profiles and feedstocks. The differences between the calculated and measured yields of the solid and gaseous products were varying only by a maximum of 2.5 wt%. The 50 wt% blends have a tight tolerance of only ±1 wt%. This would suggest that the impact of the synergetic mechanism of co-pyrolysis of fossil and biogenic fuels is negligible.

Due to the incomplete phase separation of the condensable products, the differences for the 773 K trial were significantly higher. Based on deductions from the preceding trials, this is not due to the synergetic mechanisms described in section 4.4. However, the results of the energy balance must be seen in an overall context of gas, carbonisates, and the oil composition for a concluding assessment.

The energy balances of the co-pyrolysis trials are shown in Figure 33.

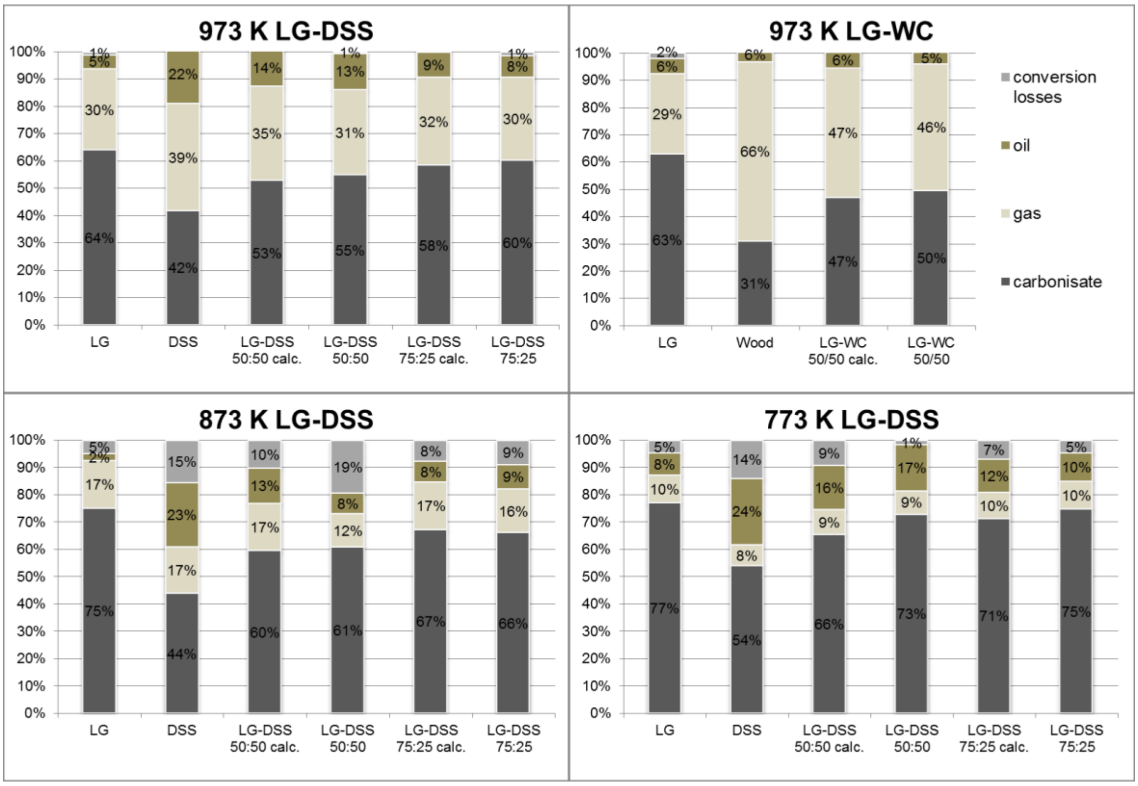

Figure 33: Energy balance of reference and co-pyrolysis trials at 973 K, 873 K, and 773 K reforming temperature

The balances of the reference trials are stringent to the results presented earlier in section 7.1.1.1, 7.1.1.2, and 7.1.2.2. This also applies to the impact of the temperature of the vertical reactor that was described for biogenic and non-biogenic feedstocks in section 7.1.1 and 7.1.2. The balances of LG-DSS at 973 and 873 K, as well as LG-WC at 973 K, show consistent tight tolerances regarding the predicted and measured yields of the co-pyrolysis trials similar to the mass balance (Figure 32). The exception to this trend was the energy content of the carbonisates. Six of the seven balances had higher energy content (1–7%) in the carbonisates than calculated. The balance of the 873 K trial with the 75 wt% blend missed this trend just about 1%.

Also, the energy content of the non-condensable gases at 973 K and 873 K for the feedstock LG-DSS 50 wt% blend is 4–5% lower than in the calculated scenarios. Accordingly, the energy content of the carbonisates is increasing. However, the increase of only 1–2% is not a clear indication of a transformation of the energy from the gaseous to the solid products. For the 873 K trials, the high energy loss of 19% could be one reason for this. Moreover, this trend is not confirmed by the other experiments.

It can be concluded that the results from the energy balance were different from the results of the mass balance.

However, the 973 K trials showed a high matching rate with the linear modeling. With regards to a non-matching linear prediction model of the energy content of the 873 K and 773 K trials, this leaves room for interpretation of the impact of the co-pyrolysis on the balances and ultimately the composition of the products. Therefore, these results of the compositions of the products must be considered.

Gas Composition and Characterization

The properties of the TCR gases of the reference and co-pyrolysis trials are depicted in Table 43.

Table 43: Properties of TCR-2 gas of reference and co-pyrolysis trials at 973 K, 873 K, and 773 K reforming temperature

973 K		**LG**	**DSS**	**LG-DSS 50:50 calc.**	**LG-DSS 50:50**	**LG-DSS 75:25 calc.**	**LG-DSS 75:25**
Density	[kg/m³]	0.95	0.97	0.95	0.94	0.95	0.95
Wobbe s	[MJ/m³]	17.8	22.5	19.1	18.5	18.0	17.9
HHV	[MJ/kg]	15.6	20.2	17.3	17.1	16.4	16.1

973 K		**LG**	**WC**	**LG-WC 50:50 calc.**	**LG-WC 50:50**
Density	[kg/m³]	0.95	0.99	0.98	0.90
Wobbe s	[MJ/m³]	17.5	18.2	17.9	17.1
HHV	[MJ/kg]	15.0	16.1	15.7	15.9

873 K		**LG**	**DSS**	**LG-DSS 50:50 calc.**	**LG-DSS 50:50**	**LG-DSS 75:25 calc.**	**LG-DSS 75:25**
Density	[kg/m³]	1.20	1.27	1.23	1.49	1.21	1.43
Wobbe s	[MJ/m³]	17.3	18.5	17.7	13.5	17.5	15.8
HHV	[MJ/kg]	14.1	14.7	14.3	9.7	14.2	11.7

773 K		**LG**	**DSS**	**LG-DSS 50:50 calc.**	**LG-DSS 50:50**	**LG-DSS 75:25 calc.**	**LG-DSS 75:25**
Density	[kg/m³]	1.40	1.54	1.45	1.44	1.42	1.37
Wobbe s	[MJ/m³]	13.8	13.5	13.7	14.1	13.7	17.3
HHV	[MJ/kg]	10.4	9.7	10.2	10.8	10.3	13.4

As described in section 5.1.3, the HHV is calculated from the Wobbe index and the specific density. Therefore, the heating value is directly dependent on the density $(\rho_{\mathrm{n,gas}})$ and the Wobbe s index. For this reason, only the density and the Wobbe index are considered in the following evaluation of the results.

The 973 K trials with sewage sludge show a high correlation between the calculated properties of the gases and the measured results. The deviations were in the range of 0.6 MJ/m for the Wobbe index which equals 3%.

The lignite wood chip blend had broader differences between the predicted and the measured results. The density and the Wobbe s index were lower than calculated (0.08 kg/m and 0.8 MJ/kg). Overall, it can be concluded that, in line with energy balance, the linear prediction model of the gas properties is reliable for TCR experiments with a high temperature in the vertical reactor.

The gas properties at lower temperatures show greater deviations. The measured density and Wobbe index exceeded the values of the reference trials. At 873 K the density was higher than the expected value based on the reference trials for both blending ratios. On the contrary, the Wobbe index was significantly lower (17.7 MJ/m to 13.5 MJ/m and 17.5 MJ/m to 15.8 MJ/m , respectively). The 773 K trial met the expectations regarding the density. The Wobbe index showed a clear distinction between the calculated and the actual values. The Wobbe index at 14.1 MJ/m (50 wt%) and 17.3 MJ/m (75 wt%) was beyond the ranges of the reference trials. Therefore, the results obtained from the mass and energy balance were in line with the observed properties of the TCR gas.

The compositions of the non-condensable TCR gases are given in Figure 34.

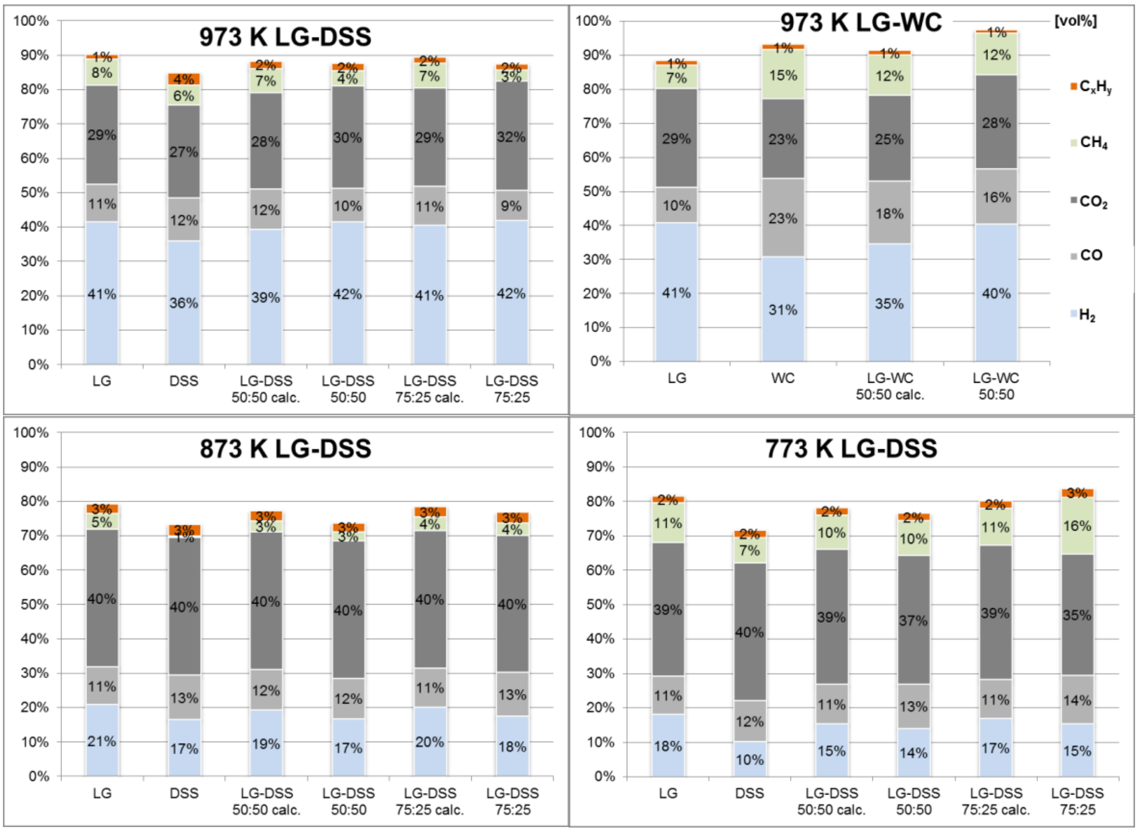

Figure 34: Composition of TCR-2 gas of reference and co-pyrolysis trials at 973 K, 873 K, and 773 K reforming temperature

The evaluation of the LG-DSS campaign at 973 K reveals consistent trends. The volumetric hydrogen contents of the gases from the blended feedstocks were higher than the calculated values (1–3 vol%). This is in line with the reduced methane content of the gases (3–4 vol%). Moreover, with both blending ratios, an increase of the carbon dioxide (2–3 vol%) and a decrease of the carbon monoxide yields (2 vol%) were detected. No differences in the volumetric quantity of higher hydrocarbons were detected. Overall, the yields of the gases did not exceed the amount of the reference trials.

The comparative trials of lignite with a woody biomass at 973 K confirmed the trend of a higher hydrogen (6 vol%), lower carbon monoxide (2 vol%), and increased carbon dioxide (3 vol%) content. The methane contents of the calculated and measured gases were consistent.

The results of the 873 K trials contrast with the results of the 973 K trials. The hydrogen content decreases for both blending ratios. The carbon monoxide volumes of the measured trials, in comparison to the reference trials, were increasing or stable. Due to the high amount of carbon dioxide beyond the detection limit of 40 vol%, no projections can be made. The calculated yields of methane and higher hydrocarbons were in line with the measured results. The trials at 773 K confirm the tendencies of the 873 K trials. Hydrogen content is lower, and carbon monoxide is higher than the expected values. Due to the lower carbon dioxide yield at 773 K, it was possible to detect the carbon yield below the calculated expected value (2–4 vol%). It is important to highlight the composition of the 773 K trials. The volumetric composition of the hydrogen, carbon monoxide, and for the 75 wt% trial also methane was beyond the measured values of the reference trials. For the 75 wt% trial, the increase of carbon monoxide and methane was significantly higher (2–5 vol%).

It can be concluded that for the 973 K trials the linear approximation is appropriate to estimate the composition and properties of the gas from different fossil and biogenic feedstocks with slight limitations for the hydrogen content. Overall, the results of the co-pyrolysis trials at a high temperature in the vertical reactor are in line with the reference trials.

The test series with lower temperatures in the vertical reactor revealed that the linear prediction model is not coherent.

However, the results of the gas measurement must be interpreted in relation to the overall detectable volumetric amount. For the trials with a temperature of 873 K and 773 K, the detectable amount of gas was around 80 vol%. Therefore, the results of the gas measurement must be considered in the light of the mass and energy balance, as well as the results of the products carbonisate and oil.

Carbonisate Characterization

The results of the analysis of carbonisate produced in the co-pyrolysis trials were prepared differently in comparison to the results presented earlier. As described at the beginning of 7.1.3, the possibility to allocate the carbonisates to the different feedstock origins made it possible to compare the results of the mixed and the reference trials. However, it must be considered that fine particles of the fractions stick together. These impurities can cause misleading results.

Due to the low hydrogen, nitrogen, and sulfur content of the TCR carbonisate, the effect of small variations in the feedstock and therefore in the solid product, as well as tolerances in the measurement systems causes high deviations (in total as well as in percentage). Due to this, the carbon and ash content, as well as the higher heating value, are more suitable parameters for the evaluation. However, some values of the sulfur and hydrogen content are conspicuous and will be described in the following section.

For the carbon content of the carbonisates from the reference and the co-pyrolysis trials at 973 K, no trend was discernible (Table 44).

Table 44: Properties of TCR-2 carbonisate of reference and co-pyrolysis trials at 973 K, 873 K, and 773 K reforming temperature (*:calculated by difference)

973 K		**LG**	**LG 50:50**	**LG 75:25**	**DSS**	**DSS 50:50**	**DSS 75:25**
C	[wt%]	86.3	87.4	84.3	28.2	26.8	26.8
H	[wt%]	1.0	1.0	0.9	0.3	0.1	0.2
N	[wt%]	1.1	1.3	1.0	2.1	1.4	1.6
S	[wt%]	0.70	1.13	0.80	1.14	1.00	0.90
Ash	[wt%]	10.9	12.4	11.5	71.7	72.5	72.9
O*	[wt%]	<1	<1	<1	<1	<1	<1
HHV	[MJ/kg]	32.1	28.7	30.4	10.2	11.8	10.0

973 K		**LG**	**LG 50:50**	**WC**	**WC 50:50**
C	[wt%]	85.7	85.7	91.7	93.7
H	[wt%]	1.1	0.9	0.9	0.7
N	[wt%]	0.8	0.9	0.5	0.6
S	[wt%]	0.79	0.45	0.43	0.21
Ash	[wt%]	11.5	10.7	3.6	2.3
O*	[wt%]	<1	<1	<1	<1
HHV	[MJ/kg]	31.1	30.9	32.2	32.5
H_2O	[wt%]	<0.5	<0.5	<0.5	<0.5

873 K		**LG**	**LG 50:50**	**LG 75:25**	**DSS**	**DSS 50:50**	**DSS 75:25**
C	[wt%]	83.9	76.9	81.3	23.7	25.3	25.2
H	[wt%]	2.2	3.0	2.5	0.1	0.9	1.0
N	[wt%]	1.1	2.4	1.2	1.6	2.6	2.5
S	[wt%]	0.31	0.47	0.65	1.79	1.83	1.72
Ash	[wt%]	7.1	11.9	10.5	71.6	68.5	70.8
O*	[wt%]	5.4	5.3	3.9	1.3	0.9	<1
HHV	[MJ/kg]	30.9	29.0	30.4	9.7	9.6	9.0

773 K		**LG**	**LG 50:50**	**LG 75:25**	**DSS**	**DSS 50:50**	**DSS 75:25**
C	[wt%]	82.9	84.8	84.6	31.1	29.1	26.1
H	[wt%]	1.7	2.4	2.2	2.2	1.8	0.5
N	[wt%]	1.2	1.1	1.2	3.9	3.1	2.4
S	[wt%]	0.54	0.35	0.34	1.57	1.66	1.15
Ash	[wt%]	7.9	6.8	6.4	63.4	62.7	66.1
O*	[wt%]	5.7	4.6	5.3	<1	1.5	3.8
HHV	[MJ/kg]	30.8	31.2	31.1	11.6	12.0	9.3

A slight increase in the carbon yield was measured for the sewage sludge and the wood chip trial. For the trials with a blending rate of 50 wt%, an increase of the carbon content was observed. An increase of 1.1 wt% was observed for the lignite carbonisates in the LG-DSS trials. In contrast, in the LG-WC trials the increase of carbon was observed in the biomass carbonisate (2 wt%). There was a significant increase of the sulfur content (0.43 wt%; 60%) of the lignite carbonisates at 973 K with 50 wt% blending. Based on the available data and the fact that this was not evident in the other trials, it must be declared as a contamination of lignite with sewage sludge. This has no impact on the overall sulfur content of the carbonisate in total. Therefore, it is negligible. Similar irregularities occurred with the ash content of lignite for the 873 K trials. The increase from 6.6 wt% to 11.9 wt% and to 10.5 wt% can only be explained by adhesions of the different feedstocks among each other. Moreover, the ash content of the related sewage sludge carbonisate is decreasing.

From the 973 K and 873 K results depicted in Table 44, the reduced HHV of the carbonisate from lignite in comparison to the reference trials becomes obvious. This is correlated by an increase of the biogenic carbonisate heating value. These results support the thesis put up of impurities by adhesion of the different particles.

For the 873 K and 773 K co-pyrolysis trials, a trend is discernible. The hydrogen content is higher than expected for all samples except the DSS mixtures at 773 K. At 873 K the hydrogen contents of the sewage sludge carbonisates were considerably higher. This indicates that the mechanism of the dehydrogenation of the solid pyrolysis products from sewage sludge at 873 K is inhibited in the presence of lignite. Therefore, regarding the quality of the carbonisates from co-pyrolysis of fossil and biogenic feedstocks, the minimum reforming temperature of the feedstocks must be selected.

Bio-Oil Characterization

The results of the analysis of the TCR oil from the reference and co-pyrolysis trials are shown in Table 45.

The reference trials revealed a clear difference between both feedstocks in terms of the properties of the oil. The quality of the TCR oil from sewage sludge regarding CHNS content, water content, TAN, and HHV are for all three temperatures comparable. The HHVs of the oils were in the range of 32.1–36.7 MJ/kg. In contrast, the oil from lignite varies significantly (32.7–21.3 MJ/kg). This is in line with the results reported earlier in section 7.1.2.1 for the fossil feedstock peat.

The 973 K test series showed consistent results for the sewage sludge and wood chips co-pyrolysis trials. The carbon content of the oils was higher than expected for the linear calculation. Also, the HNS amount decreased in each of the three different feedstock/blending set-ups. The HHVs of the LG-DSS 50:50 and LG-WC 50:50 trials are higher than the expected HHV (32.2 to 35.9 MJ/kg and 34.4 to 36.0 MJ/kg, respectively). The lower HHV of the oil from LG-DSS 75:25 at 973 K in comparison to the expected value (32.3 to 30.1 MJ/kg) is counteracting to these results. Considering the results of the CHNS and ash measurements, the spread of the results is caused by the tolerances of the measurements. The measured water contents of the oils were significantly lower than expected.

Table 45: Properties of TCR-2 oil of reference and co-pyrolysis trials at 973 K, 873 K, and 773 K reforming temperature (*: calculated by difference)

973 K		**LG**	**DSS**	**LG-DSS 50:50 calc.**	**LG-DSS 50:50**	**LG-DSS 75:25 calc.**	**LG-DSS 75:25**
C	[wt%]	79.4	74.6	76.0	81.4	77.2	79.0
H	[wt%]	8.6	8.8	8.7	8.3	8.7	8.4
N	[wt%]	2.3	7.2	5.7	5.2	4.5	4.1
S	[wt%]	0.62	0.87	0.80	0.57	0.73	0.63
O*	[wt%]	9.2	8.5	8.7	4.4	8.9	7.9
HHV	[MJ/kg]	32.4	32.1	32.2	35.9	32.3	30.1
H_2O	[wt%]	14.7	3.6	6.9	1.3	9.8	2.2
TAN	[mg KOH/g]	9.9	7.3	8.1	9.4	8.8	7.4

973 K		**LG**	**WC**	**LG-WC 50:50 calc.**	**LG-WC 50:50**
C	[wt%]	78.7	82.9	80.5	84.2
H	[wt%]	8.6	6.3	7.7	6.8
N	[wt%]	1.5	1.6	1.5	1.3
S	[wt%]	0.55	0.38	0.48	0.47
O*	[wt%]	10.7	8.8	9.9	7.2
HHV	[MJ/kg]	33.3	35.9	34.4	36.0
H_2O	[wt%]	13.2	11.6	12.5	1.1
TAN	[mg KOH/g]	8.6	13.9	10.8	59.8

873 K		**LG**	**DSS**	**LG-DSS 50:50 calc.**	**LG-DSS 50:50**	**LG-DSS 75:25 calc.**	**LG-DSS 75:25**
C	[wt%]	85.9	76.2	78.1	80.8	80.3	72.7
H	[wt%]	8.8	10.5	10.2	10.1	9.8	9.9
N	[wt%]	1.5	6.5	5.5	4.7	4.4	3.4
S	[wt%]	0.30	1.05	0.90	1.10	0.73	0.55
O*	[wt%]	3.5	5.7	5.3	3.4	4.8	13.5
HHV	[MJ/kg]	32.7	36.7	35.9	23.9	35.0	23.4
H_2O	[wt%]	1.3	3.0	2.7	42.5	2.3	21.4
TAN	[mg KOH/g]	16.0	15.6	15.7	30.3	15.8	14.3

773 K		**LG**	**DSS**	**LG-DSS 50:50 calc.**	**LG-DSS 50:50**	**LG-DSS 75:25 calc.**	**LG-DSS 75:25**
C	[wt%]	48.0	76.0	61.3	22.4	54.5	40.7
H	[wt%]	9.3	10.8	10.0	12.0	9.7	11.1
N	[wt%]	2.4	6.6	4.4	2.9	3.4	2.3
S	[wt%]	0.42	1.04	0.72	0.30	0.57	0.60
O*	[wt%]	39.9	5.5	23.5	62.4	31.9	45.3
HHV	[MJ/kg]	21.3	36.2	28.4	37.9	24.8	14.7
H_2O	[wt%]	1.9	3.6	2.7	3.3	2.3	88.0
TAN	[mg KOH/g]	30.0	15.6	23.1	14.3	26.6	38.8

Due to the compelling nature of the moisture improvements, it is reasonable to assume that this is a remarkable effect of the co-utilization of biogenic and fossil fuels within the TCR technology. The high TAN of the LG-WC co-pyrolysis oil cannot be explained. Further repetitive measurements confirmed the result, but within the scope of the work, this anomaly could not be further investigated.

A stringent evaluation of the properties of the oils from the 773 K trials was not possible. The relationship between the measured carbon content and the corresponding HHV and water content is not plausible. For example, the HHV of the oil of LG-DSS at 50 wt% at 773 K was measured 37.9 MJ/kg with a moisture content of 3.3 wt%. In contrast, the carbon content was only 22.4 wt%. This contradiction can be explained with the inhomogeneous oil due to the formed emulsion of aqueous phase and oil. At the blending ratio of 75 wt%, this inconsistency was also detected. The high water content of 88 wt% is contrary to the measured carbon content of 40.7 wt%. However, this is in line with the results of the reference trial (lignite) and the temperature variation of the peat trials in section 7.1.2.1.

At 873 K the reference trials produced oils with high carbon contents, with matching HHVs, and water contents. The results of the 873 K trial depicted in Table 45 reveal that oil from the co-pyrolysis trials had the same quality issues as the oils at 773 K. The carbon content of 80.8 wt% and 72.7 wt% are contrary to the results of the HHV and moisture content.

The scope of the series of experiments was to evaluate the impact of the synergetic mechanisms described in section 4.4 on the TCR technology.

With regards to the results of the mass and energy balance and the characterization of the products the following conclusions can be made:

- It is necessary to differentiate the three different investigated temperatures in two segments: 973 K and 873–773 K.
- At 973 K, sufficient accuracy of the linear model was proven for the mass and energy balance within the limitations regarding tolerances of the lab scale plant and the attached analytics. Therefore, it can be assumed that the specified mechanisms (section 4.4) are overshadowed by the reforming step at 973 K. However, for the composition of the gases and the properties of the oil, a clear tendency was detectable. Consequently, synergy effects are detectable at the level of the product quality. But for the carbonisate, the different composition could not be assigned exclusively to the mechanisms. The possibility could not be ruled out that the changes in the composition were caused due to the mixing of the carbonisates, without a real difference in the overall composition.
- At 873 K and 773 K, the prediction model based on the reference trials was not reliable. This is mainly attributed to the characteristics of the conversion of fossil feedstock within the TCR technology at low reforming temperatures as described in section 7.1.2.1. However, the possibility that blending with a biogenic feedstock would improve the quality of the products at low reforming temperatures can be ruled out, at least for the mixing ratios of 50 wt% and beyond.

To conclude, the synergy effects of co-pyrolysis of fossil and biogenic feedstocks within the TCR are present but in a limited extent. For the investigated feedstocks and blending ratios, there were no significant variations detectable in the mass and energy balances. The composition of the products can slightly change and be shifted to targeted values, with restriction of the minimum needed reforming temperature of one of the present feedstocks.

7.1.4 TCR Products, Utilization, and possible Upgrading

In the following section, the TCR products carbonisate, oil, and gas, as well as the byproduct aqueous phase produced in the trials described in section 7.1.1 and 7.1.2, were compared to each other. The data will be brought together with the findings of section 2.2. The objective is to classify the products, prove suitability for the applications described in section 2.2 or investigate potentials for upgrading the products to achieve the required standards. The objective is to supply the products to the highest possible utilization pathway. The energetic utilization of the products is assumed as the base scenario. The results of this section are the basis for the economic calculations in section 7.1.5.

TCR Product Distribution and Energy Balance

The product mass distribution of the seven different feedstocks described in section 7.1.1 and 7.1.2 is shown on an ash-free basis in a ternary plot in Figure 35.

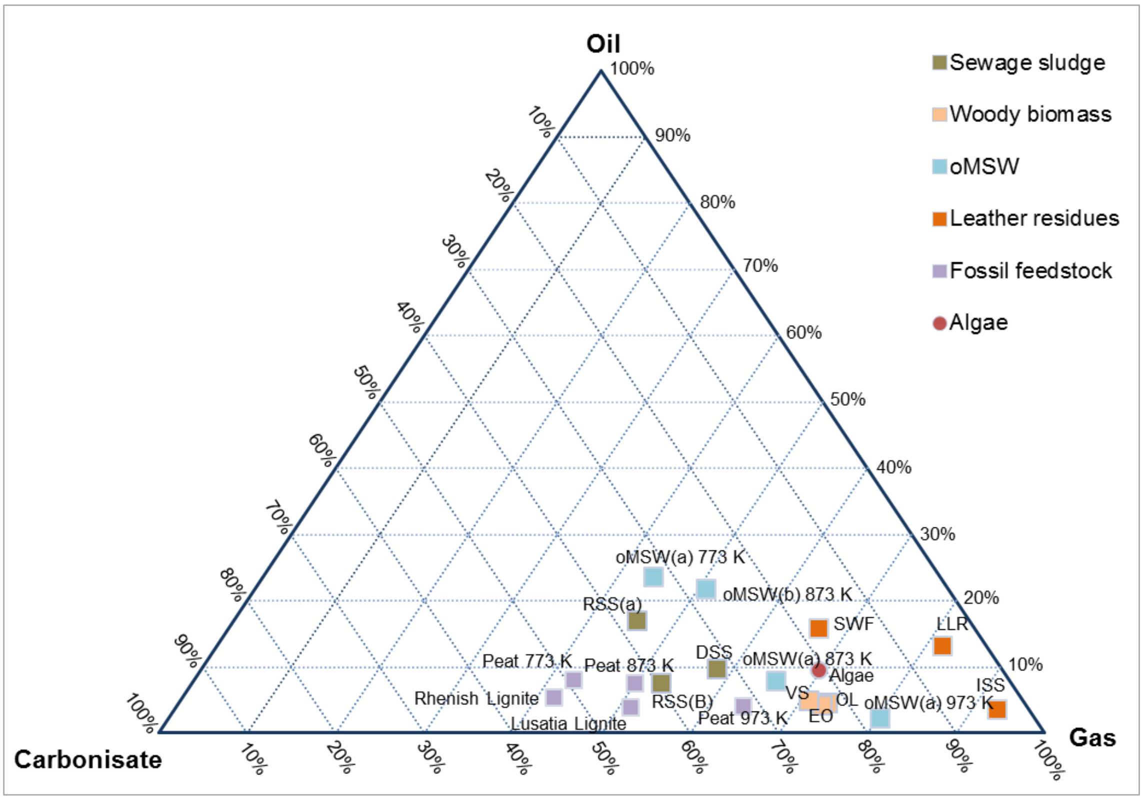

Figure 35: Product mass distribution of the TCR-2 trials with the feedstocks sewage sludge, woody biomass, oMSW, leather residues, fossil feedstocks, and algae presented in a ternary plot [257] on an ash-free basis

The three poles represent the products oil, gas, and carbonisate. The focus on the raw products without consideration of the ash and water content enabled a more transparent comparison. The distortion of the results by including the inert materials and the moisture of the feedstock to the solid pyrolysis and liquid products was thus avoided.

Figure 35 clearly shows that the main share of product for the tested feedstocks at high reforming temperatures is the gaseous phase. Furthermore, a correlation between the different feedstocks and the product yields can be observed. The product distribution of woody biomass was only minor variating. Fossil feedstocks varied regarding carbonisate and gas yields. The sewage sludge samples also had a tight tolerance in terms of the product distributions. The figure also illustrates that the two different feedstock samples, oMSW(a) and oMSW(b), were considerably different. For the vertical reactor temperature of 873 K, the oil and gas yields were varying broadly. Interestingly, the carbonisate yields were comparable. The figure also visualized the differences in the yields of leather residues. This is in line with the investigated significant differences of the feedstock compositions and the related conversion. Additionally, Figure 35 displays the correlation between vertical reactor temperature and product distributions. As described earlier, increasing temperature in the reactor results in a decreasing oil and carbonisate yield. As a result, the points in the diagram move towards the gas pole.

The energy balances of the trials described in previous sections (7.1.1, 7.1.2) were also pictured with a ternary plot. The results depictured in Figure 36 visualize the results of the evaluation of the product distribution.

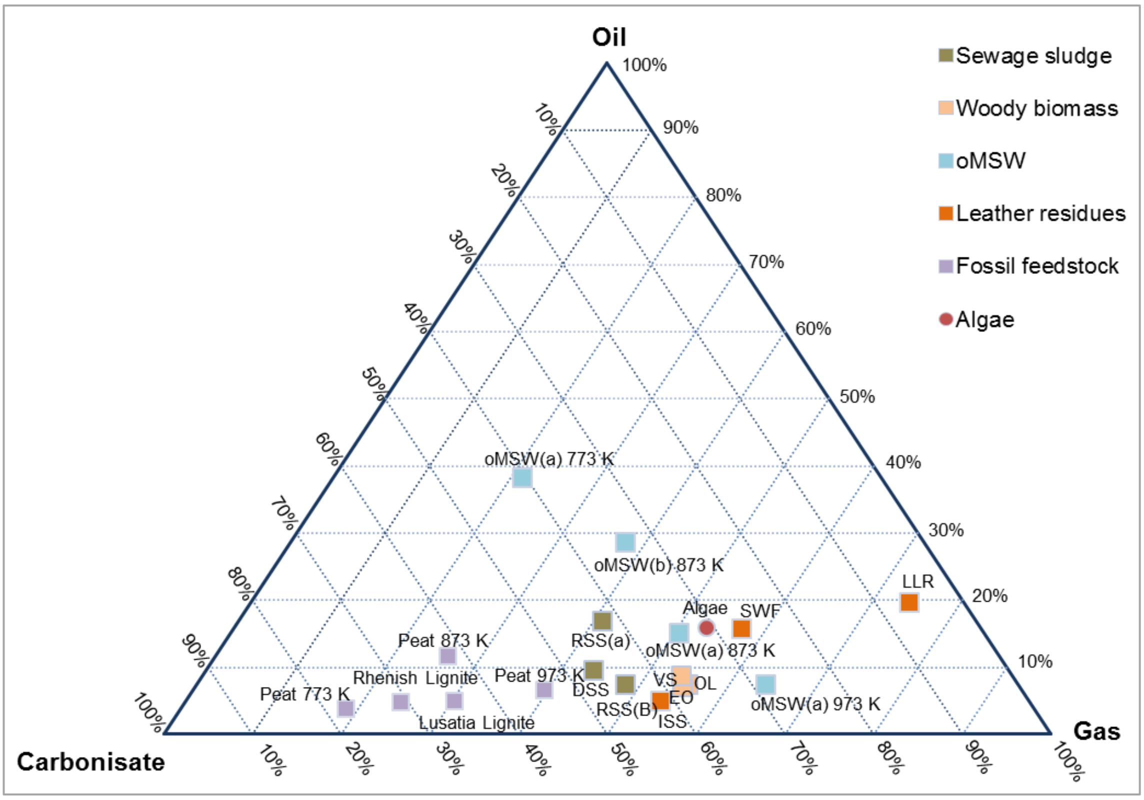

Figure 36: Energy balance of the TCR-2 trials with the feedstocks sewage sludge, woody biomass, oMSW, leather residues, fossil feedstocks, and algae presented in a ternary plot [257]

The sets of data from the samples of oMSW, sewage sludge, fossil feedstocks, and woody biomass can be grouped to their classified feedstocks. As already indicated, the leather industry samples differ widely in the composition, and therefore the product distribution and energy balance were different.

Interestingly, the data points for the energy balance were distributed between the carbonisate and gas pole. This means that, despite the feedstock oMSW, oil plays only a minor role with respect to energy distribution.

The data points of the product mass distribution plot (Figure 35) were more concentrated in the gas pole region. The difference can be attributed to the variation of the HHV of the carbonisates due to the different ash contents. It is worth to highlight that the energy of the fossil fuels is focused on the carbonisates while biogenic feedstocks are concentrated in between the carbonisate and gas pole with a tendency to the gaseous fraction.

To consolidate the results for each feedstock classification illustrated in Figure 36, it can be derived that the energy transfer from the feedstock to the product is related to the composition. Sewage sludge samples had an evenly distributed energy shift from the feedstock to all three products. The tested woody biomass samples show small deviations with the specification to the gas phase. Algae showed similar characteristics with slightly lower energy content in the carbonisate. The feedstock oMSW showed a more significant variation. The energy content in the carbonisate was observed to be only slightly variating; even for the temperature variation trials in the vertical reactor. However, the energy content in the gas and oil yield was variating significantly. From energy to product perspective, oMSW offers a broad range of possible configurations.

The leather residues feedstock samples offered the broadest range of energy distributions due to the variation of the compositions of the evaluated samples. The feedstock LLR had for all tested samples, in relation to energy of the feedstock, the most substantial yield of energy in the gaseous products. Fossil samples had the highest energy shift from the feedstock to the solid TCR product. Because of the low energy transfer rate to the liquid products, the effect of the reforming temperature on the shift in energy yields from carbonisate to gas was more pronounced.

TCR Carbonisate

The possible applications for the TCR carbonisates are diverse. As described in section 2.2.1, the carbonisates can be utilized for energy as well as for material purposes. However, the requirements towards the properties of the carbonisates are, for most applications, strict.

It is the objective to integrate the TCR carbonisates in material utilization pathways. This is in line with the premise to maximize sustainable recycling of biogenic residues and increase the vertical integration of the feedstock. Ultimately, these products have a higher value and therefore are also economically favorable. It is of interest to find correlations between the composition of the feedstocks and the related TCR products, especially the properties of the carbonisates.

The characterization of the carbonisates produced in the reference trials and already described in section 7.1.1 and 7.1.2 are compiled in one table (Table 46).

Table 46: TCR-2 carbonisates characterization (*: calculated by difference; **: 873 K reforming temperature)

		Woody biomass [48]			**Algae**	**Sewage sludge**			**oMSW****		**Leather residues**			**Fossil**		
															Lignite	
		OL	**EO**	**VS**	**Sea-weed**	**RSS (a)**	**RSS (b)**	**DSS**	**oMSW (a)**	**oMSW (b)**	**SWF**	**LLR**	**ISS**	**Peat**	**Rhenish lignite**	**Lusatia lignite**
C	[wt%]	84.2	78.1	74.4	28.3	34.4	44.8	28.2	21.2	27.2	56.1	25.8	13.3	78.8	86.8	86.3
H	[wt%]	1.2	1.2	1.0	0.1	0.2	3.0	0.3	0.2	0.5	1.2	0.2	0.2	1.1	2.2	1.1
N	[wt%]	0.8	0.9	0.9	0.9	3.0	6.1	2.1	0.6	0.7	5.9	2.1	0.6	1.4	1.0	0.8
S	[wt%]	0.1	0.1	0.1	2.5	0.7	0.4	1.1	0.3	0.7	3.1	3.7	5.0	0.34	0.36	0.79
H:C		0.17	0.18	0.16	0.04	0.07	0.8	0.13	0.11	0.22	0.25	0.05	0.18	0.17	0.3	0.15
O:C		0.01	0.02	0.01	<0.05	<0.05	<0.03	<0.05	<0.07	0.08	<0.03	0.11	0.11	<0.01	0.02	<0.01
Ash	[wt%]	12.2	18.1	23.1	71.3	59.7	52.4	71.7	81.9	67.9	31.8	68.5	94.6	18.3	7.4	11.5
O*	[wt%]	1.5	1.6	0.7	<2	<2	<2	<2	<2	2.9	<2	<4	<2	0.1	2.4	0.2
HHV	[MJ/kg]	30.3	27.3	25.5	9.7	13.0	16.5	10.2	6.8	12.5	21.1	8.2	6.9	30.7	30.8	31.1

A direct comparison of the characterizations of the feedstocks (Table 4) and the related carbonisates revealed two correlations.

- The ash content of the feedstock had a substantial impact on the composition and properties of the carbonistates. High ash content resulted in a low carbon content and therefore low HHV. This is not only relevant for the energetic utilization of the carbonisate; it also has an impact on the material utilization. Beyond the regulations regarding maximum wt% of ash for several applications (section 2.2.1.2), inorganic compounds are agglomerated in the carbonisate. The allocation of the inert materials from the feedstock to the products was investigated by EDXRF (section 5.1.3) for algae and leather residue ISS (appendix Table 50, Table 51). The focus for ISS was to trace chromium. Taking account the measurement accuracy, the inert components were transferred from the feedstock into the carbonisate. To verify these results, the allocation of metals was also investigated for the feedstock seaweed and the related TCR products. Based on the results of ISS, only the feedstock and the carbonisate were analyzed. The results confirmed the findings of the ISS investigation. A full list of allocations of detected compounds for ISS and algae are shown in Table 50 and Table 51 in the appendix.

  These results lead to the conclusion that feedstocks with high ash content do not meet the minimum standards for several material applications. Therefore, by today's standards, these utilization pathways are not an option. However, this also means that metals or nonmetals are agglomerated in the carbonisates. For example, the chromium-enriched carbonisates from the leather processing industry could be used in blast furnaces and the chromium would therefore be recycled. Besides the metal content, the carbon content of the carbonisate acts as a fuel and reduction agent. However, the quality of the steel is negatively affected by the nonmetal compounds. Especially sulfur has also a negatively impact on emissions of the process. [258] For that reason, the utilization of TCR carbonisates as fuel for blast furnaces must be further investigated.

- Hydrogen and nitrogen transfer rate from the feedstock to the carbonisates decreased with an increase of temperature in the vertical reactor. The variation of the reforming temperature for peat trials revealed this trend and was supported by the investigations of bagasse and digestate [24,26]. Interestingly, for the feedstock oMSW(a) this trend was not observed. At low reforming temperatures, the hydrogen and nitrogen content in the carbonisates were in the same range as for other feedstocks at significantly higher temperatures. Therefore, it is reasonable to assume that the dehydrogenation and denitrification of the carbonisates of oMSW(a) were apparent at temperatures below 773 K. In contrast, the analysis of the carbonisates of RSS(b) led to a different conclusion. The content of hydrogen and nitrogen in the carbonisates were in comparison to the contents of the feedstock not significantly reduced. The dehydrogenation and denitrification of the carbonisate were not apparent at a lower reforming temperature. It can be assumed that higher temperatures in the reactor are needed.

  For sulfur, this trend was not stringent. For the feedstock algae, oMSW(b) and ISS the sulfur content was transferred over 80 wt% from the feedstock to the carbonisate. In contrast, for the feedstocks RSS, oMSW(a) and SWF the transfer rate was below 30 wt%. Therefore, there is a significant difference in the sulfur to carbonisate transfer rate depending on the feedstock characteristics. Interestingly, there is no correlation between the classification of the feedstock and the distribution of the sulfur.

It can be concluded that feedstocks with low ash content like woody biomass have a wider field of possible applications beyond the energetic utilization. However, it is also possible to reduce the ash content in the carbonisates with physical, chemical or combined processes. This has been applied successfully in industrial scale. However, the limitations of the beneficiation technologies have to be considered. [259]

Within this work, demineralization of carbonisates with high ash contents was excluded in the considerations due to missing economic perspective. The upgrading of the carbonisates is thus limited to activation of the carbonisates to achieve active carbon or post-processing such as compacting and packaging to sell the product, for example, for large-scale garden applications.

TCR Oil

Possible utilization chains of TCR oil are linked with the fossil raw material crude oil. As reported earlier in section 2.2.2, the crude oil is a complex mixture of more than 11,000 compounds and has, therefore, a wide range of properties [105]. Diverse industries rely on crude oil and the products thereof.

The TCR oils described in the previous sections 7.1.1 and 7.1.2 had all similar characteristics in terms of carbon content, heating value, and TAN as well as moisture content (Table 47).

Table 47: TCR-2 oil characterization and comparison with fossil crude oil (*: calculated by difference; **: 873 K reforming temperature, °°: crude oils are desalted in the refinery by adding additional wash water (3–10 wt%) that is separated in a downstream process [12])

		Woody biomass [48]			Algae	Sewage sludge			oMSW**		Leather residues			Fossil			Crude fossil oil
		OL	EO	VS	Sea-weed	RSS (a)	RSS (b)	DSS	oMSW (a)	oMSW (b)	SWF	LLR	ISS	Peat	Lignite		[12,13, 260]
															Rhenish lignite	Lusatia lignite	
C	[wt%]	75.2	72.2	78.6	78.2	70.7	72.0	74.6	82.0	88.4	73.3	82.4	83.2	69.4	59.3	78.7	82–90
H	[wt%]	7.4	7.0	7.2	8.0	8.5	7.3	8.8	9.0	9.7	6.7	7.1	7.6	8.4	10.2	8.5	10–17.6
N	[wt%]	2.2	2.6	2.5	5.0	9.3	7.6	7.2	5.0	2.0	10.7	8.4	4.3	2.7	1.0	1.5	0–2.0
S	[wt%]	0.3	0.3	0.3	1.0	1.3	0.7	0.9	0.8	0.3	1.3	1.3	1.0	0.65	0.16	0.62	0.05–7.0
H:C		1.17	1.15	1.09	1.22	1.43	1.21	1.4	1.31	0.03	1.09	1.02	1.09	1.44	2.05	1.28	1.32–2.55
O:C		0.15	0.19	0.11	0.08	0.11	0.13	0.09	1.30	0.02	0.08	0.01	0.03	0.20	0.37	0.1	0.00–0.01
O*	[wt%]	14.9	17.9	11.4	<8	10.1	12.3	8.5	3.1	<2	8.0	0.8	3.8	18.9	29.3	10.7	0–1.5
HHV	[MJ/kg]	33.6	32.8	35.5	36.2	34.3	31.4	32.1	39.0	40.2	33.5	37.3	38.4	35.3	24.6	33.3	≈45.5 [261]
$H_2$0	[wt%]	8.2	6.0	8.4	1.8	5.1	4.2	3.6	0.9	0.6	2.6	1.4	0.1	3.4	30.0	14.7	°°
TAN	[mg KOH/g]	9.3	14.6	30.1	7.5	20.7	32.5	7.3	4.8	2.8	12.3	12.5	12.5	13.9	14.8	12.5	<0.6 [12]

In comparison to fossil crudes, TCR oils had a slightly lower carbon and hydrogen content, but a noticeable higher nitrogen and oxygen content. In addition, the HHVs were lower and moisture content higher. Attempts to separate the aqueous phase from the oil more efficiently were described earlier (section 7.1.2.2). Centrifugation and distillation were promising processes to decrease the water content to the fossil crude oil standards. This also had a positive impact on the carbon and oxygen content as well as for the HHV and TAN.

The utilization of TCR oils has been proven for energetic and material usage [148–150]. The TCR oils can be blended with fossil and biogenic fuels like diesel or biodiesel. These blends were processed in a CHP engine. The oils were distilled into different fractions (Table 20, Table 42) and therefore proved to be thermally stable. The oils had significantly lower water and oxygen content, and reduced activity in comparison to other pyrolysis oils. [12] The upgrading of the TCR oils had been successfully proven by hydrotreatment in previous work. It was possible to meet the standards EN228 and EN590 [150,262].

Consequently, all of these properties lead to the assumption that TCR oils meet the requirements identified by Talmadge et al., and can be integrated into a standard industrial crude oil refinery process [12]. As mentioned earlier in section 2.2.2, the goal is to blend fossil crude oil with TCR oil. Thus, the benchmark is not fossil crude oil but rather to achieve the minimum standards of such a blended mixture.

Talmadge and coworkers recommended a targeting blending ratio of 1:8 (bio-oil:crude oil). Considering the crude oil consumption of modern refineries of 32 million liters per day, this is a very conservative approach. [12]

A seemingly frequent problem in oils derived from higher nitrogen fuels, such as residues, is a high percentage of nitrogen when compared to crude petroleum. While the majority of crude oils contains less than 0.27 wt% nitrogen, TCR oils have levels over 2 wt% (Table 47) [12,263]. The connection between nitrogen content of the feedstock and the final nitrogen content in the TCR oil can be derived from the trials. The transformation of the nitrogen compounds of the feedstock to the oil was in a range of 3–23%. The transformation rate of woody biomass was on the high site with 18–23%. In contrast, only 7–8% of the nitrogen of the feedstock was transferred to the oil from fossil fuels. The evaluation of the trials with different reforming temperatures revealed a correlation between reforming temperature and nitrogen transfer rate. For the feedstock oMSW(a) a high reforming temperature resulted in a lower nitrogen transfer rate in the oil. The yield of oil is decreasing with an increase of reforming temperature. Therefore, nitrogen is transferred into the gas phase. This is in line with the results of the carbonisates reported earlier. In contrast, for the feedstocks peat, digestate, and bagasse the nitrogen transfer rate correlates with the increase in temperature, within the investigated temperature range [24,26].

Nitrogen components are known to cause several problems during refining of crude oil, including catalyst deactivation, gum formation, fouling, coking and prevention of further refining [260,264,265]. In addition, while nitrogen may not be specifically regulated its removal is nevertheless necessary to aid in the hydrodesulfurization reaction as well as meeting other fuel standards. Furthermore, pretreatment of the crude oil to remove nitrogen before the hydrotreating process resulted in a complete desulfurization. [263] Nitrogen-containing compounds have also been shown to affect the stability of the fuel in storage [266].

Several methods can be employed to reduce the nitrogen level in fuel, and while hydrotreating may be the most common, it may not be the most efficient when aiming for a sole hydrodenitrogenation (HDN) process. This is because the process is not selective and HDN has the greatest hydrogen demand of the hydrotreating reactions making it most difficult. [263] Over time, many correlations have been proposed for determining the hydrogen demand in hydrotreating. Experiments undertaken by Castañeda et al. proposed that different correlations are needed for the heavy gas oil or higher nitrogen fuels such as residues [267]. While these may not all be valid for the high levels of nitrogen in the TCR oil, with adaptions, it should give a reasonable estimation of the necessary hydrogen demand based on known feed properties. This could be assessed in future investigations.

Other methods include liquid-liquid extraction and adsorption. Liquid-liquid extraction with ionic liquids has been shown to be much more selective towards nitrogen-containing aromatics than those with sulfur, although overall it seems less efficient than other methods. Silica gel and activated carbon have shown to be capable absorbents for nitrogen compounds of fossil crude oils. [268]

The results of activated carbon are especially interesting for additional TCR carbonisate applications. Sano et al. investigated that the surface area and the oxygen content of the activated carbon are relevant parameters for denitrogenation [269]. Due to the low oxygen content of the TCR carbonisates, activation would be needed to increase the surface area and the amount of oxygenated compounds. The utilization of TCR carbonisates for this application could be investigated in future work. However, feeds tested usually have a nitrogen content of less than 0.05% [263]. It is also important to note that different nitrogen compounds present different complexity in their removal with any denitrogenation method. A reference that nitrogen components of fossil crude and TCR oil might be different can be derived from the distillation trials. No agglomeration of nitrogen compounds within the distillation residue of TCR oil was observed (Table 20). This contrasts with fossil crude oil. Furthermore, a correlation between a high nitrogen content of the oils and a high amount of distillation residue was also not detected [267,270].

Overall, it appears that the removal of nitrogen is, in fact, one of the more difficult parts of refining. Thus, a lower nitrogen feed provides many benefits downstream in addition to greener burning fuels. Therefore, it is necessary to decrease the amount of nitrogen within the TCR fuels from residue biomass to meet the standards for fossil fuels. Otherwise, the disadvantages of high nitrogen oils could outweigh the economic benefits of a CO_2 neutral fuel. While hydrotreating seems to be the predominant way in which nitrogen is currently removed, a more nitrogen selective process may be required for more nitrogen compound rich fuels, such as those derived from sewage sludge. Hydrotreating is a high temperature and high-pressure process with consumables of catalyst and hydrogen. Consequently, it could be economically more efficient to separate the nitrogen from the TCR crude oil with less sophisticated approaches. The target is to reduce only the nitrogen content to the minimum required amount for processing the TCR oil with fossil crude oil in a standard refinery.

Processes such as absorption and liquid-liquid extraction show some potential in this area. However, the separation of nitrogen compounds from the crude oil is accompanied by a loss of crude oil. Even for selective nitrogen processes, Prado and his co-workers calculated with a mass loss of 10–20 wt% to remove 1 wt% of nitrogen from the crude. [263]

In addition to the components mentioned above which have an impact on the quality of the oil in terms of processability in a standard refinery process, metal components like nickel, vanadium or iron are known as catalyst poisons. Oils with a high content of these metals tend to coke faster and therefore deactivate the catalyst. Burning the coke off the catalyst is only partially successful because the components stick to the catalyst and deactivate the active surface area. [260,264]

Therefore, the amount of metals, like vanadium, is an essential parameter for crude oils to estimate the suitability for refinery processes. EDXRF analysis led to the conclusion that the vanadium was primarily in the solid pyrolysis residue and only a minor part in the oils (appendix Table 51). This is in line with the results reported earlier in section 7.1.4. The quantified amount was in the lower range as for fossil crude oils (3–4 ppm in comparison to 0.5–170 ppm) [13].

GC-MS analysis of the TCR oils revealed that the composition of the oils is promising for fractionating and extraction of specific basic chemicals [26,72,138]. These chemicals would increase the added value significantly. It must be considered that the extraction of these components is costly, and the market demand is limited for most of the high-value products. Nevertheless, this is a promising link for further investigations and a promising opportunity to deepen the value creation chain of the TCR.

TCR Gas

TCR gas can be utilized for several applications. Due to the HHV of not less than 15.5 MJ/m , it can be used for energetic utilization. As described earlier in section 3.2, a combustion chamber with a maximum capacity of 150 kW_{th} and a CHP with a dual fuel engine with a capacity of 40 kW_{th} and 20 kW_{el} were successfully operating in long duration trials with TCR gas. Therefore, TCR gas could substitute natural gas. However, the composition of the gases would also be promising for material utilization. One approach could be the separation of specific gases by a PSA. Hydrogen, carbon monoxide or carbon dioxide could be used separately. The off-gases could still be used for energetic applications. The separated gases could be used for synthesis reactions like Fischer-Tropsch or synthesis of DME or urea. These material utilization pathways of the TCR gas are investigated in the EU project “To-Syn-fuel” [144].

For these applications, TCR gas is competing with natural gas and gasified coal. The majority of the worldwide syngas production is based on natural gas and coal [110,111].

It is important to note that even if TCR gas is substituting natural gas, the composition is different. For natural gas that is processed in the gas grid, requirements about the composition and tolerances of impurities are specified. For the German market, these specifications are bundled in the DVGW codes of practice G 260. [108] Gases from renewable sources follow the technical rule G 262 with slightly different standards [109]. These specifications are specific for every grid [271]. Therefore, natural gas from the Netherlands follows different specifications than natural gas within the German grid. A comparison of renewables and natural gas with TCR gases are depictured in Figure 37.

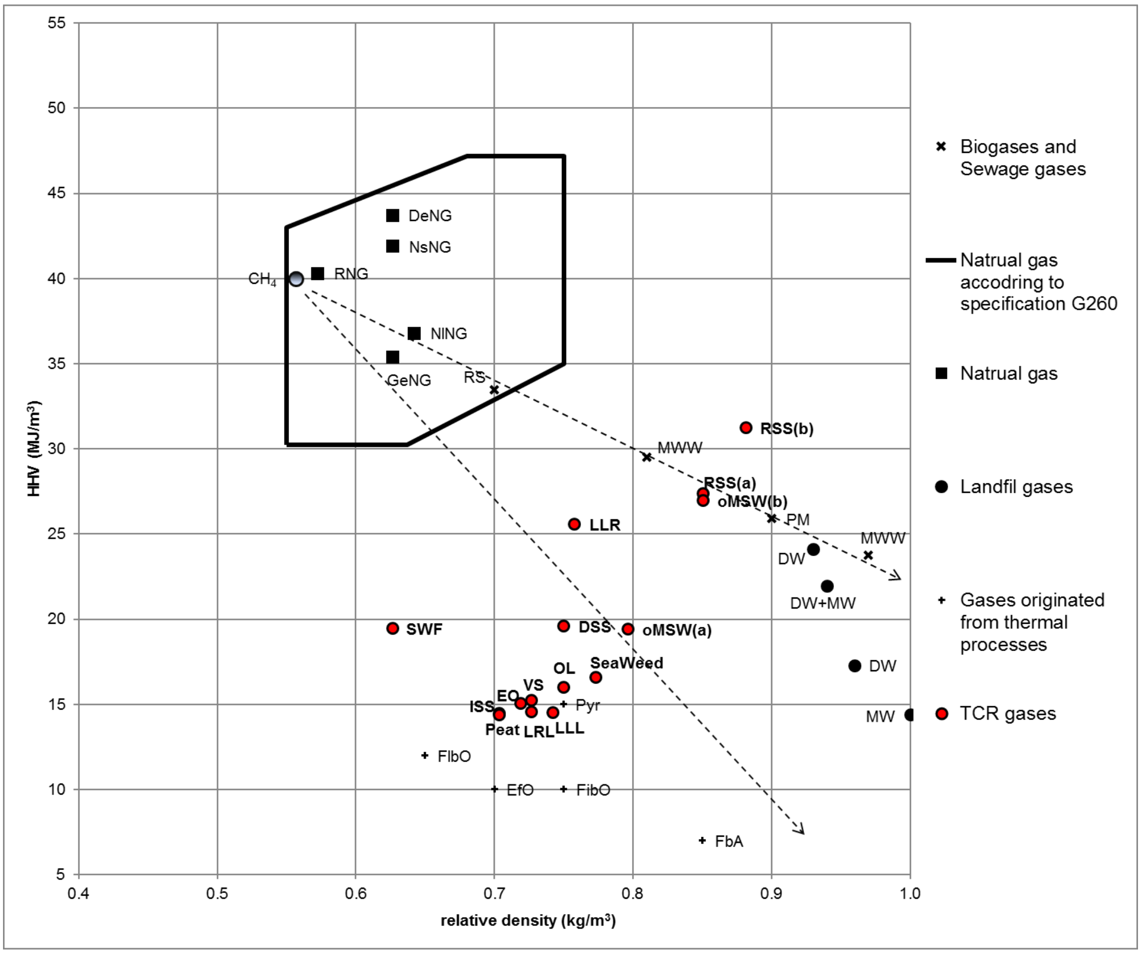

Figure 37: Comparison of renewable gases to natural gas and TCR-2 gases in terms of HHV and density (own diagram based on [109]): DW = domestic waste; MW = municipal waste; RS = rendering service; MWW = municipal waste water; PM = pig manure; FibO = fixed bed, oxygen; FbA = fixed bed, air; FlbO = fluidized bed, oxygen; EfO = entrained-flow, oxygen; Pyr = pyrolysis gas; RNG = Russian natural gas; NsNG = North Sea natural gas; DeNG = Denmark natural gas; NlNG = Netherland natural gas; GeNG = German natural gas

The primary component of natural gas is methane with over 83 vol%. Therefore, the properties regarding Wobbe s index and density are very different to TCR gas (Table 48). For energy applications, the value of the TCR syngas must be evaluated by the HHV in comparison to the values of natural gas. It is important to highlight that for material utilization of the gases this could be an advantage. The refining step that is needed for natural gas to achieve the optimum syngas parameters could be not entirely necessary. However, it is also important to mention that also the requirements of gas accompanying compounds like sulfur or ammonia are strictly regimented in natural gas.

The comparison of the different TCR gas compositions and properties with the requirements of natural gas is depictured in Table 48.

Table 48: Quality of TCR-2 gas and natural gas (*: two different gas classifications that are, beyond other things, classified by their HHV: L = lower HHV, H = higher HHV; X: no regimentation in the G 260 in terms of hydrogen content, only the specifications of Wobbe s index, density and HHV have to be fulfilled; G 262 states the gas limits of gas turbines and gas storage tanks as regimentation; **: 873 K reforming temperature)

		Woody biomass [48]			Algae	Sewage sludge			oMSW**		Leather residues			Fossil			Natural gas [108,109]
															Lignite		G 260
		OL	EO	VS	Sea-weed	RSS (a)	RSS (b)	DSS	(a)	(b)	SWF	LLR	ISS	Peat	Rhe-nish	Lu-satia	L & H*
H_2	[vol%]	33	36	36	33	26	17	36	38	29	37	33	48	39	46	41	<1–2^X
CO	[vol%]	16	17	16	19	20	23	12	6	8	31	13	12	15	8	10	×
CO_2	[vol%]	27	27	27	29	31	7	27	32	25	5	11	30	27	31	28	0.2–2.1
CH_4	[vol%]	11	12	11	4	-	-	6	-	-	11	-	2	8	3	7	83.6–97.0
C_xH_y	[vol%]	1	1	1	3	>5	>5	4	4	>5	2	>5	2	1	1	1	1.2–9.1
H_2:CO		2.1	2.1	2.3	1.7	1.3	0.7	3.0	6.3	3.6	1.2	2.5	4.0	2.6	5.8	4.1	×
Den-sity	[kg/m³]	0.97	0.93	0.94	1.0	1.10	1.14	0.97	1.03	1.1	0.81	0.98	0.91	0.91	0.94	0.96	0.74–0.83
Wobbes	[MJ/m³]	18.5	17.8	17.7	18.7	28.3	32.8	22.5	21.8	29.3	24.2	28.7	16.8	17.2	16.6	17.1	44.6 +2.2 -5.0 54.0 +2.5 -5.0
HHV	[MJ/kg]	16.5	16.2	16.2	16.6	24.9	27.4	20.2	18.85	24.5	24.0	26.1	15.9	15.8	15.5	15.1	43.7–54.5

As for the products carbonisate and oil, it was possible to classify the gas samples to the six different feedstock classifications. The samples from woody biomass and fossil fuels showed, within each classification, tight tolerances in relation of composition and properties. The feedstock inhomogeneity of the sludge samples, oMSW, and leather residues had a noticeable higher impact on the quality of the gases then on the oil phase. The overall volumetric hydrogen content of the gases varied between 17–48 vol%. However, it should be considered that the low hydrogen content was measured from the feedstock oMSW(b). As reported in section 7.1.1.4, the gas measurement was affected by the high content of higher hydrocarbons (>5 vol%) in the gas stream. It can be assumed that the real volumetric hydrogen content was higher. The carbon monoxide contents of the gas samples were in the range of 6–31 vol%. The molar ratio between hydrogen and carbon monoxide was therefore also strongly varying. The minimum ratio of 0.7 was related to RSS(b). Again, the measurement of the gas composition of this sample had to be further investigated. The highest ratio of 6.3 was measured for the feedstock oMSW(a).

The density of the gas strongly correlated with the hydrogen and higher hydrocarbon content and therefore variated between 0.94–1.14 kg/m . The Wobbe s index of the gases was in the range of 16.6 for lignite and 32.8 MJ/m for digested sludge.

TCR aqueous phase

The aqueous phase is a byproduct of the TCR process. The elemental analysis of the aqueous phase revealed that the fluid comprises of water with carbon and nitrogen compounds (Table 49).

Table 49: CHNS-O composition of the aqueous phase (*: calculated by difference; **: 873 K reforming temperature)

		Woody biomass [48]			Algae	Sewage sludge			oMSW**		Leather residues			Fossil		
															Lignite	
		OL	EO	VS	Sea-weed	RSS (a)	RSS (b)	DSS	oMSW (a)	oMSW (b)	SWF	LLR	ISS	Peat	Rhenish lignite	Lusatia lignite
C	[wt%]	2.2	3.1	2.6	3.7	8.4	5.5	7.6	1.9	3.5	6.9	5.8	2.1	3.2	1.5	2.9
H	[wt%]	11.7	13.8	11.3	11.7	11.7	10.8	10.9	9.8	11.5	11.1	11.0	11.8	11.9	11.4	12.1
N	[wt%]	1.2	2.1	2.4	3.2	10.0	4.5	6.5	2.4	4.5	11.7	9.7	2.9	1.7	1.3	3.0
S	[wt%]	0.03	0.03	0.06	0.2	0.6	0.1	0.2	0.1	0.1	0.6	0.6	0.3	0.2	0.1	0.1
O*	[wt%]	85.4	81.0	83.6	81.3	70.0	79.1	74.7	85.9	83.2	68.9	73.0	83.0	82.9	85.8	81.9

These analyses confirmed the sensory impression. The fluids had a yellowish-white to dark brown color with a pungent ammonia odor.

The comparison of the elemental composition of the samples from the six different feedstock classifications revealed specific trends for the different classifications. Sewage sludge tended to have higher carbon content in the aqueous phase of 5–8.5 wt%. Interestingly, no correlation between the pretreatment of the sewage sludge and the elemental composition of the aqueous phase was observed. The aqueous phase of SWF and LLR had a carbon content in a similar range (6.9 and 5.8 wt%). It is worth highlighting that the aqueous phase of ISS, the sewage sludge from the wastewater treatment of leather residues, was not comparable with the results from the municipal wastewater sludge. The significant lower carbon content in the aqueous phase was an additional indicator of the differences in the feedstocks and the thermochemical conversion thereof.

The hydrogen content varied between 9.8–13.8 wt% and no trend was observed for the feedstock classifications. This is not surprising, as the majority of the hydrogen correlates with the water content of the aqueous phase. The nitrogen content was in the range of 1.2–11.7 wt% of the samples investigated. Therefore, a broad variation was observed. A correlation of the nitrogen content of the feedstock and the content within the aqueous phase was only partly confirmed. In contrast to the nitrogen transfer rate to the oil, for the aqueous phase, a broad transfer range from the feedstock to the product was observed.

The sulfur content in the aqueous phase varied between 0.03–0.6 wt%. The sulfur content within the different feedstock classifications varied only slightly and was in line with the sulfur content of the feedstocks.

The initial approach was to utilize the aqueous phase within the digestion plant [272]. Therefore, a part of the aqueous phase would be fed back into the digester to improve the methane production [273]. This pathway was based on the initial development of the TCR for the utilization of digestate and implementation of a TCR plant at a site of a modern biogas plant. Therefore, the suitability of TCR aqueous phase in standard digesters was further investigated. The higher temperatures in the vertical reactor favor the correlation of a decreasing chemical oxygen demand (COD) described by Hübner and Mumme. Indeed, the COD of TCR aqueous phase from oMSW(a) were in line with the values reported in literature (45 g/l at 873 K and 22 g/l at 973 K, respectively). Thus, the organic content of the liquid was decreased. Hübner and Mumme have investigated in their work that the COD removal rate decreases with lower COD content in the aqueous phase. [274]

Therefore, the results reported in literature cannot be transferred directly into practice. The TCR aqueous phase with high reforming temperatures must be upgraded for the utilization in a biogas plant. Due to the changed focus of the TCR technology regarding a broader range of feedstocks, the utilization of the aqueous phase as a digestate enhancer was not further pursued. This has led to the situation that the aqueous phase was considered subsequently as a waste stream. The target is to dispose of the aqueous phase as wastewater that can be treated in municipal wastewater treatment plants. This would enable a flexible site selection and economic development. Preliminary results showed that further investigation is needed to meet local requirements. A comparison with maximum discharge values for wastewater revealed demand for optimization [275,276].

However, it must be considered that the aqueous phase was not diluted. An integration of the TCR technology in an industrial surrounding, would make it possible to merge the aqueous phase with additional wastewater streams to meet the minimum standards of wastewater treatment plants. Also, in an industrial application, the condensing unit will be designed to minimize the content of light boiling compounds in the aqueous phase.

Further opportunities could arise by adaption of technologies from the treatment of wastewaters from coking plants. One department of FhG UMSICHT is investigating this matter among other things.

For the utilization of digested sewage sludge at a wastewater treatment plant, the recycling of the aqueous phase in the digester is a promising option and should be further investigated.

Overall, it can be concluded that the composition and properties of the TCR products are predominately dependent on the related feedstocks and determines the potential utilization pathways.

The utilization pathways of the TCR carbonisates are diverse and include among others incineration, gasifying, soil enhancement, substitute for fossil char/coke or active carbon.

Utilization chains of TCR oil are linked with fossil crude oil. TCR oil is distillable and thermally stable and can be burned in heavy-duty motors and CHP engines. Moreover, it is possible to upgrade the oil by hydrotreatment. Therefore, integration in fossil crude oil petrochemical infrastructure and thus to substitute fossil crude oil is possible. The composition of the TCR gas was diverse and strongly dependent on the related feedstock. An energetic, as well as a material utilization of the gas, is possible.

7.1.5 Development and Optimization of the TCR

The operation of the TCR-2 lab scale plant within over 250 trials at various parameters and broad variation of feedstocks created a large dataset.

The gained experience enabled the successful utilization of the feedstocks within the TCR-2 and created valuable information for the design and operation of the TCR technology on an industrial scale.

The developments can be divided into two segments: only related to the lab scale plant or related to lab, pilot, and industrial scale plants.

The differences are mainly related to the purpose of the plants. The lab scale plant is a batch process for feedstock and parameter variations. After every trial, the plant is disassembled, cleaned, maintained, and assembled. Therefore, it is not needed to implement components that would enable a continuous operation from an economic perspective.

One important building block was to implement a routine for the TCR trials including pre- and post-processing, feedstock and product characterization, maintenance and calibration, data collection, and data processing. These routines have been documented in a manual and checklist for each process.

The thermal insulation of the plant is of importance for several reasons. First, the efficiency of the plant is increased and the risk of injuries minimized. Moreover, the insulation of the reactors is essential to avoid condensation on cold spots that are not externally heated. Experience has shown that the transition from the horizontal to the vertical reactor and the bottom of the vertical reactor were vulnerable areas for condensation. It was observed that these areas caused blockages in the reactor resulting in reduced gas and material flow and ultimately increase pressure. At these spots, the thermal insulation was intensified. Based on the results of a hazard analysis, insulation sleeves made from high-temperature suitable glass fiber mats were used. These mats can be easily assembled and disassembled, and the risk of harmful emissions is decreased.

For feedstocks with a low solid softening temperature of the intermediate product, blockages were observed within the transition zone of the horizontal to the vertical reactor. This caused a pressure increase in the system, and additionally, the last screw segment blocked due to the accumulation of solid products within the reactor. This phenomenon was observed for woody biomass and feedstocks with a similar chemical composition like bagasse. The aim was to move the temperature frame where the intermediate solids are softening from the second to the first segment of the discharging zone. Thus, the temperature in the third zone was increased by 100 K. Because of the higher wall temperature, the heat flow is increased, and the adhesive phase is passed faster and earlier before the transition zone. This effect has also been described in literature for rotary kilns [208]. Ultimately these changed parameters enabled reproducible experiments of feedstocks with a low softening point.

As described earlier in section 5.1.1, at the beginning of the trials fine particles of solid pyrolysis products and polymerizations of organic carbon compounds caused blockages in the mesh of the riser pipe. This caused increasing pressure in the plant and ultimately termination of the trial. Practice has proven that the blockages can be efficiently avoided by using TCR carbonisate from previous trials in the vertical reactor. Approximately 300 ml is sufficient to submerge the mesh in the carbonisate. The carbonisate acts as a filter and prevents blockages very efficiently. Thus, the starting phase of the process can be significantly reduced.

Further efforts to improve the TCR-2 lab scale process towards a more efficient gas cleaning were made. In preliminary trials, the concentrations of aerosols and fine particles in the gas stream were identified as a risk for the tubing and gas measurement system. These impurities can accumulate inside the tubes, especially in constricted areas, and must be removed on a regular basis. This causes a reduction of operational time and increases maintenance costs. This is not a critical factor for a lab scale plant, but it would have an impact on the efficiency of an industrial scale plant. The aerosols and fine particles have a great impact on the accuracy of the analyzer and can also damage the measuring cells. In addition, the calorific value of the aerosols falsifies the HHV measurements. From an economic perspective, it is of importance to use a gas treatment system that suits the requirements of a lab scale and industrial plant. TCR-2 tests have demonstrated that two condensing units, an additional washing bottle, and three different fabric filters fulfill the requirements (as described in section 5.1.1).

However, GC-MS analysis of the oil proved impurities caused by biodiesel used as a fluid in the washing bottle. This was caused by possible backflow at the end of the trial.

Cooling down of the hot gases in the cooler caused negative pressure that sucked biodiesel back into the condenser. Therefore, experiments with alternative designs of the plant and fluids were done. The utilization of the aqueous phase was the most promising approach. Consequently, aqueous phase from previous trials was used without any further adaptions of the plant. The deposition rate was not as high as for biodiesel or other solvents, but in combination with the connected fibrous filter elements, loads of aerosols in the gas stream could be reduced to the acquired minimum.

For the industrial application of the TCR technology, fabric filters are not a sufficient solution for separating aerosols and particles from the gas stream. A multi-stage redundant filter line would cause much maintenance and increase possible downtime of the plant. Therefore, industry proven separation technologies were evaluated to separate fine particle and aerosols from the gas stream [122,277]. Two complementary technologies were tested in the demonstration scale of the TCR: a cyclone and an electrostatic precipitator (ESP). The cyclone was installed between the vertical reactor and the condensation unit. The purpose was to separate particles from the gas stream before condensation to avoid agglomeration of solid particles and oil in the condensation unit. This issue was observed in the inlet area of the heat exchanger in the lab scale plant. Due to the non-continuous operation of the plant, this caused no issues. However, for an industrial scale plant, this would cause downtimes on a regular basis.

The operation of the demonstration scale TCR proved the efficiency of the cyclone. External heating of the cyclone and the particle container to keep the temperature level of the gases above 723 K is mandatory to avoid condensation [122].

After the condensing unit, the gases pass a wet ESP to remove remaining particles and aerosol.

By using these two technologies, the operation time of the plant could be significantly increased. The issues with aerosols in downstream processing were solved.

The results of the conversion of fossil feedstocks and mixtures of fossil feedstocks with biomass were so promising that these resulted in filing an international patent application in 2016.

7.2 Economic Evaluation

In the following section, the results of the economic evaluation are highlighted. The goal is to evaluate the economic position of the TCR technology and its products in the market. The concept demonstrates that a long-term orientated investment decision of processes with not only one primary product can be evaluated on the basis of levelized costs (LC) and levelized revenues (LR).

The economic basis, elaborated economic variables, underlying assumptions, and the developed tool for the economic calculation were described in section 6. The specific feedstock related values were presented in section 5.2. The data related to the conversion of the feedstock samples within the TCR technology were presented in the preceding section 7.1.

The large number of possible configurations of feedstocks, products, processes, and scenarios, lead to high complexity of the investigated system. However, as the characteristics of the feedstocks and the products have been classified, the number of possible process chains that need to be considered can be reduced significantly.

Consequently, the quantity of possible data sets is reduced to 3906. Hence, strategic recommendations can be derived regarding optimal process configurations. The breakdown of the specific levelized costs of the products enabled the assessment of the sensitivity of the results. The main results of the economic evaluations of each feedstock group are presented in the following section.

7.2.1 Biomass and biogenic Residues

The results of the economic assessment of the biogenic feedstocks are presented in the following section. The averaged data from the trials presented in section 7.1 were the basis of the calculations.

7.2.1.1 Sewage Sludge

7.2.1.1.1 Raw Sludge

The composition of the products from the averaged processed raw sludge samples within the TCR technology led to 396 different data sets (appendix Table 52). The composition of the solid product enabled two different utilization pathways. The base scenario is the energetic utilization as a substitute for fossil steam coal as described in section 6. Depending on the source of heating, the utilization pathway of CCS is also possible. For the usage of steam coal for heating, CCS was not taken into consideration due to the higher CO_2 emissions of the steam coal in comparison to the potential savings via CCS.

Due to the high ash content of the solid product and the potential metal content, higher material utilization like biochar, BBQ, and active carbon was excluded from further considerations.

Based on the background of the techno-economic evaluation explained in section 6, the conversion of raw sewage sludge within the TCR technology is sustainable and could be competitive from an economic point of view. The evaluation of the results proved that in the majority of the scenarios, the processing of raw sludge is economically feasible (indicated by green cells in appendix Table 53).

To cover the heating demand of the plant, feedstock or carbonisates is preferred. The optimum process configuration is depending on the actual gate fee. The scenario with a high gate fee favored the configuration CHP and PSA, basic scenario, and only CHP in that order. Therefore, a secure demand for hydrogen and heat would have the highest potential. Interestingly, the basic scenario was only negligibly unfavorable. For the low and medium gate fee cases, the basic scenario is dominant. The observed shift from energetic carbonisates utilization to CCS was due to the scenario change of Current policy, New policy, and 450. If no long-term contract for the carbonisate utilization is made, the pathways could be changed easily on demand. The negative LC of the products in the high gate fee case implies that the costs of the operation of the plant are entirely covered by the income of the gate fee. The results of the most promising pathway are pictured in Figure 38.

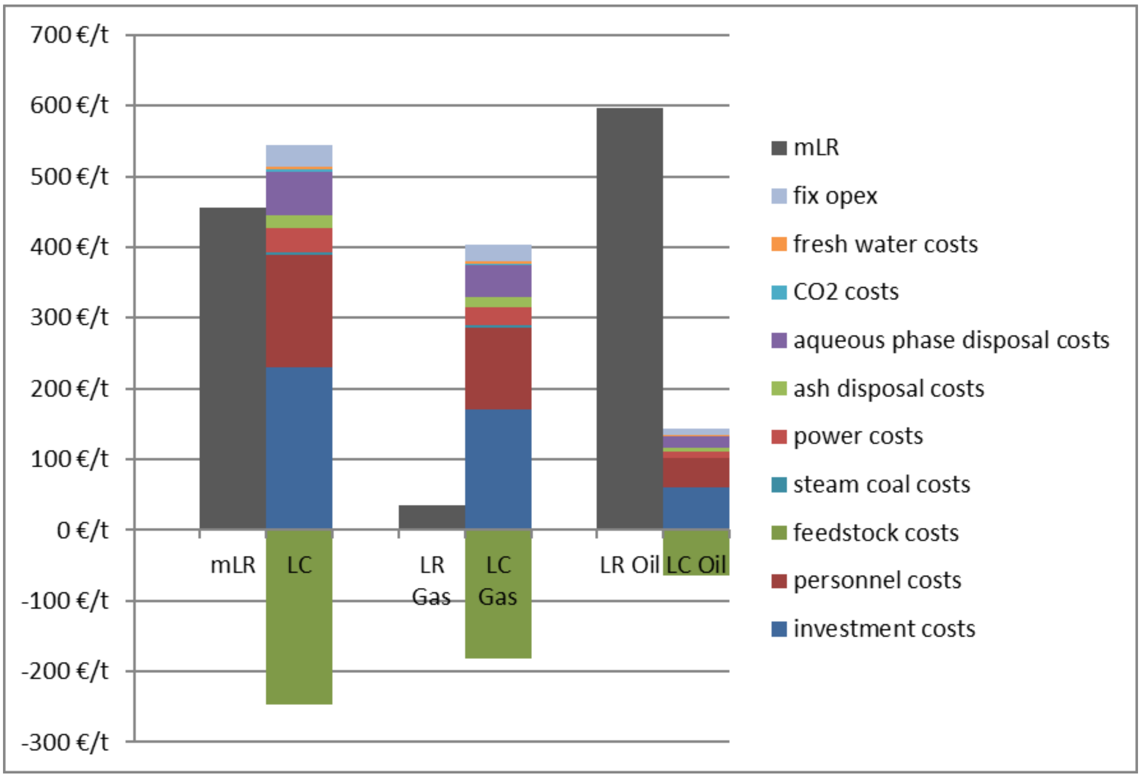

Figure 38: Breakdown of the levelized costs of the products gas and oil and comparison with levelized revenues in €/t for the feedstock RSS (Current Policies scenario, medium gate fee, basic usage of oil and gas, heat demand of the plant covered with carbonisate)

The direct comparison of LC of the TCR products with the mLR illustrates the market competitiveness. The gate fee reduces the costs and leads to a lower LC than the mLR. In the scenario pictured in Figure 38, the plant is heated with the solid product. Due to the fact that the product carbonisates could not meet the entire energy demand, additional steam coal is used. Therefore, carbon dioxide emissions are accounted. The remaining marketable products, gas and oil, are sold as substitutes of natural gas and crude oil based on the underlying assumptions (section 6). Due to the allocation of the LC to each product accorded with their quantities, as described in section 6, the costs of the product oil are significantly lower than the cost of crude oil (adjusted for HHV). In contrast, the LR of the gas is significantly lower than the LC. However, the visualization of the mLR with the overall LC shows that the oil income outweighs the low gas income.

The breakdown of the specific costs reveals that investment and labor costs were the primary cost drivers. It is also important to mention that the gate fee of the raw sludge has an essential contribution to the competitiveness of the utilization pathways.

7.2.1.1.2 Digested Sludge

The composition of the products from the digested sewage sludge within the TCR technology led to 396 different data sets (appendix Table 54). The possible utilization pathways of the carbonisates are the same as described earlier for the raw sewage sludge samples. Depending on the heating system and the related fuel, the carbonisates are utilized as a substitute for steam coal or CCS purposes.

The evaluation of the economic calculations revealed similar results as for the utilization of raw sludge (appendix Table 55). For the low gate fee case, the utilization of digested sludge within the TCR technology was not as competitive as for raw sludge. This is in line with the results of the experimental trials and the differences in the mass balance. Nevertheless, based on the assumptions, the conversion of digested sewage sludge within the TCR technology is sustainable and competitive from an economic point of view in the majority of the medium and high gate fee cases in all WEO scenarios.

Feedstock or carbonisates should meet the heat demand of the plant. The provision of hydrogen by a PSA is advantageous and within a direct comparison of a CHP economically superior. This changes with a shift from the medium to the high gate fee cases. For some scenarios, the CHP configuration is more favorable. As described earlier for raw sludge, negative LC of the products in the high gate fee cases occur when the gate fee completely covers all costs of the operation.

The comparison of the levelized cost with the specific levelized revenues for the most favorable case is shown in Figure 39.

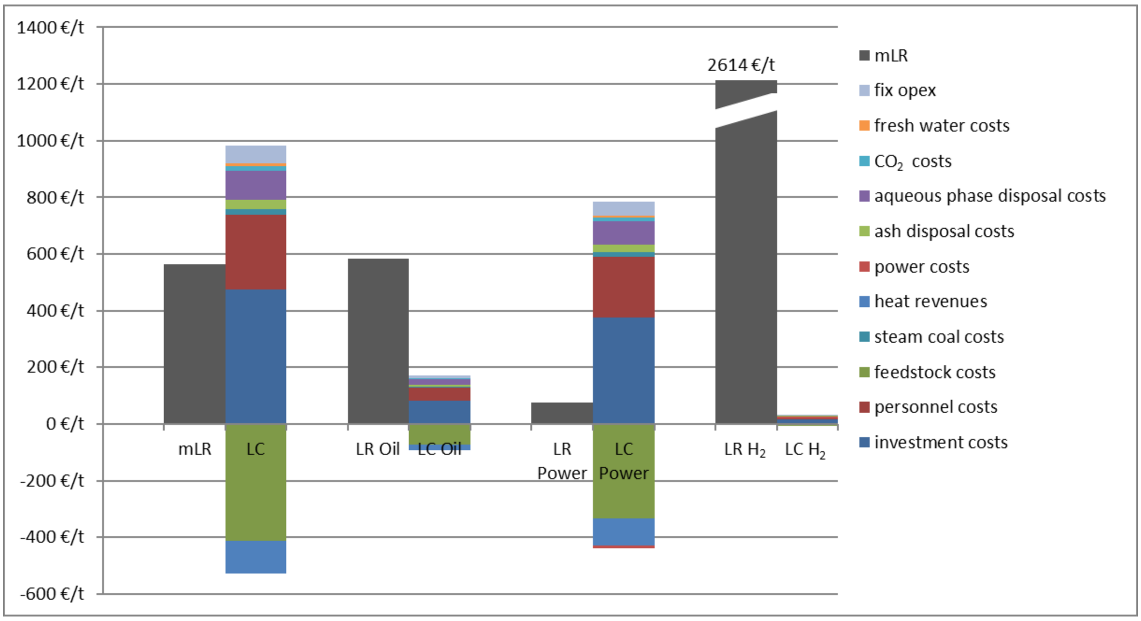

Figure 39: Breakdown of the levelized costs of the products oil, power, and hydrogen and comparison with levelized revenues in €/t for the feedstock DSS (Current Policies scenario, medium gate fee, heat demand of the plant covered with carbonisate, CHP+PSA, heat of CHP sold for 40 €/MWh, oil sold as a crude oil substitute)

By comparing the mLR with the LC of the products from the conversion of digested sludge in the TCR process, it becomes clear that the overall costs of the production of the products are lower than the cumulated costs of the possible substitutes. It is important to highlight that the gate fee of the feedstock and the revenues of the heat from the CHP contribute significantly to the competitiveness of the process. As reported earlier, the assigned costs for the power production are significantly higher than the market price in the Current Policies scenario. However, the product hydrogen and oil subsidize the costs. Therefore, the overall mixture of the products is economically competitive. Investment and personnel costs were the primary cost drivers of the products.

7.2.1.2 Woody Biomass

The characteristics of the woody biomass sample averaged from the three woody biomass OL, EO, and VL led to 486 different data sets (appendix Table 56). The high complexity is caused by the number of possible utilization pathways of the carbonisates. Depending on the heating source of the TCR system, the carbonisates could be utilized for energetic, biochar, BBQ, and CCS applications. If the heating source is not biogenic, like natural gas or steam coal, biochar application is excluded due to EBC classifications. As mentioned in section 2.2.1.2, there is no official biochar standard. Therefore, the utilization of the carbonisates as biochar is not entirely excluded but must be investigated with official regulations. Based on the assumptions made, the conversion of woody biomass within the TCR technology is sustainable from an economic point of view (appendix Table 57). The precondition for this is a high-value application for the product carbonisate. Under the assumption that the carbonisates were capitalized as biochar, all three gate fee cases and WEO scenarios are sustainably profitable. For the heating of the plant, feedstock or gaseous product is the preferred option. The product gas is superior to feedstock if the gas is not utilized in further process chains. The process chain with the highest possible potential includes a PSA and a CHP. In two of the three gate fee cases (medium and low), this is the superior option. This assumes a hydrogen and heat demand at the facility and that the TCR oil can be integrated into a standard refinery.

For the high gate fee case, the basic scenario is predominant.

The comparison of the levelized costs break down to the specific products with the specific levelized revenues is shown in Figure 40. The best case at mid gate fees is depictured.

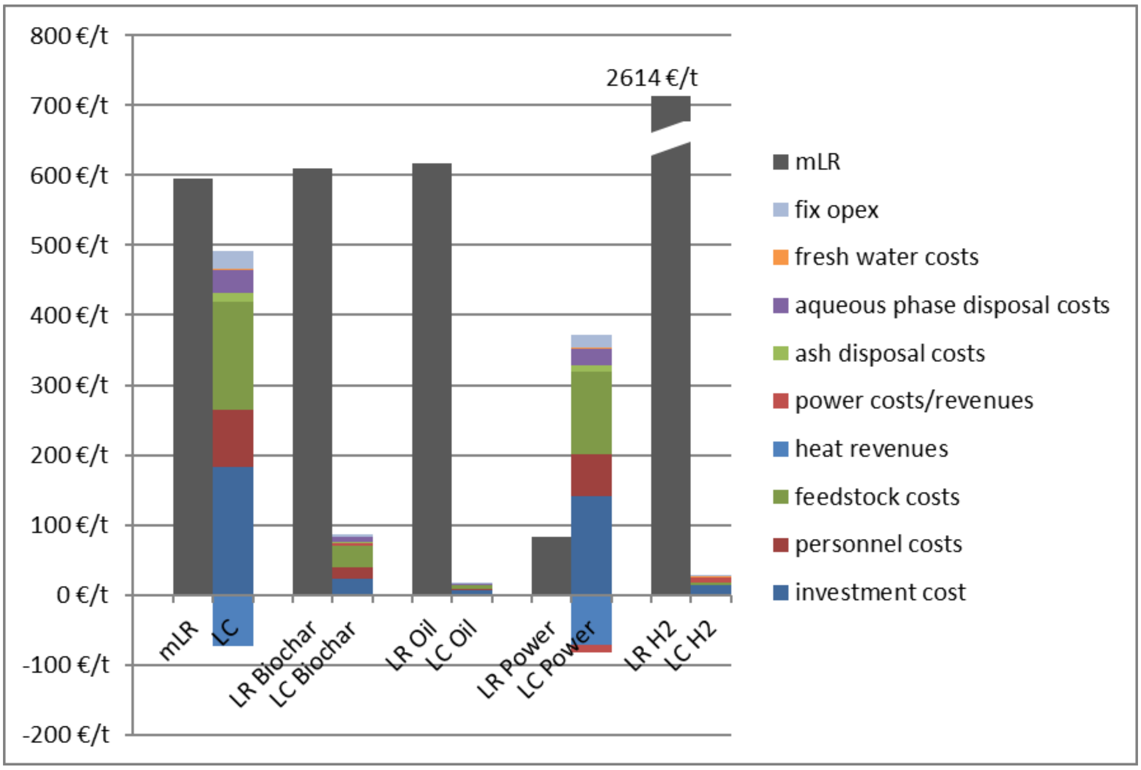

Figure 40: Breakdown of the levelized costs of the products biochar, oil, power, and hydrogen and comparison with levelized revenues in €/t for the feedstock woody biomass (Current Policies scenario, medium gate fee, heat demand of the plant covered with feedstock, CHP+PSA, carbonisates marketable as biochar, heat of CHP sold for 40 €/MWh, oil sold as a crude oil substitute)

The comparison of the mLR and LC bars reveal that the utilization of woody biomass within the TCR combined with CHP and PSA is economically sustainable. The mLR are more significant than the LC in this scenario. Due to the breakdown of the LC, it becomes evident that investment and feedstock costs are the primary cost drivers followed by costs for personnel. The comparison of the product-specific LR and LC shows a different picture. The LC of biochar, oil, and H_2 are significantly lower than the LR and therefore subsidize the product power. The LC of power was over three times higher than the levelized power revenue.

7.2.1.3 Algae

The characteristics of the averaged algae samples from different seaweed collections led to 396 different data sets (appendix Table 58). Due to the high ash content of the algae samples, the possible utilization pathways of the carbonisates were limited to energetic and CCS applications. As described earlier in section 5.2, the high ash content is not typical for seaweed. Therefore, for other seaweed samples, different utilization pathways for the carbonisates are probable.

The economic evaluation of the possible utilization pathways revealed that for the tested feedstock algae, the heating with natural gas, steam coal, and feedstock was favorable (appendix Table 59). The investment of a PSA for the separation of hydrogen was in the majority of the considered scenarios economically. If the plant is heated with the product carbonisate, no economic sustainable scenario was achieved. Moreover, the amount of carbonisate is not enough to heat the plant entirely. Additional steam coal is needed. If it is possible to heat the plant with feedstock as a fuel, all considered scenarios are competitive. The highest benefit is generated with a CHP and PSA configuration. This plant configuration within the 450 scenario is pictured in Figure 41.

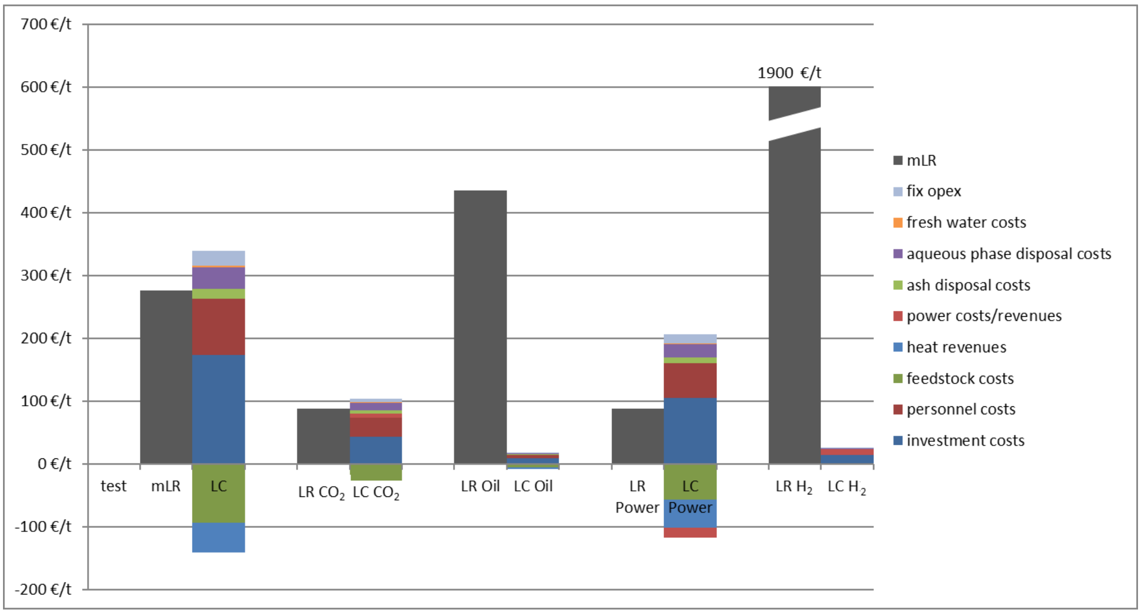

Figure 41: Breakdown of the levelized costs of the products CO_2 for storage (CCS), oil, power, and hydrogen and comparison with specific and overall levelized revenues in €/t for the feedstock algae (450 scenario, medium gate fee, heat demand of the plant covered with feedstock, CHP+PSA, carbonisates marketable for CCS applications, heat of CHP sold for 40 €/MWh, oil sold as a crude oil substitute)

The comparison of the overall LC and the mLR showed that in the medium gate fee and 450 WEO scenario the conversion of algae in the TCR is economically viable. If the investment and the personnel cost could be reduced, the dependency on the gate fees would be significantly minimized. The comparison of the levelized CCS costs (LC CO_2) and LR CO_2 reveal that even in the scenario with the highest CO_2 prices (450 scenario), the breakeven just regarding CCS is not achieved. The income of the products oil and hydrogen enable CCS to be economically sustainable. However, it has to be considered that in the 450 scenario the future pricing of coal and therefore also of the substitute carbonisate is low. Thus, in this scenario, CCS would be the most competitive utilization pathway of the carbonisate.

7.2.1.4 Organic Fraction of Municipal Solid Waste (oMSW)

The results of the analysis of the feedstock samples and the TCR products defined the system boundaries and reduced the possible number of data sets to 396 (appendix Table

60). The most versatile fuel for heating the plant was natural gas and feedstock. Due to the high content of ash and therefore also metals, the carbonisates were only considered for energetic or CCS applications. Within the medium and high gate fee cases, the considered utilization pathways were all sustainable, with the restriction that the oil is substituting crude oil and is not utilized in a CHP (appendix Table 61). For the low gate fee cases, several configurations were also economical with the exception of the 450 scenario.

In Figure 42 the impact of the Current policy and 450 scenario on costs and revenues of the products is shown.

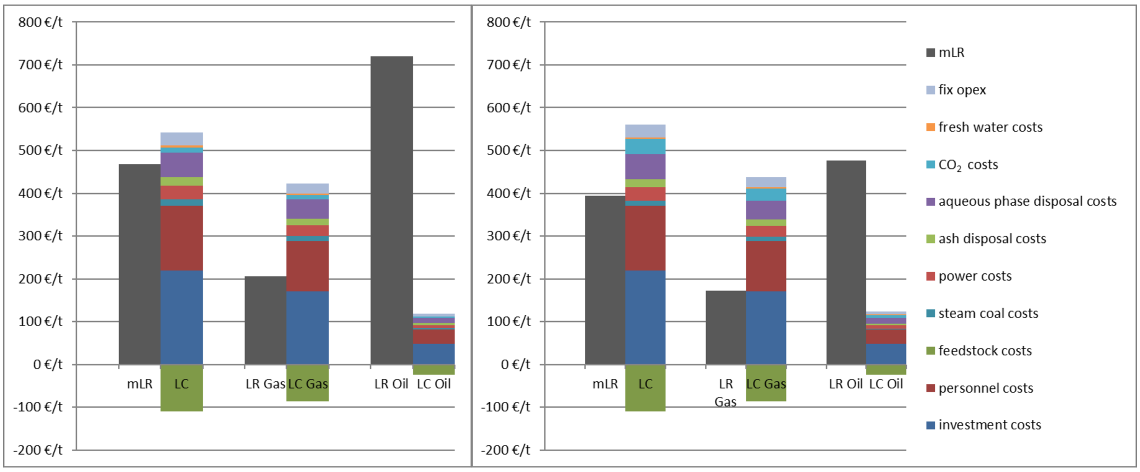

Figure 42: Comparison of the effects of the Current policy (left) and the 450 scenario (right) for the feedstock oMSW; Breakdown of the levelized costs (LC) of the products gas and oil and comparison with specific and overall levelized revenues in €/t for both scenarios (medium gate fee, heat demand of the plant covered with product carbonisate and steam coal, product gas sold as substitute for natural gas, oil sold as a crude oil substitute)

The comparison of the mLR of the Current policy scenario (left) with the mLR of the 450 scenario reveals that prices of fossil fuels are lower in the 450 scenario. From this point of view, the profitability of the process is reduced. Also, the LCs of the products are slightly higher. This is due to higher costs of the CO_2 emissions for the usage of steam coal to close the gap of the heating demand. This is the reason why within the

450 scenario an economical operation of the plant is not possible. The cost breakdown of the LC identified the investment and personnel costs as the highest potential costs savers of the plant.

7.2.1.5 Leather Residues

The results of the analysis of the feedstock samples from the leather processing industry (section 5.2) and the results of the TCR trials (section 7.1.1.5) revealed that each process residue has to be considered separately.

In the following subsections, the results of the economic calculations of SWF, LLR, and ISS is provided and evaluated.

Due to the composition of the feedstock, and also as a result of the solid products, the carbonisate is only marketable for energetic or CCS purposes.

7.2.1.5.1 Swarf

Based on the assumptions, swarf (SWF) is a promising feedstock for the TCR process. In the majority of the 396 investigated utilization pathways and scenarios, the process adds significant value (appendix Table 62). The fuel for heating the plant could be adapted to the conditions of possible locations. The highest potentials are observed by the utilization of feedstock and TCR gas as a fuel to meet the process heat demand (appendix Table 63). The most value creating process chain was PSA in combination with substituting hard coal, crude oil, and natural gas. Consequently, only the separation of hydrogen was considered and the off-gases of the PSA were sold. Due to the high hydrogen content in the TCR gas, combined with the high amount of produced gas, over 50 t/a of hydrogen could be produced in a TCR-500. If there is a demand for such an amount of hydrogen, this would be the most promising process chain. The base scenario and the CHP scenario are for several gate fee and WEO scenarios also economically sustainable.

The cost breakdown, as shown in Figure 43, confirms the previous observations.

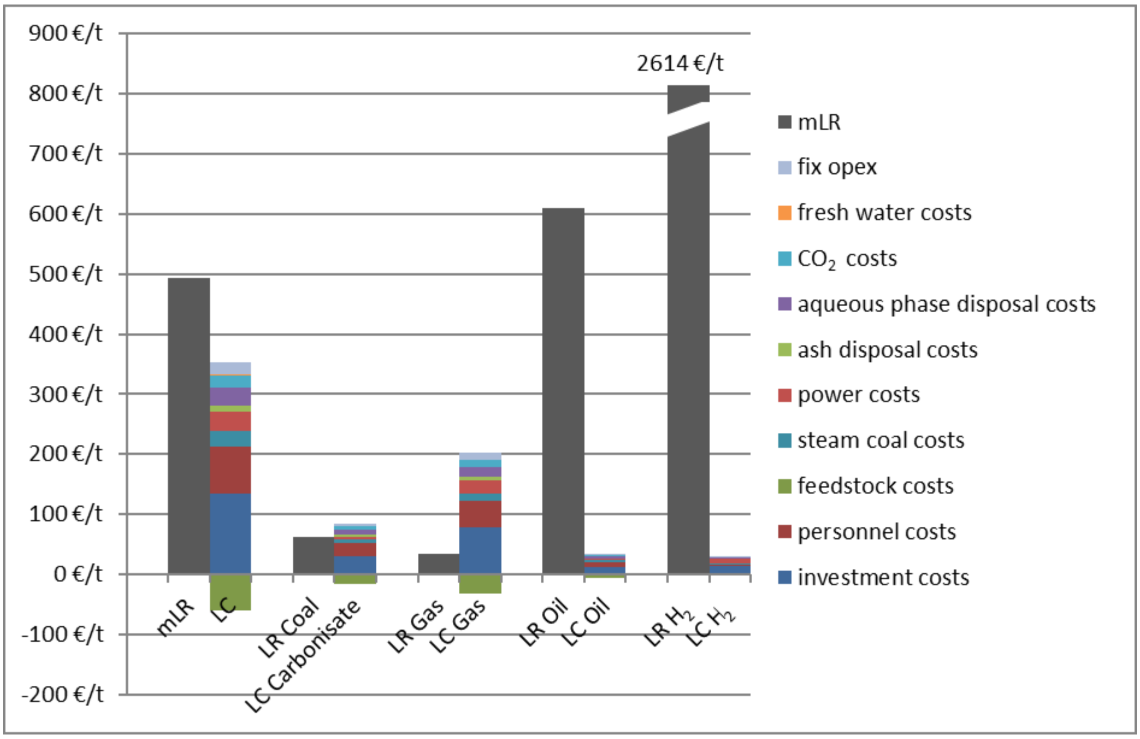

Figure 43: Breakdown of the levelized costs of the products carbonisate, gas, oil, and hydrogen and comparison with specific and overall levelized revenues in €/t for the feedstock SWF (medium gate fee, heat demand of the plant covered with product carbonisate and steam coal, product off-gas sold as substitute for natural gas, oil sold as a crude oil substitute)

The investment and personnel costs were the most significant costs. The high-value products hydrogen and oil subsidize the lower value products carbonisate and gas. The overall LC in comparison with the aggregated mLR proves the competitiveness of the TCR technology with the feedstock SWF.

7.2.1.5.2 Limed Leather Residues

The economic evaluation of the 387 different possible configurations of the conversion of limed leather residues (LLR) with the TCR technology revealed that for the basic and PSA pathway the process was sustainable (appendix Table 64). It is worth to highlight that in these configurations, all gate fee and WEO scenarios show promising results. (appendix Table 65).

The products oil and hydrogen are the pillars of the economic potential (Figure 44).

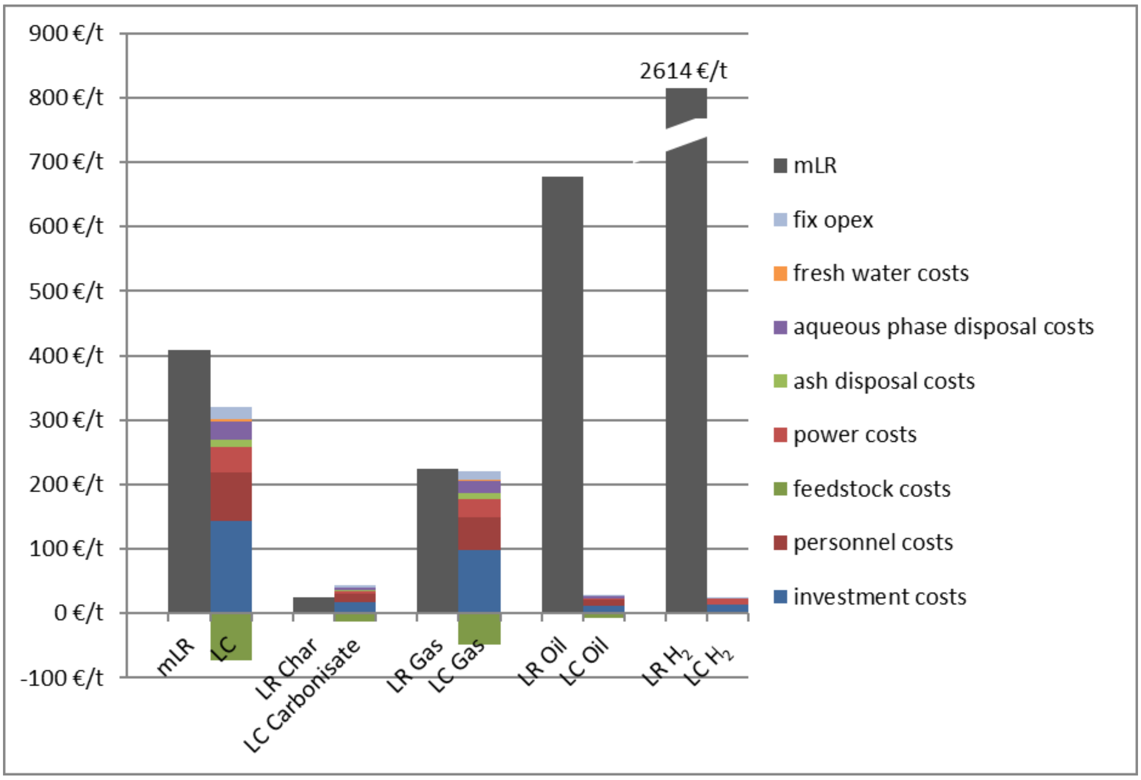

Figure 44: Breakdown of the levelized costs of the products carbonisate, gas, oil, and hydrogen and comparison with specific and overall levelized revenues in €/t for the feedstock LLR (medium gate fee, heat demand of the plant covered with feedstock, product off-gas sold as substitute for natural gas, oil sold as a crude oil substitute)

Due to the low carbon content, and therefore low HHV, the value of the product carbonisates for energetic and CCS application is limited. As described in section 6, the expected market revenue of the substitutes is linked to the fossil fuel equivalent with an HHV related discounted value. The results of the cost breakdown are in line with the results reported earlier in this section. The investment and personnel costs were identified as the highest cost saving potentials.

7.2.1.5.3 Industrial Sewage Sludge

The economic evaluation of the conversion of the feedstock sewage sludge (ISS) with the TCR endorsed the results of the feedstock analysis (section 5.2) and the TCR trials (section 7.1.1.5). Due to the fact that the feedstock samples had the highest ash content and the lowest HHV of all feedstocks considered in this work, the economic results were also unique. Among all considered 387 scenarios, less than 12% were sustainable under the considered conditions (appendix Table 66, Table 67). It is worth highlighting that in the high gate fee cases the overall LC were negative. As described earlier for the feedstock raw sludge, this is the case if the income due to the gate fee overwhelmed the cost of the process.

A comparison of two configurations within the medium gate fee case is shown in Figure 45.

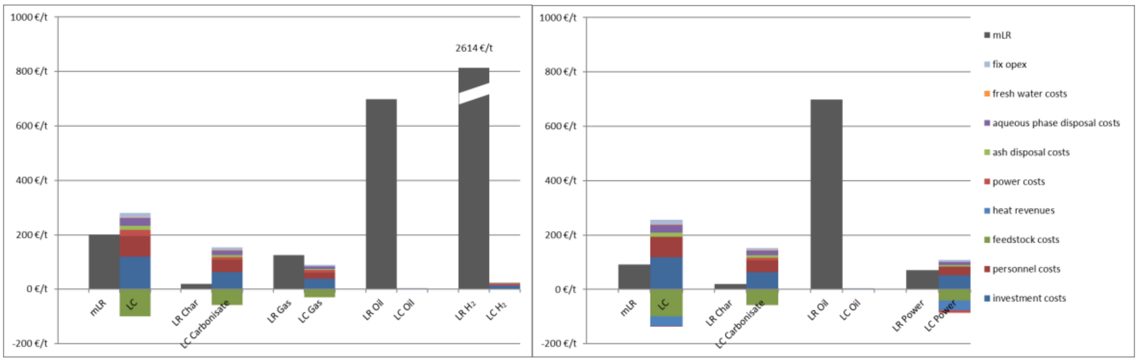

Figure 45: Comparison of PSA (left) and CHP (right) configurations for the feedstock ISS; Breakdown of the levelized costs of the products carbonisate, off-gas, oil, hydrogen, and power and comparison with specific and overall revenues in €/t for both scenarios (medium gate fee, heat demand of the plant covered with feedstock, product off-gas sold as substitute for natural gas, oil sold as a crude oil substitute, heat from CHP sold for 40 €/MWh)

Only the configuration including a PSA is economically sustainable in the high and medium gate fee cases. The low income for the quantitative largest product share carbonisate was compensated by the high-value products oil and hydrogen; even if the quantitative proportion of both products was low (1.3 and 1.5 wt%, respectively).

The diagram on the right-hand side of Figure 45 reveals a contrary effect. The LC of the TCR–CHP configuration is higher than the mLR, and therefore this scenario would not be sustainable from an economic point of view. The main products carbonisate and power generate not enough values. Only a small proportion of high-value oil is available but does not lift the process out of the red numbers. The analysis of the cost breakdown reveals that an increased gate fee would enable an economical utilization of ISS. This is confirmed by the results of the high gate fee case. In addition, a cost reduction in investment costs and staff expenses would increase the competitiveness of the utilization pathway.

7.2.2 Fossil Feedstocks

In the following section, the results of the economic evaluation of the conversion of fossil feedstocks within the TCR technology are presented. For fossil feedstocks, the focus was to evaluate the impact of feedstock costs and CO_2 emissions. As the considered feedstocks are also fossil fuels, steam coal was not considered as an additional fuel option for heating the plant. Furthermore, in the TCR fossil fuel scenarios, the feedstock is also the most appropriate fuel to meet the heating demand of the process.

CCS applications of the carbonisates from a fossil feedstock were not considered. It is presumed that it is not reasonable to expect revenues for this business approach from a regulatory perspective.

7.2.2.1 Peat

Due to the relatively high ash content of the tested peat sample, only energetic utilization of the carbonisates was considered. This reduced the number of possible utilization pathways within the system boundaries to 279 (appendix Table 68). The evaluation of the results revealed that the pricing of the feedstock has a significant impact on the possible competitiveness of the products and therefore on the TCR processing (appendix Table 69). This becomes apparent with the different gate fee cases and was underlined by the results of the cost breakdown illustrated exemplarily by two cases in Figure 46.

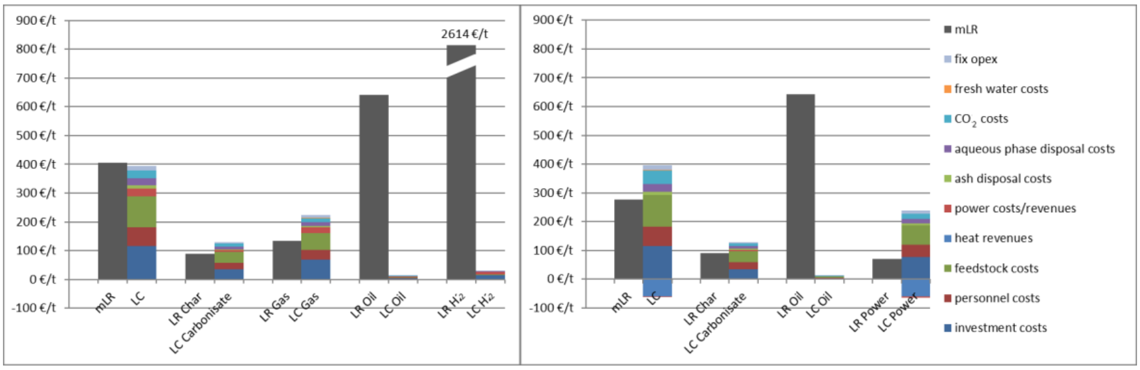

Figure 46: Comparison of PSA (left) and CHP (right) configurations for the feedstock peat; Breakdown of the levelized costs of the products carbonisate, off-gas, oil, hydrogen, and power and comparison with specific and overall levelized revenues in €/t for both scenarios (medium gate fee, heat demand of the plant covered with feedstock, product off-gas sold as substitute for natural gas, oil sold as a crude oil substitute, heat from CHP sold for 40 €/MWh)

The comparison of both LC and mLR reveal that the PSA case is, from an economic perspective under the considered framework, sustainable. This is not the case for the

CHP case. Thus, the overall LC of the PSA case are only slightly lower than the mLR of the marketable products.

The cost breakdown reveals that the highest cost drivers are the feedstock costs, followed by investment and personnel costs. The associated costs of CO_2 emissions were below 9% of the overall cost.

The comparison of the PSA and CHP case illustrates the impact of a high-value product like hydrogen on the overall process economics. The utilization of the gas in a CHP to produce heat and power does not create similar revenues for the process. Overall the same effects were observed with biogenic feedstocks. The possibility to substitute high-value fossil products, even if the qualitative share is low, creates substantial value and subsidized the overall process.

Therefore, the economic evaluation of the conversion of peat within the TCR process revealed promising value chains. It must be considered that the pricing of the feedstock has a high impact on the overall economic efficiency of the configuration. High-value products, even in low quantities, can increase the sustainability of the overall process significantly.

7.2.2.2 Lignite

Due to the low ash content of the lignite samples, the possible utilization pathways for the solid product are diverse. This results in over 387 different investigated cases in the considered system boundaries (appendix Table 70).

The valuation of the results of the economic calculations revealed that the energetic utilization of the products is not economically sustainable (appendix Table 71). This generates too little value to bear the costs of the processing of the feedstock. Therefore, the potential of the products has to be fully exploited. Figure 47 depictured the impact of a high-value carbonisate on the overall process profitability of the whole process chain.

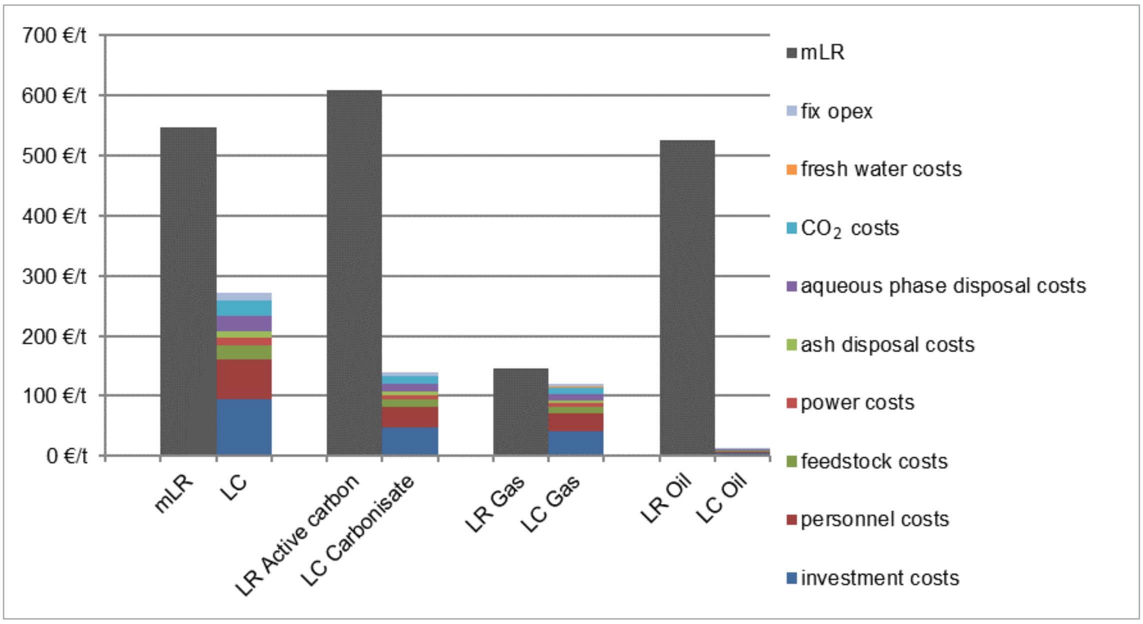

Figure 47: Breakdown of the levelized costs of the products carbonisate, gas, and oil and a comparison with specific and overall levelized revenues in €/t for the feedstock lignite (medium gate fee, heat demand of the plant covered with feedstock, product off-gas sold as substitute for natural gas, oil sold as a crude oil substitute, carbonisate sold as active carbon)

Although, the minimum standards of active carbon were accomplished (ash content, metal load), process specific requirements like surface area were not achieved. However, it is worth to highlight that the potential, illustrated by the difference of LC carbonisate and LR active carbon, are significant. Consequently, further upgrading of the product carbonisates should be taken into consideration.

The separation of hydrogen from the gas stream is another example of this strategy. For these scenarios, hydrogen separation and/or utilization of the solid carbonisates as a higher value product beyond the energetic utilization have proven the most promising value chains for the overall process. In contrast to the feedstock peat, the sensibility regarding the feedstock price was not distinct. However, it must be noted that the cost boundaries of peat were significantly wider. In line with the results reported earlier, the highest potential of increasing the competitiveness of the process was identified as investment and personnel costs.

The results of the economic evaluation can be summarized in four key messages:

I. The method of LC and LR comparison was successfully adapted to evaluate a multi-product process. The breakdown of the overall LC of the TCR on the cogenerated products carbonisate, gas, and oil and the products of further processing and upgrading of these (power, hydrogen) was suitable. The approach of allocating the additional costs of every additional upgrading process only to the treated product is proved to be effective. The cost breakdown of the overall LC and the specific products was substantial to identify starting areas to increase the competitiveness of the process chains.

II. The impact of high-value products like hydrogen or biochar on the overall process economics is significant. High-value products, even in low quantities, can increase the sustainability of the overall process significantly. The potential of the products must be fully exploited. Extraction of single components like hydrogen off the gas stream is only one example that is assessed in the framework of the work. The extraction of components within the TCR oil was only touched and should be investigated further. The integration of the oil within a refinery process implies this and could, therefore, increase the value of the TCR crude oil even if the value-creating separation process step would be not included in the framework of the TCR plant.

III. For almost every investigated feedstock and the related products, competitive pathways could be found in all WEO scenarios and for all considered gate fee/feedstock price cases. For the feedstock ISS, higher feedstock gate fees are needed to achieve economic competitiveness of the process. For peat, low feedstock prices are a precondition for a promising business case.

IV. The primary cost drivers of the considered scenarios are independent of the utilized feedstock. The investment and personnel costs have the most significant share of the overall costs of the products. Consequently, these stakes have the highest cost saving potentials. In addition, the gate fee/costs of the feedstocks have a significant impact on the competitiveness of the products.

8 SUMMARY OF THE RESULTS

Within the framework of this work, a techno-economic assessment of the conversion of biogenic and non-biogenic feedstocks for energetic and material utilization was investigated. State of the art technologies and the products thereof have been the benchmark for the evaluation. A broad selection of biogenic feedstocks was processed with the Thermo-Catalytic Reforming (TCR$^{®}$) technology with gas, carbonisates, and oil as marketable products. The selection of the feedstocks was focused on covering a broad spectrum of feedstocks, not only, but with an emphasis on biogenic residues and unused potentials. The target was to develop a sustainable solution for these residues beyond the state of the art utilization pathways of combustion or landfilling and to address present environmental, energy, and resource challenges. Therefore, the optimum utilization pathways of the TCR products gas, carbonisates, and oil needed to be identified. In addition, it was targeted to obtain correlations between feedstock properties, process parameters, and product quantities and qualities and the optimum utilization pathway thereof. This basis allows adapting the results for initial evaluation of the potentials of feedstocks beyond the investigated spectrum.

Furthermore, low-rank fossil fuels were tested to enable a material use of these resources in line with environmental and sustainable targets [278].

The results of the biogenic and fossil feedstock trials proved the robustness of the process. The lab scale trials in the batch TCR process lead to further improvements that were successfully tested in the demonstration scale TCR plant at the Fraunhofer UMSICHT site.

The conversion of six different types of feedstocks with the TCR technology was successful. Different samples of sewage sludge, woody biomass, algae, oMSW, industrial residues from the leather processing industry, peat, and lignite were converted into the storable products oil, gas, and carbonisate. A correlation between the different feedstock and the product yields was observed. For all tested feedstocks, the gaseous phase is the primary quantitative product of the process at high reforming temperatures on ash and water free basis. The distribution of the feedstock related energy content is more diverse. The energy transfer of the fossil fuels is focused on the carbonisates while energy from biogenic feedstocks is transferred mainly to the carbonisate and gas with a tendency to the gaseous fraction.

The composition of the gaseous product is dependent on the feedstocks and varied strongly regarding composition and characteristics. The HHV of the gases varied between 15.1–26.1 MJ/kg and the Wobbe index between 16.6–32.8 MJ/m . The hydrogen content, and also the H_2:CO ratio as the relevant indicator for synthesis processes, varied widely between 17–48 vol% and 0.7–6.3, respectively. Therefore, utilization pathways for the gases and possible gas cleaning or upgrading have to be designed specifically for the different feedstocks.

Biogenic feedstocks vary in composition and occurrence throughout the course of a year. This underlines the importance of the results of the co-pyrolysis trials. Thus, seasonal fluctuations can be compensated with correlating fossil or countervailing biogenic feedstocks. Especially for material utilization of the gases, this is important due to the fact that these processes are less robust than the energetic utilization for example in a CHP plant. This flexibility increases the capacity and sustainability of the plant.

The compositions and therefore the properties of the carbonisates were strongly related to the ash content and the elemental composition of the feedstocks. High ash content resulted in a low carbon content and therefore low HHV. This is not only relevant for the energetic utilization of the carbonisate, but it also has an impact on the material utilization. Beyond the regulations regarding maximum weight percentage of ash for several applications, inorganic compounds are agglomerated in the carbonisate and single compounds could exceed the prescribed thresholds. The co-pyrolysis of the different feedstocks provided the possibility to influence the composition of the carbonisates to meet the minimum requirements for a higher value utilization pathway. The oil yield was found to be correlating with the feedstock classifications, not in terms of elemental composition, but for the composition of organic compounds. Thus, it is not possible to approximate the oil yield based on the elemental composition of the feedstock. This calls for a different approach of classifying the feedstocks, beyond CHNS analysis. A purposeful approach could be the detailed analysis of the organic components of the feedstock regarding fatty acids, sugars, cellulose, hemicellulose, and proteins.

The main characteristics of TCR oil were similar for all tested feedstocks. The oils had a high heating value and were thermal stable. Consequently, the integration of the TCR crude oil in a standard refinery process is desirable also from an economic point of view. This would enable the substitution of fossil crude oil with sustainable TCR oil, thus enable the production of standardized transportation fuels, and also integrate TCR oils in the petrochemical industry.

The data from the TCR experiments were used for an economic evaluation. The concept of evaluating long-term investment decisions on the basis of levelized costs (LC) and levelized revenues (LR) was adapted for processes with not only one primary product. A user-friendly tool to analyze and optimize the relevant parameters has been developed. With the tool, it is possible to evaluate and rank utilization pathways considering different scenarios. The tool could easily be adapted for other multi-product processes.

The application of the enhanced method of LC and LR for a multi-product process was purposeful. The economic evaluation of the conversion of biogenic and fossil feedstocks within the TCR process revealed promising value chains. The scenario analysis based on the predictions of the WEO in combination with variations of gate fees/feedstock pricings revealed opportunities, potentials, and risks of different pathways of utilization. For almost every investigated feedstock and the related products, competitive pathways could be found in all WEO scenarios and for many considered gate fee/feedstock price cases. The breakdown of the overall LC on the three TCR cogenerated products carbonisates, gas, and oil and the products of further processing and upgrading of these (power, hydrogen) was successful. The approach of allocating the additional costs of every additional upgrading process only to the treated product was proved to be effective.

The impact of high-value products like hydrogen or biochar is significant in the overall process economics. High-value products, even in low quantities, can increase the sustainability of the overall process significantly. The potential of these products has to be fully exploited. Extraction of single components like hydrogen off the gas stream as one example was accessed in the framework of the work. The extraction of components from the TCR oil was only broached. The integration of the oil in a refinery process implies this and could, therefore, increase the value of the TCR crude oil; even if this value-creating separation process step would be not included in the framework of the TCR.

The cost breakdown of the overall LC and of the specific products was substantial to identify starting points to increase the competitiveness of the process chains. The main cost drivers of the considered scenarios were independent of the feedstocks. The investment and personnel costs had the most significant share of the overall costs of the products. Therefore, these stakes have the highest cost saving potentials. Also, the gate fees/costs of the feedstock have a significant impact on the competitiveness of the process. On the revenue site, the high-value products oil and hydrogen are crucial for the competitiveness of the TCR process.

To build on the results of the economic and technical evaluation, the site and specific environment have to be considered, and the key assumptions validated accordingly. Therefore, the possible stakeholders of the utilization pathways of the feedstocks and products need to be engaged. This includes companies and institutions with relevant residue quantities, industrial end users, and downstream processors. Additional considerations of non-monetary factors are also crucial for the sustainable success of technologies in the market. Holistic process integration is needed to identify interfaces and lower the entry barriers. Based on these results, requirements for further improvements and potentials could be addressed. Possible synergy effects could include heat energy potentials or wastewater treatment. One very promising option is the integration of the TCR in a petrochemical plant.

It is necessary to integrate these results in the forthcoming upscale of the TCR technology from the demonstration scale with a capacity of 30 kg/h to the first industrial scale with a capacity of 500 kg/h. Steps in this direction were the projects initiated in 2017 within the funding by the EU framework of Horizon 2020 and the Bavarian Ministry of Economic Affairs and Media, Energy and Technology [144,145].

9 CONCLUSION AND OUTLOOK

In the present thesis, a techno-economic evaluation of the TCR technology, with a particular focus on biogenic residue conversion, was investigated.

Overall it was proved that TCR as a platform technology is able to convert a broad range of different biogenic feedstocks into high-quality fossil fuel substitutes. Process parameters influence the yields and composition of the products and thus the possible utilization pathways. It was possible to find correlations regarding the composition of a feedstock and the potential utilization pathways for the related products.

The trials with fossil feedstocks were also successful. The target was to upgrade low-rank fossil fuels to higher quality products. It has been shown that the process conditions used to produce high-quality oil from fossil feedstocks with the TCR technology are of broader importance than for the utilization of biomass. Subsequent investigations of mixtures of biogenic and fossil feedstocks extended the versatility of the process and proved a linear correlation regarding mixture ratios, product yields and compositions at optimum process conditions. These results can be used to optimize the design and the operation of the plan if a particular site and feedstocks are defined.

The improvements of the TCR technology accomplished within the framework of this work were implemented in the upscale of laboratory scale to the demonstration and the commercial scale.

Within the framework of this work, the range of possible feedstocks that can be converted within the TCR technology was expanded to low-rank fossil fuels and resulted in filing an international patent application in 2016.

The economic evaluation of the process proved the competitiveness of the TCR technology and its products in a wide range of utilization pathways against state of the art. It was possible to identify the critical factors regarding feedstocks, products, and market evolutions. The optimum utilization of the products is of crucial importance. Therefore, feedstocks and products must be analyzed and evaluated to implement the products in the optimum utilization pathway for maximum sustainable value creation. For this purpose, a tool to analyze and optimize the relevant parameters has been developed. This tool could be adopted by companies and municipalities to evaluate specific application scenarios. A wide range of possible applications of the TCR products beyond the energetic utilization by substituting fossil fuels has been identified. Low-rank feedstocks and residues can be integrated into industrial proven processes.

To boost the market launch for the highlighted most promising utilization pathways, the relevant markets should be screened to find an appropriate industrial partner and site for a flagship project.

BIBLIOGRAPHY

[1] B.G. Miller, The Future Role of Coal, in: Clean Coal Engineering Technology, Elsevier, 2017, pp. 757–774. ISBN 978-0-12-811365-3.

[2] T. Linnemann, G.S. Vallana, Windenergie in Deutschland und Europa: Status quo, Potenziale und Herausforderungen in der Grundversorgung mit Elek-trizität. Teil 1: Entwicklungen in Deutschland seit dem Jahr 2010, VGB PowerTech 97 (6) (2017) 63–73.

[3] F. Huneke, c.p. Linkenheil, M.-L. Niggemeier, Kalte Dunkelflaute: Robustheit des Stromsystems bei Extremwetter, Berlin, 2017.

[4] T. Linnemann, G.S. Vallana, Windenergie in Deutschland und Europa Potenziale und Herausforderungen in der Grundversorgung mit Strom: Teil 2: Europäische Situation im Jahr 2016. VGB-Windstudie 2017, Teil 2, Fachaufsatz und Foliensatz, 2017.

[5] H.-M. Henning, A. Palzer, 100 % Erneuerbare Energien für Strom und Wärme in Deutschland, Freiburg, 2012.

[6] P.J. Crutzen, A.R. Mosier, K.A. Smith, W. Winiwarter, N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels, Atmospheric Chemistry and Physics 8 (2) (2008) 389–395.

[7] C. Winkler, Daten-Fakten-Rohstoffbasis-der-chemischen-Industrie, 2017.

[8] P. Basu, Biomass Characteristics, in: Biomass Gasification Design Handbook, Elsevier, 2010, pp. 27–63. ISBN 978-0-12-374988-8.

[9] S.V. Vassilev, D. Baxter, L.K. Andersen, C.G. Vassileva, An overview of the chemical composition of biomass, Fuel 89 (5) (2010) 913–933.

[10] Verordnung über die Erzeugung von Strom aus Biomasse: BiomasseV, in: Bundesgesetzblatt, pp. 2258–2357.

[11] A.-P. Zeng, Biomasse. RÖMPP online, available at https://roempp.thieme.de/roempp4.0/do/data/RD-02-01523 (accessed on October 14, 2017).

[12] M.S. Talmadge, R.M. Baldwin, M.J. Biddy, R.L. McCormick, G.T. Beckham, G.A. Ferguson, S. Czernik, K.A. Magrini-Bair, T.D. Foust, P.D. Metelski, C. Hetrick, M.R. Nimlos, A perspective on oxygenated species in the refinery integration of pyrolysis oil, Green Chem. 16 (2) (2014) 407–453.

[13] H.-G. Franck, J.W. Stadelhofer, Industrial Aromatic Chemistry: Raw Materials · Processes · Products, Springer Berlin Heidelberg, Berlin, Heidelberg, 1988. ISBN 978-3-64-273434-2.

[14] H. Schulz, The history of wood utilization in the 19th, 20th and 21st century, Holz als Roh - und Werkstoff 51 (2) (1993) 75–82.

[15] B. Gales, A. Kander, P. Malanima, M. Rubio, North versus South: Energy transition and energy intensity in Europe over 200 years, European Review of Economic History 11 (2) (2007) 219–253.

[16] P. O'Connor, C. Cleveland, U.S. Energy Transitions 1780–2010, Energies 7 (12) (2014) 7955–7993.

[17] P. McKendry, Energy production from biomass (part 1): Overview of biomass, Bioresource technology 83 (1) (2002) 37–46.

[18] G. Mao, H. Zou, G. Chen, H. Du, J. Zuo, Past, current and future of biomass energy research: A bibliometric analysis, Renewable and Sustainable Energy Reviews 52 (2015) 1823–1833.

[19] L. Wang, L. Zhao, G. Mao, J. Zuo, H. Du, Way to accomplish low carbon development transformation: A bibliometric analysis during 1995–2014, Renewable and Sustainable Energy Reviews 68 (2017) 57–69.

[20] P. McKendry, Energy production from biomass (part 2): Conversion technologies, Bioresource technology 83 (1) (2002) 47–54.

[21] O. Reale, Modeling the effects of vegetation on Mediterranean climate during the Roman Classical Period: Part II. Model simulation, Global and Planetary Change 25 (3-4) (2000) 185–214.

[22] O. Reale, Modeling the effects of vegetation on Mediterranean climate during the Roman Classical Period Part I: Climate history and model sensitivity, Global and Planetary Change 25 (3-4) (2000) 163–184.

[23] J. Neumann, S. Binder, A. Apfelbacher, J.R. Gasson, P. Ramírez García, A. Hornung, Production and characterization of a new quality pyrolysis oil, char and syngas from digestate – Introducing the thermo-catalytic reforming process, Journal of Analytical and Applied Pyrolysis 113 (2015) 137–142.

[24] J. Neumann, J. Meyer, M. Ouadi, A. Apfelbacher, S. Binder, A. Hornung, The conversion of anaerobic digestion waste into biofuels via a novel Thermo-Catalytic Reforming process, Waste management (New York, N.Y.) 47 (Pt A) (2016) 141–148.

[25] R. Conti, N. Jäger, J. Neumann, A. Apfelbacher, R. Daschner, A. Hornung, Thermocatalytic Reforming of Biomass Waste Streams, Energy Technol. 5 (1) (2017) 104–110.

[26] E. Ahmad, N. Jäger, A. Apfelbacher, R. Daschner, A. Hornung, Pant, K.K., Integrated thermo-catalytic reforming of residual sugarcane bagasse in a laboratory scale reactor, Fuel Processing Technology (171) (2018) 277–286.

[27] R. Leschber, U. Loll, Klärschlamm, 4th ed., Ernst, Berlin, 1996. ISBN 978-3-43-300909-3.

[28] Statistisches Bundesamt und DWA-Arbeitsgruppe KEK-1.2 „Statistik“, Abwasser und Klärschlamm in Deutschland – statistische Betrachtungen, KA - Korrespondenz Abwasser, Abfall 62 (1) (2015) 48–55.

[29] H.A. Leslie, M.J.M. van Velzen, A.D. Vethaak, Microplastic survey of the Dutch environment: Novel data set of microplastics in North Sea sediments, treated wastewater effluents and marine biota, 2013.

[30] J. Talvitie, M. Heinonen, Synthetic microfibers and particles at a municipal waste water treatment plant, 2014.

[31] S. Mintenig, I. Int-Veen, M. Löder, G. Gerdts, Mikroplastik in ausgewählten Kläranlagen des Oldenburgisch- Ostfriesischen Wasserverbandes (OOWV) in Niedersachsen: Probenanalyse mittels Mikro-FTIR Spektroskopie. im Auftrag des Oldenburgisch-Ostfriesischen Wasserverbands (OOWV) und des Niedersächsischen Landesbetriebs für Wasserwirtschaft, Küsten- und Naturschutz (NLWKN), 2014.

[32] PlasticsEurope, Plastics – the Facts 2013: An analysis of European latest plastics production, demand and waste data, available at https://www.plasticseurope.org/application/files/7815/1689/9295/2013plastics_the_facts_PubOct2013.pdf (accessed on May 19, 2018).

[33] PlasticsEurope, Plastics – the Facts 2016: An analysis of European plastics production, demand and waste data, available at https://www.plasticseurope.org/application/files/4315/1310/4805/plastic-the-fact-2016.pdf (accessed on May 19, 2018).

[34] Health at a Glance 2015, OECD Publishing, 2015. ISBN 978-9-26-423257-0.

[35] EurEau-Umfrage: In Europa überwiegt stoffliche Verwertung von Klärschlamm, EUWID Wasser und Abwasser 20 (26) (2017) 2.

[36] Fast zwei Drittel des Klärschlamms in Deutschland gingen 2015 in die Verbrennung, EUWID Wasser und Abwasser 19 (51/52) (2016) 13.

[37] Verordnung zur Neuordnung der Klärschlammverwertung: AbfKlärV, in: Bundesgesetzblatt, pp. 3465–3512.

[38] Statistisches Bundesamt und DWA-Arbeitsgruppe KEK-1.2 „Statistik“, Abwasser und Klärschlamm in Deutschland – statistische Betrachtungen, KA - Korrespondenz Abwasser, Abfall 61 (12) (2014) 1106–1112.

[39] Klärschlamm-Verwertung wird schwieriger und teurer, EUWID Wasser und Abwasser 20 (14) (2017) 16.

[40] A. Wagenführ, F. Scholz (Eds.), Taschenbuch der Holztechnik, 2nd ed., Fachbuchverl. Leipzig, Munich, 2012. ISBN 978-3-446-42605-4.

[41] R. Pastusiak, Charakterisierung von Zellstoffkomponenten: Analytik, Spektroskopie, Reaktionskinetik und Modellierung, Universitätsbibliothek der TU München, Munich.

[42] Agriculture, forestry and fishery statistics, 2016th ed., Publications Office of the European Union, Luxembourg, op. 2016. ISBN 978-9-27-963351-5.

[43] S. Gärtner, G. Hienz, H. Keller, M. Müller-Lindenlauf, Gesamtökologische Bewertung der Kaskadennutzung von Holz: Intergovernmental Panel on Climate Change, Heidelberg, 2013.

[44] R. Raunikar, J. Buongiorno, J.A. Turner, S. Zhu, Global outlook for wood and forests with the bioenergy demand implied by scenarios of the Intergovernmental Panel on Climate Change, Forest Policy and Economics 12 (1) (2010) 48–56.

[45] Europäischer Wirtschaftsdienst, Holz und Holzwerkstoffe, Europa: Holzwerkstoffproduktion ist weiter gestiegen, available at http://www.euwid-holz.de/news/holzwerkstoffe/einzelansicht/Artikel/europa-holzwerkstoffproduktion-ist-weiter-gestiegen.html (accessed on August 9, 2017).

[46] C. Calderon, European Wood chips plants - Country analysis: BASIS – Biomass Availability and Sustainability Information System, 2015.

[47] P. Lauri, P. Havlík, G. Kindermann, N. Forsell, H. Böttcher, M. Obersteiner, Woody biomass energy potential in 2050, Energy Policy 66 (2014) 19–31.

[48] N. Jäger, R. Conti, J. Neumann, A. Apfelbacher, R. Daschner, S. Binder, A. Hornung, Thermo-Catalytic Reforming of Woody Biomass, Energy Fuels 30 (10) (2016) 7923–7929.

[49] J. Wingender, D.R. Kammerer, Algen. RÖMPP online, available at https://roempp.thieme.de/roempp4.0/do/data/RD-01-01398 (accessed on August 8, 2017).

[50] R. Rosello Sastre, C. Posten, Die vielfältige Anwendung von Mikroalgen als nachwachsende Rohstoffe, Chemie Ingenieur Technik 82 (11) (2010) 1925–1939.

[51] L. Barsanti, P. Gualtieri, Algae: Anatomy, Biochemistry, and Biotechnology, Second Edition, 2nd ed., Taylor and Francis, Hoboken, 2014. ISBN 978-1-43-986732-7.

[52] B. Bharathiraja, M. Chakravarthy, R. Ranjith Kumar, D. Yogendran, D. Yuvaraj, J. Jayamuthunagai, R. Praveen Kumar, S. Palani, Aquatic biomass (algae) as a future feed stock for bio-refineries: A review on cultivation, processing and products, Renewable and Sustainable Energy Reviews 47 (2015) 634–653.

[53] M. Vigani, C. Parisi, E. Rodríguez-Cerezo, M.J. Barbosa, L. Sijtsma, M. Ploeg, C. Enzing, Food and feed products from micro-algae: Market opportunities and challenges for the EU, Trends in Food Science and Technology 42 (1) (2015) 81–92.

[54] H. Chen, D. Zhou, G. Luo, S. Zhang, J. Chen, Macroalgae for biofuels production: Progress and perspectives, Renewable and Sustainable Energy Reviews 47 (2015) 427–437.

[55] S. Yamaguchi, Y. Kawada, H. Yuge, K. Tanaka, S. Imamura, Development of New Carbon Resources: Production of Important Chemicals from Algal Residue, Scientific reports 7 (1) (2017) 855.

[56] B. Kaps, Die grüne Plage - Algen vor der Bretagne: Gesichter Europas, available at http://www.deutschlandfunk.de/die-grune-plage-algen-vor-der-bretagne-pdf-dokument.media.4ae98011a53afecda319653f6b2afcde.pdf (accessed on August 8, 2017).

[57] U.S. Environmental Protection Agency, A Compilation of Cost Data Associated with the Impacts and Control of Nutrient Pollution, 2015.

[58] D.M. Anderson, P.M. Glibert, J.M. Burkholder, Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences, Estuaries 25 (4) (2002) 704–726.

[59] E. Kateregga, T. Sterner, Indicators for an invasive species: Water hyacinths in Lake Victoria, Ecological Indicators 7 (2) (2007) 362–370.

[60] G.M. Hallegraeff, A review of harmful algal blooms and their apparent global increase, Phycologia 32 (2) (1993) 79–99.

[61] F.J. Rahel, J.D. Olden, Assessing the effects of climate change on aquatic invasive species, Conservation biology the journal of the Society for Conservation Biology 22 (3) (2008) 521–533.

[62] X.H. Wang, L. Li, X. Bao, L.D. Zhao, Economic cost of an algae bloom cleanup in China's 2008 olympic sailing venue, Eos 90 (28) (2009) 238–239.

[63] FhG-IBP, D 2.2 Waste Profiling, 2014.

[64] European Environment Agency, Managing municipal solid waste: A review of achievements in 32 European countries, European Environment Agency, Copenhagen, 2013. ISBN 978-9-29-213355-9.

[65] L. Sørum, M.G. Grønli, J.E. Hustad, Pyrolysis characteristics and kinetics of municipal solid wastes, Fuel 80 (9) (2001) 1217–1227.

[66] R. Campuzano, S. González-Martínez, Characteristics of the organic fraction of municipal solid waste and methane production: A review, Waste management (New York, N.Y.) 54 (2016) 3–12.

[67] M.N. Rao, R. Sultana, S.H. Kota, Municipal Solid Waste, in: Solid and Hazardous Waste Management, Elsevier, 2017, pp. 3–120. ISBN 978-0-12-809734-2.

[68] European Commission, Municipal waste generation and treatment, by type of treatment method: kg per capita, available at http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&plugin=1&pcode=tsdpc240&language=en (accessed on August 10, 2017).

[69] A. Liu, F. Ren, W.Y. Lin, J.-Y. Wang, A review of municipal solid waste environmental standards with a focus on incinerator residues, International Journal of Sustainable Built Environment 4 (2) (2015) 165–188.

[70] M. El-Fadel, A.N. Findikakis, J.O. Leckie, Environmental Impacts of Solid Waste Landfilling, Journal of Environmental Management 50 (1) (1997) 1–25.

[71] VOLATILE consortium, Deliverable D1.1 State-of-the-Art of bio waste valorisation in the test regions and beyond, 2017.

[72] M. Ouadi, N. Jaeger, C. Greenhalf, J. Santos, R. Conti, A. Hornung, Thermo-Catalytic Reforming of municipal solid waste, Waste management (New York, N.Y.) (2017).

[73] S.P. Gundupalli, S. Hait, A. Thakur, A review on automated sorting of source-separated municipal solid waste for recycling, Waste management (New York, N.Y.) 60 (2017) 56–74.

[74] Umwelt Bundesamt, Referenzdokument über die Besten Verfügbaren Techniken für die Lederindustrie: mit ausgewählten Kapiteln in deutscher Übersetzung, Dessau, 2003.

[75] M. Black, M. Canova, S. Roudier, L. Delgado Sancho, S. Rydin, B.M. Scalet, Best available techniques (BAT) reference document for the tanning of hides and skins: Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control), Publications Office, Luxembourg, 2013. ISBN 978-9-27-932947-0.

[76] J. Hu, Z. Xiao, R. Zhou, W. Deng, M. Wang, S. Ma, Ecological utilization of leather tannery waste with circular economy model, Journal of Cleaner Production 19 (2-3) (2011) 221–228.

[77] V. Beghetto, L. Agostinis, R. Taffarello, R. Samiolo, Innovative Active Cross-Linking Agents for Sustainable Leather Manufacturing, in: R. Setchi, R.J. Howlett, Y. Liu, P. Theobald (Eds.), Sustainable Design and Manufacturing 2016, Springer International Publishing, Cham, 2016, pp. 149–155. ISBN 978-3-31-932098-4.

[78] J. Rajaram, B. Rajnikanth, A. Gnanamani, Preparation, Characterization and Application of Leather Particulate-Polymer Composites (LPPCs), J Polym Environ 17 (3) (2009) 181–186.

[79] M. Haubold-Rosar, J. Kern, J. Reinhold, Chancen und Risiken des Einsatzes von Biokohle und anderer "veränderter" Biomasse als Bodenhilfsstoffe oder für die C-Sequestrierung in Böden, Forschungsinst. für Bergbaufolgelandschaften, Finsterwalde, 2014.

[80] P. Quicker, K. Weber, Biokohle: Herstellung, Eigenschaften und Verwendung von Biomassekarbonisaten, Springer Fachmedien Wiesbaden, Wiesbaden, 2017. ISBN 978-3-65-803688-1.

[81] F. Alobaid, J.-P. Busch, J. Ströhle, B. Epple, Investigations on torrefied biomass for co-combustion in pulverized coal-fired furnaces: Untersuchungen torrefizierter Biomasse zur Mitverbrennung in Kohlenstaubfeuerungen, VGB PowerTech Journal 92 (11) (2012) 50–54.

[82] H.-P. Schmidt, 55 Uses of Biochar, Ithaka Journal (1) (2012) 286–289.

[83] J. Lehmann, J. Gaunt, M. Rondon, Bio-char Sequestration in Terrestrial Ecosystems – A Review, Mitig Adapt Strat Glob Change 11 (2) (2006) 403–427.

[84] A. Hornung, A. Apfelbacher, S. Sagi, Intermediate pyrolysis: A sustainable biomass-to-energy concept-biothermal valorisation of biomass (BtVB) process, Journal of Scientific and Industrial Research 70 (8) (2011) 664–667.

[85] A. Hornung, E. Schröder, Production of Biochar and Activated Carbon via Intermediate Pyrolysis - Recent Studies for Non-Woody Biomass, in: Transformation of Biomass: Theory to Practice, 2014, pp. 321–338. ISBN 978-1-11-869364-3.

[86] J. Lehmann, S. Joseph (Eds.), Biochar for environmental management: Science, technology and implementation, earthscan from Routledge, London, New York, 2015. ISBN 978-0-20-376226-4.

[87] S. Shackley, G. Ruysschaert, K. Zwart, B. Glaser (Eds.), Biochar in European soils and agriculture: Science and practice, Routledge Taylor & Francis Group Earthscan from Routledge, London, New York, 2016. ISBN 978-0-41-571166-1.

[88] Y.-s. Ok, S.M. Uchimiya, S.X. Chang, N. Bolan (Eds.), Biochar: Production, characterization, and applications, CRC Press Taylor & Francis Group, Boca Raton, London, New York, 2016. ISBN 978-1-48-224229-4.

[89] S. Joseph, C. Peacocke, J. Lehmann, P. Munroe, Developing a Biochar Classification and Test Methods, in: J. Lehmann, S. Joseph (Eds.), Biochar for environmental management: Science, technology and implementation, earthscan from Routledge, London, New York, 2015, pp. 107–126. ISBN 978-0-20-376226-4.

[90] International Biochar Initiative, Standardized Product Definition and Product Testing Guidelines for Biochar That is Used in Soil. Product Definition and Specification Standards, 2015.

[91] Hans-Peter Schmidt, European Biochar Certificate (EBC) - guidelines version 6.3, Unpublished, 2017.

[92] S. Maurer-Wohlatz, Hersteller von Pyrolyseanlagen für Pflanzenkohle (Karbonisierungsanlagen), auch mobilen Karbonisierungsanlagen sowie Hersteller von Pflanzenkohle, Pflanzenkohle-basierten Komposten und Bodenverbesserern. Stand März 2017, available at http://region-hannover.bund.net/fileadmin/bundgruppen/bcmshannover/Terra_Preta/2017/_Liste_aller_Hersteller_Pflkkohle_Substrate_und_Anlagen_25-4-2017__1_.pdf (accessed on August 22, 2017).

[93] DIN Deutsches Institut für Normung e.V., Geräte, feste Brennstoffe und Anzündhilfen zum Grillen – Teil 2: Grill-Holzkohle und Grill-Holzkohlebriketts – Anforderungen und Prüfverfahren; Deutsche Fassung EN 1860-2:2005, Beuth Verlag GmbH, Berlin 75.160.10, 2005.

[94] Food and Agriculture Organization of the United Nations, Forestry Production and Trade, available at http://www.fao.org/faostat/en/#data/FO (accessed on September 3, 2017).

[95] Statistisches Bundesamt, 227 000 Tonnen Holzkohle zum Grillen im Jahr 2015 importiert. Zahl der Woche vom 28. Juni 2016, WIESBADEN, 2016.

[96] J. Wingender, C. Achten, Aktivkohle. RÖMPP online, available at https://roempp.thieme.de/roempp4.0/do/data/RD-01-01229 (accessed on September 3, 2017).

[97] DIN Deutsches Institut für Normung e.V., Pulver-Aktivkohle, Beuth Verlag GmbH, Berlin 71.100.80, 2003.

[98] DIN Deutsches Institut für Normung e.V., Granulierte Aktivkohle Teil 1: Frische granulierte Aktivkohle, Beuth Verlag GmbH, Berlin 71.100.80, 2003.

[99] DIN Deutsches Institut für Normung e.V., Granulierte Aktivkohle Teil 2: Reaktivierte granulierte Aktivkohle, Beuth Verlag GmbH, Berlin 71.100.80, 2003.

[100] COMMISSION REGULATION (EU) No 68/2013 of 16 January 2013 on the Catalogue of feed materials, Official Journal of the European Union (56) (2013).

[101] R. Knutti, J. Rogelj, J. Sedláček, E.M. Fischer, A scientific critique of the two-degree climate change target, Nature Geosci 9 (1) (2015) 13–18.

[102] S. Nanda, S.N. Reddy, S.K. Mitra, J.A. Kozinski, The progressive routes for carbon capture and sequestration, Energy Science and Engineering 4 (2) (2016) 99–122.

[103] A. Demirbas, Biorefineries: For biomass upgrading facilities, Springer, Dordrecht, New York, 2010. ISBN 978-1-84882-721-9.

[104] O.D. Mante, F.A. Agblevor, Catalytic pyrolysis for the production of refinery-ready biocrude oils from six different biomass sources, Green Chem. 16 (6) (2014) 3364–3377.

[105] C.A. Hughey, R.P. Rodgers, A.G. Marshall, Resolution of 11 000 Compositionally Distinct Components in a Single Electrospray Ionization Fourier Transform Ion Cyclotron Resonance Mass Spectrum of Crude Oil, Anal. Chem. 74 (16) (2002) 4145–4149.

[106] S. Brysch, Biogene Kraftstoffe in Deutschland: Biodiesel, Bioethanol, Pflanzenöl und Biomass-to-Liquid im Vergleich. Zugl.: Berlin, Fachhochsch. für Technik und Wirtschaft, Diplomarbeit, 2007 u.d.T.: Brysch, Stephanie: Erfolgsbedingungen und Entwicklungsperspektiven biogener Kraftstoffe in Deutschland, Diplomica Verl., Hamburg, 2008. ISBN 978-3-83-660671-4.

[107] T. Werpy, G. Petersen, Top Value Added Chemicals from Biomass: Volume I -- Results of Screening for Potential Candidates from Sugars and Synthesis Gas.

[108] DVGW Deutscher Verein des Gas- und Wasserfaches e.V., DVGW G 260 (A) Gasbeschaffenheit, 7th ed., DVGW e.V., Bonn, 2013.

[109] DVGW Deutscher Verein des Gas- und Wasserfaches e.V., DVGW G 262 Nutzung von Gasen aus regenerativen Quellen in der öffentlichen Gasversorgung, 4th ed., DVGW e.V., Bonn, 2011.

[110] C.-J. Winter, J. Nitsch, Wasserstoff als Energieträger: Technik, Systeme, Wirtschaft, Springer Berlin Heidelberg, Berlin, Heidelberg, s.l., 1989. ISBN 978-3-64-261538-2.

[111] M. Bertau, H. Offermanns, L. Plass, F. Schmidt, H.-J. Wernicke (Eds.), Methanol: The basic chemical and energy feedstock of the future Asinger's vision today ; based on "Methanol - Chemie- und Energierohstoff: die Mobilisation der Kohle" by Friedrich Asinger published in 1986, Springer, Berlin, 2014. ISBN 978-3-64-239709-7.

[112] H. Antrekowitsch, Wasserstoff: Rahmenbedingungen, Stand der Technik, Potenzial. Initiative Risiko:dialog: Grüner Wasserstoff – Zukunft der, available at http://www.umweltbundesamt.at/fileadmin/site/aktuelles/veranstaltungen/2013/Vortrag_Antrekowitsch.pdf (accessed on September 3, 2017).

[113] Wasserstoff aus Methan ohne CO_2-Ausstoß, Erdoel Erdgas Kohle 129 (6) (2013) 235.

[114] G. Mao, X. Liu, H. Du, J. Zuo, L. Wang, Way forward for alternative energy research: A bibliometric analysis during 1994-2013, Renewable and Sustainable Energy Reviews 48 (2015) 276–286.

[115] T. Bridgwater, Thermochemical and biochemical biomass conversion activities, Biomass and Bioenergy 2 (1-6) (1992) 307–318.

[116] R.C. Saxena, D.K. Adhikari, H.B. Goyal, Biomass-based energy fuel through biochemical routes: A review, Renewable and Sustainable Energy Reviews 13 (1) (2009) 167–178.

[117] T. Bhaskar, B. Bhavya, R. Singh, D.V. Naik, A. Kumar, H.B. Goyal, Chapter 3 Thermochemical Conversion of Biomass to Biofuels, in: Biofuels Alternative Feedstocks and Conversion Processes, 2011, pp. 51–77. ISBN 978-0-12-385099-7.

[118] T. Nussbaumer, Combustion and Co-combustion of Biomass: Fundamentals, Technologies, and Primary Measures for Emission Reduction †, Energy Fuels 17 (6) (2003) 1510–1521.

[119] M. Kaltschmitt, H. Hartmann, H. Hofbauer (Eds.), Energie aus Biomasse, Springer Berlin Heidelberg, Berlin, Heidelberg, 2016. ISBN 978-3-66-247437-2.

[120] M. Lundin, M. Olofsson, G.J. Pettersson, H. Zetterlund, Environmental and economic assessment of sewage sludge handling options, Resources, Conservation and Recycling 41 (4) (2004) 255–278.

[121] Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Düngen: DüMV, in: Bundesgesetzblatt, pp. 1305–1348.

[122] P. McKendry, Energy production from biomass (part 3): Gasification technologies, Bioresource technology 83 (1) (2002) 55–63.

[123] H. Hofbauer, M. Kaltschmitt, F. Keil, U. Neuling, H. Wagner, Vergasung in der Gasatmosphäre, in: M. Kaltschmitt, H. Hartmann, H. Hofbauer (Eds.), Energie aus Biomasse, Springer Berlin Heidelberg, Berlin, Heidelberg, 2016, pp. 1059–1182. ISBN 978-3-66-247437-2.

[124] Svenskt Gastekniskt Center AB, Gasification database, available at http://www.sgc.se/ckfinder/userfiles/files/gasification_database.zip (accessed on September 7, 2017).

[125] U.S. Department of Energy, U. S. Department of Energy, National Energy Technology Laboratory's Gasification Plant Databases: United States Proposed Gasification Plant Database, available at https://www.netl.doe.gov/File%20Library/Research/Coal/energy%20systems/gasification/worldwide%20database/US-Gasification-Database.xlsx (accessed on September 7, 2017).

[126] U.S. Department of Energy, U. S. Department of Energy, National Energy Technology Laboratory's Gasification Plant Databases: World (Non-U.S.) Proposed Gasification Plant Database, available at https://www.netl.doe.gov/File%20Library/Research/Coal/energy%20systems/gasification/worldwide%20database/World-non-US-Gasification-Database.xlsx (accessed on September 7, 2017).

[127] P. Weiland, Biogas production: Current state and perspectives, Applied Microbiology and Biotechnology 85 (4) (2010) 849–860.

[128] L. Melville, A. Weger, S. Wiesgickl, M. Franke, Anaerobic Digestion, in: Transformation of Biomass: Theory to Practice, 2014, pp. 31–59. ISBN 978-1-11-869364-3.

[129] C. Dieckmann, W. Edelmann, M. Kaltschmitt, J. Liebetrau, S. Oldenburg, M. Ritzkowski, F. Scholwin, H. Sträuber, S. Weinrich, Biogaserzeugung und -nutzung, in: M. Kaltschmitt, H. Hartmann, H. Hofbauer (Eds.), Energie aus Biomasse, Springer Berlin Heidelberg, Berlin, Heidelberg, 2016, pp. 1609–1755. ISBN 978-3-66-247437-2.

[130] A. Hornung, Pyrolysis, in: Transformation of Biomass: Theory to Practice, 2014, pp. 99–112. ISBN 978-1-11-869364-3.

[131] K. Tiilikkala, L. Fagernäs, J. Tiilikkala, History and Use of Wood Pyrolysis Liquids as Biocide and Plant Protection ProductHistory and Use of Wood Pyrolysis Liquids as Biocide and Plant Protection Product, TOASJ 4 (1) (2010) 111–118.

[132] J.A. Garcia-Nunez, M.R. Pelaez-Samaniego, M.E. Garcia-Perez, I. Fonts, J. Abrego, R.J.M. Westerhof, M. Garcia-Perez, Historical Developments of Pyrolysis Reactors: A Review, Energy Fuels 31 (6) (2017) 5751–5775.

[133] W.F. Hosford (Ed.), Iron and Steel, Cambridge University Press, Cambridge, 2012. ISBN 978-1-13-908623-3.

[134] H.H. Schobert, Chemistry of fossil fuels and biofuels, Cambridge University Press, Cambridge, 2013. ISBN 978-0-52-111400-4.

[135] M. Jahirul, M. Rasul, A. Chowdhury, N. Ashwath, Biofuels Production through Biomass Pyrolysis —A Technological Review, Energies 5 (12) (2012) 4952–5001.

[136] N. Jäger, J. Neumann, A. Apfelbacher, R. Daschner, A. Hornung, Two Decades of Intermediate Pyrolysis: a Major Step Towards CHP Applicable Bio-Oils, in: Papers of the 25th European Biomass Conference: Setting the course for a biobased economy. Extracted from the Proceedings of the International Conference held in Stockholm, Sweden, Stockholm, Sweden, Florence, Italy, 2017, pp. 1194–1197. ISBN 978-88-89407-17-2.

[137] S. Binder, M. Jakuttis, A. Apfelbacher, A. Hornung (Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e. V.) WO2015158732 (A1), 2015.

[138] A. Hornung, A. Apfelbacher, M. Ouadi, J. Neumann (Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e. V.) DE102015108552 (A1), 2015.

[139] K. Jähnig, S. Krzack, Braunkohlenhochtemperatur-Verkokung(BHT), in: J. Schmalfeld (Ed.), Die Veredlung und Umwandlung von Kohle: Technologien und Projekte 1970 bis 2000 in Deutschland, DGMK, Hamburg, 2008, pp. 105–138. ISBN 978-3-93-641888-0.

[140] T.B. Reed, A. Das, Handbook of biomass downdraft gasifier engine systems - SERI/SP-271-3022, Solar Energy Research Inst., Golden, CO (USA); Sponsoring Organization: Not Available, 1988.

[141] W. Machu, Chemie und chemische Technologie, Springer Vienna, Vienna, s.l., 1949. ISBN 978-3-70-912395-9.

[142] P. Arendt, M. Hein, F. Huhn, W. Wanzl, Verkokung, in: J. Schmalfeld (Ed.), Die Veredlung und Umwandlung von Kohle: Technologien und Projekte 1970 bis 2000 in Deutschland, DGMK, Hamburg, 2008, pp. 13–156. ISBN 978-3-93-641888-0.

[143] G. Migliavacca, E. Parodi, L. Bonfanti, T. Faravelli, S. Pierucci, E. Ranzi, A general mathematical model of solid fuels pyrolysis, Energy 30 (8) (2005) 1453–1468.

[144] S. Capaccioli, TO-SYN-FUEL: Turning sewage sludge into fuels and hydrogen, available at http://www.eubce.com/fileadmin/DATA/Documents_and_Pictures/06_Conference_2017/03_Exhibition/Press_release_EUBCE_2017.pdf (accessed on August 6, 2017).

[145] Konsortium testet in Schwandorf Thermo-Katalytisches Reforming von Klärschlamm, EUWID Wasser und Abwasser 20 (14) (2017) 20.

[146] BSI - British Standards Institution, Space systems. Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment, BSI - British Standards Institution, London 49.140, 2013.

[147] F. Stenzel, M. Heberlein (Eds.), Green Carbon Upcycling mit TCR®, 2017.

[148] N. Jäger, R. Conti, J. Neumann, A. Apfelbacher, R. Daschner, S. Binder, A. Hornung, Thermo-Catalytic Reforming (TCR®): a Platform Technology to Contribute Present Energy, Environmental and Resource, in: Papers of the 24th European Biomass Conference: Setting the course for a biobased economy. Extracted from the Proceedings of the International Conference held in Amsterdam, The Netherlands, Amsterdam, Florence, Italy, 2016, pp. 990–992. ISBN 978-88-89407-165.

[149] A. Apfelbacher, A. Hornung, J. Neumann, N. Jäger, R. Conti, R. Daschner, Combined Heat and Power Generation from Solid Biomass Derived Bioliquids and Syngas, in: Papers of the 24th European Biomass Conference: Setting the course for a biobased economy. Extracted from the Proceedings of the International Conference held in Amsterdam, The Netherlands, Amsterdam, Florence, Italy, 2016, pp. 441–444. ISBN 978-88-89407-165.

[150] J. Neumann, N. Jäger, A. Apfelbacher, R. Daschner, S. Binder, A. Hornung, Upgraded biofuel from residue biomass by Thermo-Catalytic Reforming and hydrodeoxygenation, Biomass and Bioenergy 89 (2016) 91–97.

[151] Fraunhofer UMSICHT Institute Branch Sulzbach-Rosenberg, TO-SYN-FUEL: Turning sewage sludge into fuels and hydrogen, available at https://www.umsicht-suro.fraunhofer.de/en/press-and-media/press-releases/2017/TO-SYN-FUEL-Turning-sewage-sludge-into-fuels-and-hydrogen.html (accessed on December 15, 2017).

[152] D. Riedel, Kohle ist nicht gleich Kohle, Praxis der Naturwissenschaften - Chemie in der Schule 58 (1) (2009) 6–9.

[153] Statistik der Kohlenwirtschaft e.V., Internationale Klassifikation der Kohle, available at http://www.kohlenstatistik.de/files/kohlearten.pdf (accessed on June 3, 2017).

[154] BP p.l.c., BP Statistical Review of World Energy 2016, 65th ed., 2016.

[155] N. Jäger, Bewertung der Herstellung von Sekundärenergieträgern aus Braunkohle. Diplomarbeit, Aachen, 2013.

[156] S. Döring, Energieerzeugung nach Novellierung des EEG: Konsequenzen für regenerative und nicht regenerative Energieerzeugungsanlagen, Springer Vieweg, Berlin, Heidelberg, 2015. ISBN 978-3-64-255170-3.

[157] B.R. Mitchell, International historical statistics, 1750-2010, Palgrave Macmillan, Basingstoke, Hampshire, 2013. ISBN 978-1-34-967190-8.

[158] Statistik der Kohlenwirtschaft e.V., Braunkohlenförderung, 2017.

[159] Bundesverband Braunkohle, Braunkohle in Deutschland: Daten und Fakten 2016, 2017.

[160] B. Burger, Stromerzeugung in Deutschland im Jahr 2016, Freiburg, 2017.

[161] L. Kulik (Ed.), Future alignment of lignite in harmony with: Zukunftsausrichtung der rheinischen Braunkohle, GDMB-Verl; GDMB-Medienverl., Clausthal-Zellerfeld, Clausthal-Zellerfeld, 2017.

[162] R. Elsen, CtL-Annex Konzept: Wege zur wirtschaftlichen Nutzung der Braunkohle als Rohstoff für die (Petro-)chemische Industrie, in: Symposium: CO_2-arme stoffliche Nutzung der Braunkohle in Deutschland: Eine Perspektive mit Zukunft!, Freiberg, 11.03.2015.

[163] B. Meyer, Stoffliche Nutzung von Braunkohle: zur Zukungt der chemischen Industrie in Nordrhein-Westfalen im Hinblick auf nachhaltige Rohstoffbasen, Produkte und Produktionsverfahren. Gutachten für den Landtag Nordrhein-Westfalen; Enquetekomission II, 2015.

[164] D. Thamm, Stoffliche Nutzung der Braunkohle bei ROMONTA, in: Symposium: CO_2-arme stoffliche Nutzung der Braunkohle in Deutschland: Eine Perspektive mit Zukunft!, Freiberg, 11.03.2015.

[165] F.H. Franke, M. Mohtadi, B. Böhnke, Einsatz von Braunkohlen-Herdofenkoks als Adsorptionskoks zur Reinigung kommunaler Abwässer, Westdeutscher Verlag, Opladen, 1977. ISBN 978-3-53-102678-7.

[166] C. Voss, Zur Bestimmung der Adsorptionsgleichgewichte von Gasen und Dämpfen an Herdofenkoks. Zugl.: Cottbus, Techn. Univ., Diss., 2000, Shaker, Aachen. ISBN 978-3-82-658352-0.

[167] R.D. Stoll (Ed.), Der Braunkohlentagebau: Bedeutung, Planung, Betrieb, Technik, Umwelt; mit 60 Tabellen, 1st ed., Springer, Berlin, Heidelberg, 2009. ISBN 978-3-54-078400-5.

[168] J. Ciuches, R. Ostertag, RWE power and Siemens implement IEC 61850 in power plant auxiliary power supply, VGB PowerTech 88 (4) (2008).

[169] M. Kaltschmitt, H. Hartmann, H. Hofbauer (Eds.), Energie aus Biomasse: Grundlagen, Techniken und Verfahren, 2nd ed., Springer, Berlin, 2009. ISBN 978-3-54-085095-3.

[170] International Renewable Energy Agency, Renewable Energy Cost Analysis: Biomass for Power Generation: Biomass for Power Generation, 1st ed., 2012.

[171] D. Reichel, M. Klinger, S. Krzack, B. Meyer, Comparative investigations into pyrolysis of biomass and brown coal - Material balance and heat requirement in correlation with fuel properties, Erdoel Erdgas Kohle 127 (2) (2011) 78–83.

[172] R. Reimert, W. Köppel, C. Higman, Vergasung: Ähnlichkeiten und Unterschiede beim Einsatz von Kohle und von Biomasse, Chemie Ingenieur Technik 77 (8) (2005) 1169–1170.

[173] G. Birkenroth, E. Rammler (Bilkenroth, Georg; Rammler, Erich) DD 000000004630 A1, 1952.

[174] L. Walz, H. Bockhorn, D. Reichert, J. Steinbrueck, M. Rossbach, D. Eyler, J. Steinbrück (ENBW AG [DE]) EP2390301 (A2), 2011.

[175] F.R. Sierp, A. Splittgerber, H. Holthöfer, B. Bleyer, W. Diemair, Wasser und Luft: Erster Teil Technologie des Wassers, Springer, Berlin, Heidelberg, 1939. ISBN 978-3-64-298220-0.

[176] F. Trippe, Techno-ökonomische Bewertung alternativer Verfahrenskonfigurationen zur Herstellung von Biomass-to-Liquid (BtL) Kraftstoffen und Chemikalien. Zugl.: Karlsruhe, KIT, Diss., 2013, KIT Scientific Publishing; Technische Informationsbibliothek u. Universitätsbibliothek, Karlsruhe, Hannover, 2013. ISBN 978-3-73-150031-5.

[177] H. Suopajärvi, A. Kemppainen, J. Haapakangas, T. Fabritius, Extensive review of the opportunities to use biomass-based fuels in iron and steelmaking processes, Journal of Cleaner Production 148 (2017) 709–734.

[178] P. Modde, S. Krzack, Festbettruckvergasung von Salzkohlen: Charakterisierung und Verbreitung von Salzkohlen, in: J. Schmalfeld (Ed.), Die Veredlung und Umwandlung von Kohle: Technologien und Projekte 1970 bis 2000 in Deutschland, DGMK, Hamburg, 2008, pp. 322–336. ISBN 978-3-93-641888-0.

[179] H. Hartmann, Brennstoffzusammensetzung und -eigenschaften, in: M. Kaltschmitt, H. Hartmann, H. Hofbauer (Eds.), Energie aus Biomasse: Grundlagen, Techniken und Verfahren, 2nd ed., Springer, Berlin, 2009, pp. 248–286. ISBN 978-3-54-085095-3.

[180] A. Kalde, T. Willms, T. Demus, T. Echterhof, H. Pfeifer, Determining the Potential of Biogenic Calcium- and Carbon-Rich Residues as Substitutes in the Electric Steelmaking, in: Papers of the 24th European Biomass Conference: Setting the course for a biobased economy. Extracted from the Proceedings of the International Conference held in Amsterdam, The Netherlands, Amsterdam, Florence, Italy, 2016, pp. 1642–1649. ISBN 978-88-89407-165.

[181] H.-J. Klutz, C. Moser, D. Block, Stand der Entwicklung der Wirbelschicht-Trocknung mit interner Stand der Entwicklung der Wirbelschicht-Trocknung mit interner Abwärmenutzung (WTA) für Braunkohle bei der RWE Power AG, in: M. Beckmann, A. Hurtado (Eds.), Kraftwerkstechnik: Sichere und nachhaltige Energieversorgung - Band 2 ; [Beiträge des 42. Kraftwerkstechnischen Kolloquiums 12. und 13. Oktober 2010 in Dresden], TK-Verl. Thomé-Kozmiensky, Neuruppin, 2010, pp. 427–444. ISBN 978-3-93-531757-3.

[182] N.S. Dong, Utilisation of low rank coals, CCC/182, 2011.

[183] D. Vamvuka, E. Kakaras, E. Kastanaki, G. Panagiotis, Pyrolysis characteristics and kinetics of biomass residuals mixtures with lignite, Fuel 82 (15-17) (2003) 1949–1960.

[184] T. Sonobe, N. Worasuwannarak, S. Pipatmanomai, Synergies in co-pyrolysis of Thai lignite and corncob, Fuel Processing Technology 89 (12) (2008) 1371–1378.

[185] S. Krerkkaiwan, C. Fushimi, A. Tsutsumi, P. Kuchonthara, Synergetic effect during co-pyrolysis/gasification of biomass and sub-bituminous coal, Fuel Processing Technology 115 (2013) 11–18.

[186] X. Yang, C. Yuan, J. Xu, W. Zhang, Co-pyrolysis of Chinese lignite and biomass in a vacuum reactor, Bioresource technology 173 (2014) 1–5.

[187] A. Tchapda, S. Pisupati, A Review of Thermal Co-Conversion of Coal and Biomass/Waste, Energies 7 (3) (2014) 1098–1148.

[188] C. Quan, N. Gao, Copyrolysis of Biomass and Coal: A Review of Effects of Copyrolysis Parameters, Product Properties, and Synergistic Mechanisms, BioMed research international 2016 (2016).

[189] E. Kastanaki, D. Vamvuka, A comparative reactivity and kinetic study on the combustion of coal–biomass char blends, Fuel 85 (9) (2006) 1186–1193.

[190] S. Li, X. Chen, A. Liu, L. Wang, G. Yu, Co-pyrolysis characteristic of biomass and bituminous coal, Bioresource technology 179 (2015) 414–420.

[191] BSI - British Standards Institution, Gas meters - Diaphragm gas meters, BSI - British Standards Institution 91.140.40, 2017.

[192] Dr. Födisch Umweltmesstechnik AG, MGA 12 Product information, 3rd ed., 2016.

[193] DIN Deutsches Institut für Normung e.V., Referenzzustand, Normzustand, Normvolumen; Begriffe und Werte, Beuth Verlag GmbH, Berlin 17.060, 1990.

[194] BSI - British Standards Institution, Natural gas. Standard reference conditions, BSI - British Standards Institution, London 75.060, 1997.

[195] Union Instruments GmbH, CWD 2005: Betriebsanweisung. Verbrennungskalorimeter zur Messung von brennbaren Gasen.

[196] BSI - British Standards Institution, Solid biofuels — Determination of moisture content — Oven dry method, BSI - British Standards Institution 75.160.40, 2017.

[197] BSI - British Standards Institution, Solid recovered fuels —Determination of moisture content using the oven dry method Part 3: Moisture in general analysis sample, BSI - British Standards Institution 75.160.10, 2011.

[198] BSI - British Standards Institution, The analysis and testing of coal and coke. Total moisture of coal, BSI - British Standards Institution 75.160, 1973.

[199] ASTM International, Test Method for Moisture Analysis of Particulate Wood Fuels, ASTM International, West Conshohocken, PA, 2013 (accessed on December 8, 2017).

[200] ASTM International, Test Method for Determination of Ash Content of Particulate Wood Fuels, ASTM International, West Conshohocken, PA, 2013 (accessed on December 8, 2017).

[201] BSI - British Standards Institution, Methods for analysis and testing of coal and coke. Determination of ash content, BSI - British Standards Institution 73.040, 1998.

[202] BSI - British Standards Institution, Solid recovered fuels — Determination of ash content, BSI - British Standards Institution 75.160.10, 2011.

[203] BSI - British Standards Institution, Solid biofuels — Determination of ash content, BSI - British Standards Institution 75.160.40, 2015.

[204] BSI - British Standards Institution, Methods of test for petroleum and its products. BS 2000-4: Determination of ash, BSI - British Standards Institution, London 75.080, 2001.

[205] BSI - British Standards Institution, Solid biofuels. Determination of calorific value, BSI - British Standards Institution, London 27.190, 2017.

[206] DIN Deutsches Institut für Normung e.V., Guide to the expression of uncertainty in measurement, 1st ed., Beuth Verlag, Berlin 17.020, 2008.

[207] BSI - British Standards Institution, Guide to statistical interpretation of data. Routine analysis of quantitative data, BSI - British Standards Institution, London, 1991.

[208] W. Wanzl, H.F. Werner, Umwandlung von Kohle, Kohleprodukten und organischen Restoffen im Drehrohr, in: J. Schmalfeld (Ed.), Die Veredlung und Umwandlung von Kohle: Technologien und Projekte 1970 bis 2000 in Deutschland, DGMK, Hamburg, 2008, pp. 281–298. ISBN 978-3-93-641888-0.

[209] M. Bachhiesl, J. Tauschitz, H. Zefferer, G. Zellinger, Mitverbrennung von Sekundärbrennstoffen: Untersuchungen zur thermischen Verwertung von Biomasse und heizwertreichen Abfallfraktionen als Sekundärbrennstoffe in Wärmekraftwerken, 2001.

[210] M.B. Folgueras, R.M. Díaz, J. Xiberta, Pyrolysis of blends of different types of sewage sludge with one bituminous coal, Energy 30 (7) (2005) 1079–1091.

[211] L. Shi, Q. Liu, X. Guo, W. Wu, Z. Liu, Pyrolysis behavior and bonding information of coal: A TGA study, Fuel Processing Technology 108 (2013) 125–132.

[212] N. Gao, J. Li, B. Qi, A. Li, Y. Duan, Z. Wang, Thermal analysis and products distribution of dried sewage sludge pyrolysis, Journal of Analytical and Applied Pyrolysis 105 (2014) 43–48.

[213] F. Ferrara, A. Orsini, A. Plaisant, A. Pettinau, Pyrolysis of coal, biomass and their blends: Performance assessment by thermogravimetric analysis, Bioresource technology 171 (2014) 433–441.

[214] P. Konstantin, Praxisbuch Energiewirtschaft, Springer Berlin Heidelberg, Berlin, Heidelberg, 2017. ISBN 978-3-66-249822-4.

[215] A.K. Dixit, Investment under uncertainty, Princeton Univ. Press, Princeton, NJ, 1994. ISBN 978-0-69-103410-2.

[216] W. Breuer, Investition I: Entscheidungen bei Sicherheit, 4th ed., Gabler Verlag / Springer Fachmedien Wiesbaden GmbH Wiesbaden, Wiesbaden, 2012. ISBN 978-3-83-492367-7.

[217] Verein Deutscher Ingenieure, Betriebswirtschaftliche Berechnungen für Investitionsgüter und Anlagen Economy calculation systems for capital goods and plants, Beuth Verlag, Berlin 03.100.01, 91.140.10, 2012.

[218] U.S. Energy Information Administration, Levelized Cost of Electricity and Levelized Avoided Cost of Electricity Methodology Supplement, Washington, 2013.

[219] L. Schneider, Stromgestehungskosten von Großkraftwerken: [Entwicklungen im Spannungsfeld von Liberalisierung und Ökosteuern], Öko-Inst, Freiburg (Breisgau), 1998. ISBN 978-3-928433-84-6.

[220] T. Bruckner, H. Chum, A. Jäger-Waldau, Å. Killingtveit, L. Gutiérrez-Negrín, J. Nyboer, W. Musial, A. Verbruggen, R. Wiser, D. Arvizu, R. Bain, J.-M. Devernay, D. Gwinner, G. Hiriart, J. Huckerby, A. Kumar, J. Moreira, S. Schlömer, Recent Renewable Energy Cost and Performance Parameters, in: O. Edenhofer (Ed.), Renewable energy sources and climate change mitigation: Special report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2012, pp. 1001–1022. ISBN 978-1-13-915115-3.

[221] C. Kost, J.N. Mayer, J. Thomsen, N. Hartmann, C. Senkpiel, S. Philipps, S. Nold, S. Lude, N. Saad, T. Schlegl, Levelized cost of electricity - renewable energy technologies: November 2013, Fraunhofer ISE, Freiburg/Brsg, Freiburg, 2013.

[222] U.S. Energy Information Administration, Assessing the Economic Value of New Utility - Scale Electricity Generation Projects. Workshop Discussion Paper: LCOE and LACE, Washington, 2013.

[223] U.S. Energy Information Administration, Levelized cost and levelized avoided cost of new generation resources in the Annual Energy Outlook 2014. 2019 Levelized Costs AEO 2014, Washington, 2014.

[224] Nuclear Energy Agency, Organisation for Economic Co-operation and Development, International Energy Agency, Projected Costs of Generating Electricity. 2015 Edition, OECD Publishing, Paris, 2015. ISBN 978-9-26-424440-5.

[225] K. Rohrig, P. Hochloff, U. Holzhammer, F. Schlögl, W. Lehnert, K. Rehfeldt, J. Dieckmann, L. Hofmann, Flexible Stromproduktion aus Biogas und Biomethan: Die Einführung einer Kapazitätskomponente als Förderinstrument, 2011.

[226] V. Tcherveniachki, Kapitalgesellschaften und Private Equity Fonds: Unternehmenskauf durch Leveraged Buyout. Zugl.: Saarbrücken, Univ., Diss, 2007 u.d.T.: Tcherveniachki, Vassil: Leveraged Buyouts deutscher Kapitalgesellschaften durch ausländische Private Equity Fonds, Schmidt, Berlin, 2007. ISBN 978-3-50-310351-5.

[227] Bundesministerium für Finanzen, Die wichtigsten Steuern im internationalen Vergleich 2016: Ausgabe 2017, Berlin, 2017.

[228] Eurostat, HICP (2015 = 100) - annual data (average index and rate of change) (prc_hicp_aind), available at http://ec.europa.eu/eurostat/web/hicp/data/database# (accessed on October 2, 2017).

[229] International Renewable Energy Agency, Renewable Energy Cost Analysis: Biomass for Power Generation, 2012.

[230] D. Hogg, Costs for Municipal Waste Management in the EU: Final Report to Directorate General Environment, European Commission, 2002.

[231] Intergovernmental Panel on Climate Change, Database on greenhouse gas emission factors (IPCC-EFDB), available at http://www.ipcc-nggip.iges.or.jp/EFDB/find_ef_s1.php (accessed on December 9, 2017).

[232] Thomson Reuters, Thomson Reuters Datastream. data retrieved August 2017 (accessed on December 9, 2017).

[233] M. Bakhat, K. Würzburg, Price relationships of crude oil and food commodities. WP FA06/2013, 2013.

[234] Amna, Awad Abdel Hameed, M.A. Fatimah, The Impact of Petroleum Prices on Vegetable Oils Prices: Evidence from Co-integration Tests, in: Global changes: Corporate responsibility proceedings of the 3rd International Borneo Business Conference (IBBC) 2008, Universiti Malaysia Sabah, Kota Kinabalu, Sabah, Malaysia December 15-17, 2008, School of Business & Economics, Universiti Malaysia Sabah, Kota Kinabalu, 2008.

[235] United States Environmental Protection Agency, LEED® CHP Calculator Version 1.0, available at https://www.epa.gov/chp/chp-documents-and-tools (accessed on October 4, 2017).

[236] OECD Publishing, OECD, World Energy Outlook 2016, 1st ed., Organisation for Economic Co-operation and Development OECD, Paris, 2016. ISBN 978-9-26-426494-6.

[237] Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare- Energien-Gesetz - EEG 2017): EEG 2017, in: Bundesgesetzblatt, pp. 2532–2539.

[238] S. Sircar, T.C. Golden, Purification of Hydrogen by Pressure Swing Adsorption, Separation Science and Technology 35 (5) (2000) 667–687.

[239] Sonnenerde Gerald Dunst Kulturerden GmbH, Preisliste 2017: Gültig bis 31.12.2017, available at http://www.sonnenerde.at/preisliste.1223.html (accessed on December 23, 2017).

[240] H. Suopajärvi, T. Fabritius, Towards More Sustainable Ironmaking—An Analysis of Energy Wood Availability in Finland and the Economics of Charcoal Production, Sustainability 5 (3) (2013) 1188–1207.

[241] U. Bossel, Wasserstoff löst keine Energieprobleme, Technikfolgenabschätzung, Theorie und Praxis 15 (1) (2006) 27–33.

[242] G. Maisonnier, J. Perrin, R. Steinberger-Wilckens, S.C. Trümper, PART II: Industrial surplus hydrogen and markets and production: "European Hydrogen Infrastructure Atlas" and "Industrial Excess Hydrogen Analysis", 2007.

[243] B. Wiechmann, C. Dienemann, C. Kabbe, S. Brandt, I. Vogel, A. Roskosch, Klärschlammentsorgung in der Bundesrepublik Deutschland, 01th ed., Umweltbundesamt, Dessau-Roßlau.

[244] T. Norgate, D. Langberg, Environmental and economic aspects of charcoal use in steelmaking, ISIJ International 49 (4) (2009) 587–595.

[245] S. Kühner, Feedstock costs: Biomass based energy intermediates boosting biofuel production. Bioboost, 2013.

[246] Schmid Heizung - Sanitär, Allgemeines zu Torfpellets, available at http://www.schmid-oberried.de/pages/bilder/Torpellets.pdf (accessed on September 7, 2017).

[247] K. Görner, D.U. Sauer, Konventionelle Kraftwerke: Technologiesteckbrief zur Analyse „Flexibilitätskonzepte für die Stromversorgung 2050“. Schriftreihe Energiesysteme der Zukunft, 2016.

[248] D. Drosihn, P. Icha, G. Kuhs, F. Sandau, J. Pabst, B. Hain, M. Nowakowski, D. Pfeiffer, K. Juhrich, B. Bünger, L. Köder, B. Lünenbürger, D. Osiek, A. Matthey, G. Penn-Bressel, W. Straff, D. Plaß, D. Wintermeyer, R. Wolter, C. Baumgarten, S. Grimm, I. Kirst, J. Frauenstein, M. Langner, R. Beckers, D. Lewandrowski, C. Gibis, J. Weiß, S. Schlömer, Daten und Fakten zu Braun- und Steinkohlen: Status quo und Perspektiven, Dessau-Roßlau, 2017.

[249] J. Neumann, A. Hornung, A. Apfelbacher, R. Daschner, Pyrolysis of Residual Biomass via Thermo-Catalytic Reforming - Experimental Investigation of Sewage Sludge, in: Papers of the 25th European Biomass Conference: Setting the course for a biobased economy. Extracted from the Proceedings of the International Conference held in Stockholm, Sweden, Stockholm, Sweden, Florence, Italy, 2017, pp. 949–951. ISBN 978-88-89407-17-2.

[250] K.T. Volkmann, Chemische Technologie des Leuchtgases, Springer Berlin Heidelberg, Berlin, Heidelberg, 1915. ISBN 978-3-66-234658-7.

[251] D. Mohan, C.U. Pittman, P.H. Steele, Pyrolysis of wood/biomass for bio-oil: A critical review, Energy Fuels 20 (3) (2006) 848–889.

[252] D.L. Klass, Biomass for renewable energy, fuels, and chemicals, Academic Press, San Diego, 1998. ISBN 978-0-12-410950-6.

[253] H. McLaughlin, P.S. Anderson, F.E. Shields, T.B. Reed, All Biochars are not Created Equal and How to Tell them Apart, 2009.

[254] S.P. Veetil, L.-C. Pasquier, J.-F. Blais, E. Cecchi, S. Kentish, G. Mercier, Direct gas-solid carbonation of serpentinite residues in the absence and presence of water vapor: a feasibility study for carbon dioxide sequestration, Environmental science and pollution research international 22 (17) (2015) 13486–13495.

[255] M.E. Kirby, A. Hornung, M. Ouadi, M.K. Theodorou, The role of thermo-catalytic reforming for energy recovery from food and drink supply chain wastes, Energy Procedia 123 (2017) 15–21.

[256] E. Ranzi, A. Cuoci, T. Faravelli, A. Frassoldati, G. Migliavacca, S. Pierucci, S. Sommariva, Chemical Kinetics of Biomass Pyrolysis, Energy Fuels 22 (6) (2008) 4292–4300.

[257] Will Vaughan, Ternary plots, available at http://wvaughan.org/ternaryplots.html (accessed on July 26, 2017).

[258] B.G. Miller, Introduction to Coal Utilization Technologies, in: Clean Coal Engineering Technology, Elsevier, 2017, pp. 147–229. ISBN 978-0-12-811365-3.

[259] P. Meshram, B.K. Purohit, M.K. Sinha, S.K. Sahu, B.D. Pandey, Demineralization of low grade coal – A review, Renewable and Sustainable Energy Reviews 41 (2015) 745–761.

[260] J.G. Speight, The chemistry and technology of petroleum, 4th ed., CRC Press/Taylor & Francis, Boca Raton, 2007. ISBN 978-0-84-939067-8.

[261] R.G. Boundy, S.W. Diegel, L.L. Wright, S.C. Davis, Biomass Energy Data Book: Edition 4, 2011.

[262] J. Neumann, A. Hornung, N. Schmitt, N. Jäger, R. Conti, A. Apfelbacher, R. Daschner, Hydrodeoxygenation of Bio-Oils from Thermo-Catalytic Reforming - High Energy Efficient Route to Renewable Gasoline and Diesel, in: Papers of the 24th European Biomass Conference: Setting the course for a biobased economy. Extracted from the Proceedings of the International Conference held in Amsterdam, The Netherlands, Amsterdam, Florence, Italy, 2016, pp. 1259–1261. ISBN 978-88-89407-165.

[263] G.H.C. Prado, Y. Rao, A. de Klerk, Nitrogen Removal from Oil: A Review, Energy Fuels 31 (1) (2017) 14–36.

[264] B. Riediger, Die Verarbeitung des Erdöles, Springer, Berlin, Heidelberg, 1971. ISBN 978-3-64-252166-9.

[265] G.W. Young, Fluid catalytic cracker catalyst design for nitrogen tolerance, J. Phys. Chem. 90 (20) (1986) 4894–4900.

[266] J. Speight, The Desulfurization of Heavy Oils and Residua, CRC Press, 1999. ISBN 978-0-82-478921-3.

[267] L.C. Castañeda, J.A.D. Muñoz, J. Ancheyta, Comparison of approaches to determine hydrogen consumption during catalytic hydrotreating of oil fractions, Fuel 90 (12) (2011) 3593–3601.

[268] A.R. Hansmeier, G.W. Meindersma, A.B. de Haan, Desulfurization and denitrogenation of gasoline and diesel fuels by means of ionic liquids, Green Chem. 13 (7) (2011) 1907.

[269] Y. Sano, K.-H. Choi, Y. Korai, I. Mochida, Selection and Further Activation of Activated Carbons for Removal of Nitrogen Species in Gas Oil as a Pretreatment for Its Deep Hydrodesulfurization, Energy Fuels 18 (3) (2004) 644–651.

[270] J.S. Ball, M.L. Whisman, W.J. Wenger, Nitrogen Content of Crude Petroleums, Ind. Eng. Chem. 43 (11) (1951) 2577–2581.

[271] K. Altfeld, P. Schley, Development of natural gas qualities in Europe, GWF, Gas - Erdgas 152 (9) (2011) 544–550.

[272] N. Jäger, R. Conti, J. Neumann, A. Apfelbacher, R. Daschner, S. Binder, A. Hornung, Thermo-Catalytic Reforming (TCR®): a Platform Technology to Contribute Present Energy, Environmental and Resource Challenges: Slide presentation, Amsterdam, 2016.

[273] C. Torri, D. Fabbri, Biochar enables anaerobic digestion of aqueous phase from intermediate pyrolysis of biomass, Bioresource technology 172 (2014) 335–341.

[274] T. Hübner, J. Mumme, Integration of pyrolysis and anaerobic digestion--use of aqueous liquor from digestate pyrolysis for biogas production, Bioresource technology 183 (2015) 86–92.

[275] D. Weismann, M. Lohse, Sulfid-Praxishandbuch der Abwassertechnik: [biogene Korrosion, Geruch, Gefahr verhindern und Kosten beherrschen], Vulkan-Verl., Essen, 2007. ISBN 978-3-80-272845-7.

[276] A. Steinel, A. Margane, Best Management Practice Guideline for Wastewater Facilities in Karstic Areas of Lebanon: with Special Respect to the Protection of Ground- and Surface water, 2011.

[277] A.K. Coker, Mechanical Separations, in: Ludwig's Applied Process Design for Chemical and Petrochemical Plants, Elsevier, 2007, pp. 371–443. ISBN 978-0-75-067766-0.

[278] Deutscher Bundestag, Antwort der Bundesregierung: auf die Kleine Anfrage der Abgeordneten Oliver Krischer, Annalena Baerbock, Sylvia Kotting-Uhl, weiterer Abgeordneter und der Fraktion BÜNDNIS 90/DIE GRÜNEN – Drucksache 18/8282 –. Kosten, Nutzen und klimapolitische Auswirkungen der stofflichen Nutzung der, Berlin, 2016.

Note citation format:

[X].
The reference X refers to the preceding sentence only.

.[X]
The reference X refers to the preceding paragraph.

APPENDICES

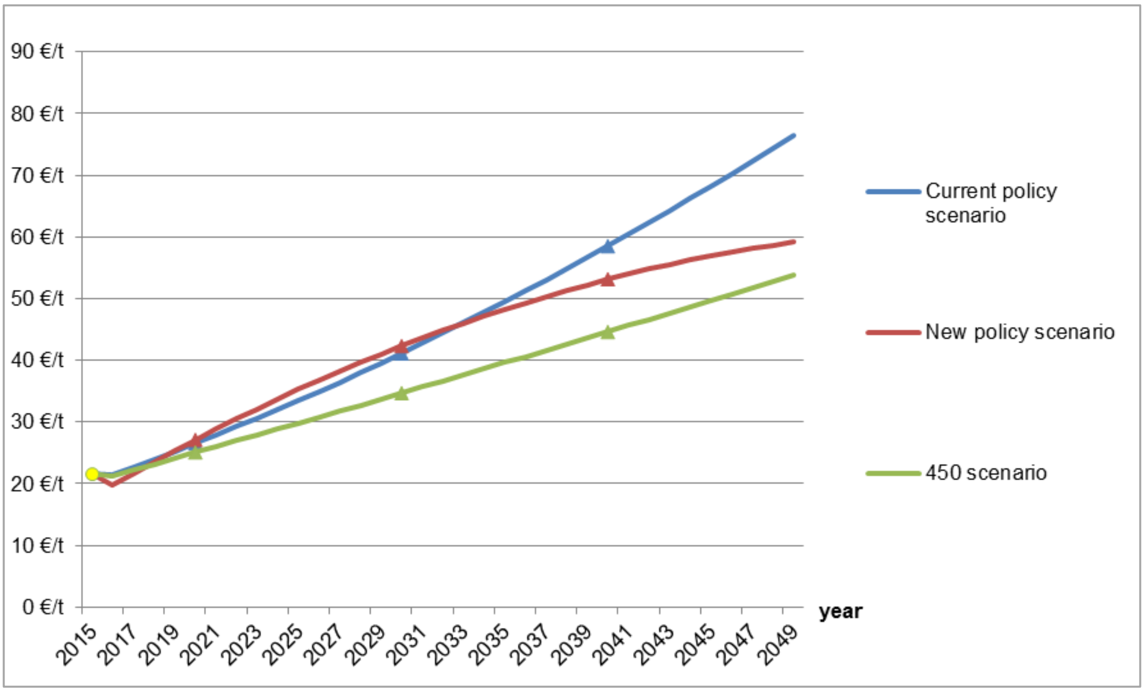

Figure 48: Extrapolated **natural gas price** scenarios based on the 2016 World Energy Outlook (WEO) on a nominal basis; colored triangles are the values given in the scenarios

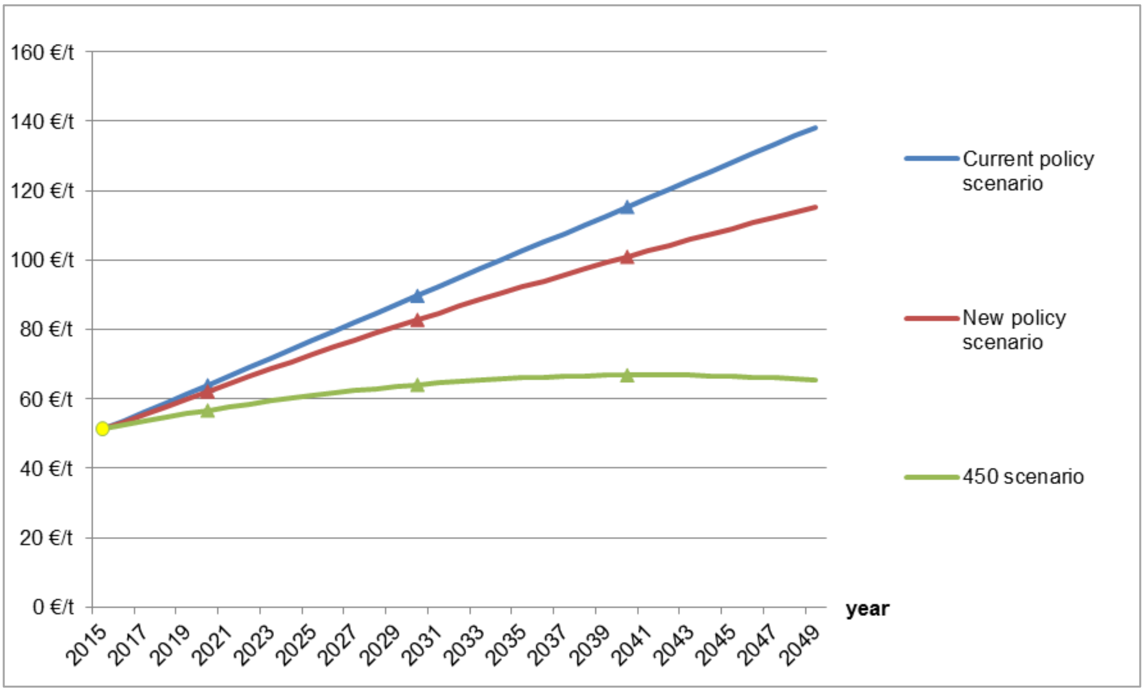

Figure 49: Extrapolated **steam coal price** scenarios based on the 2016 World Energy Outlook (WEO) on a nominal basis; colored triangles are the values given in the scenarios

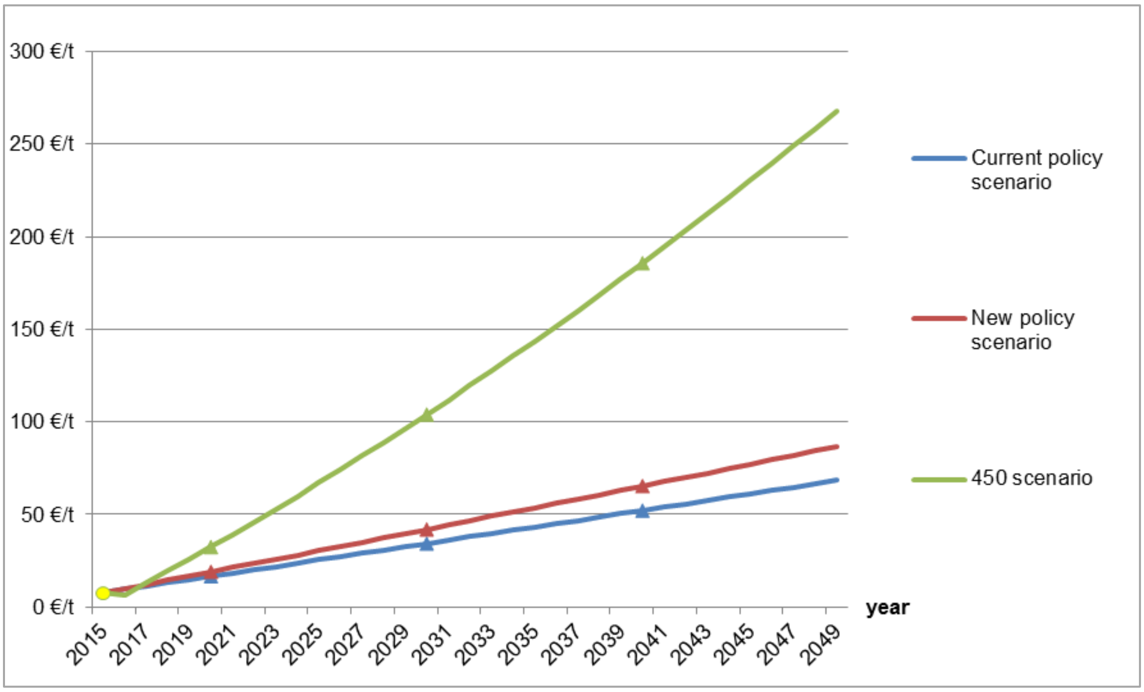

Figure 50: Extrapolated **CO_2 price** scenarios based on the 2016 World Energy Outlook (WEO) on a nominal basis; colored triangles are the values given in the scenarios

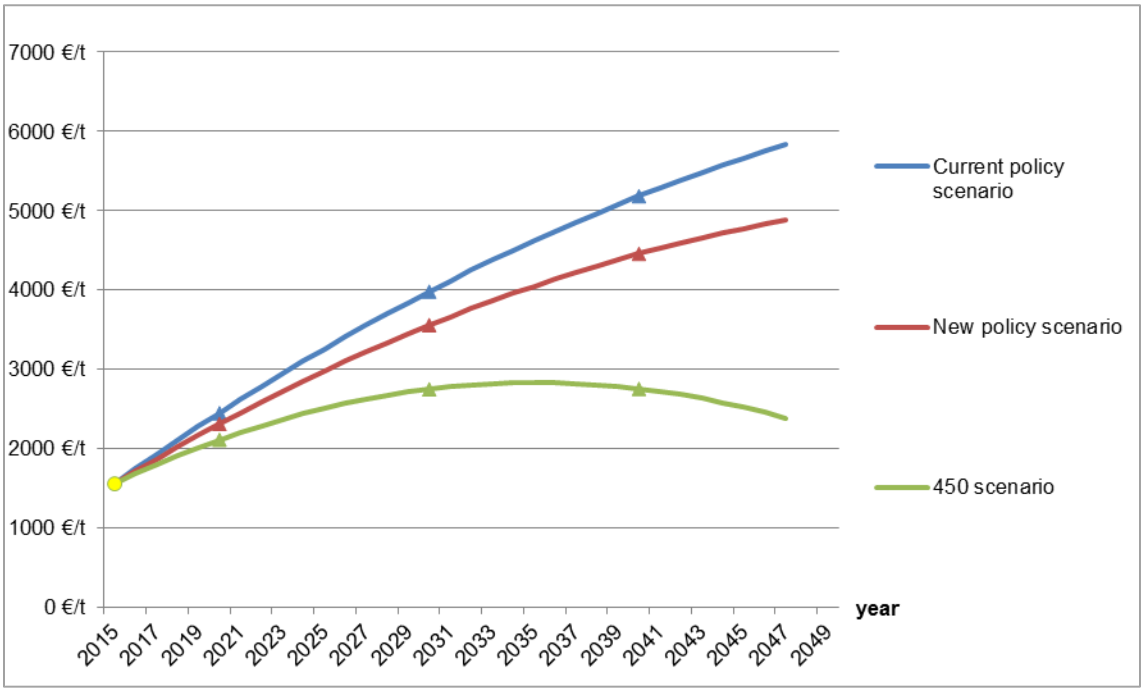

Figure 51: Extrapolated **biodiesel price** scenarios correlated to fossil crude oil price scenarios (2016 World Energy Outlook) on a nominal basis; colored triangles are the values given in the scenarios

Table 50: EDXRF analysis of algae feedstock and carbonisates

	Algae #2		Algae #4		Algae #6		Algae #8	
	Feed-stock	Carbo-nisate	Feed-stock	Carbo-nisate	Feed-stock	Carbo-nisate	Feed-stock	Carbo-nisate
	[wt%]	[wt%]	[wt%]	[wt%]	[wt%]	[wt%]	[wt%]	[wt%]
Na	3.069	10.212	3.486	8.843	1.878	8.842	2.533	9.353
Mg	0.244	0.671	0.235	0.602	0.143	0.590	0.296	0.620
Al	≈0.000	≈0.000	≈0.000	0.470	≈0.000	≈0.000	0.359	≈0.000
Si	0.317	0.630	0.323	0.599	0.150	0.449	0.134	0.258
P	0.186	0.406	0.178	0.398	0.150	0.360	0.202	0.372
S	0.691	1.476	0.854	1.751	0.485	1.630	0.733	1.666
Cl	4.823	18.112	5.344	14.360	2.959	14.051	5.295	14.960
K	3.617	12.195	3.779	9.669	2.419	9.773	4.454	11.777
Ca	1.562	4.834	1.385	3.447	1.043	4.074	0.878	3.115
Ti	0.00029	0.00158	0.00180	0.00954	0.00004	≈0.00000	≈0.00000	≈0.00000
Cr	≈0.00000	0.00004	0.00035	0.00069	0.00057	0.00180	≈0.00000	≈0.00000
Mn	0.00209	0.00294	0.00044	0.00199	0.00208	0.00416	≈0.00000	0.00077
Fe	0.102	0.220	0.095	0.228	0.065	0.217	0.022	0.105
Cu	0.02955	0.07204	0.02640	0.05058	0.01901	0.05200	0.02664	0.07201
Zn	0.00743	0.01654	0.01204	0.03653	0.00842	0.01908	0.00465	0.02102
As	0.00411	0.00552	0.00418	0.00457	0.00349	0.00401	0.00534	0.00966
Br	0.08743	0.26100	0.09534	0.22000	0.06599	0.21000	0.10500	0.24400
Sr	0.061	0.188	0.055	0.128	0.044	0.132	0.060	0.144
Y	≈0.00000	0.00062	≈0.00000	0.00060	≈0.00000	≈0.00000	≈0.00000	0.00068
Zr	0.00032	0.00125	0.00034	0.00136	0.00017	0.00083	0.00010	0.00056
I	0.446	1.568	0.434	≈0.000	0.357	0.945	0.461	1.056
Pr	0.00198	0.00685	0.00170	0.00462	0.00083	0.00378	0.00123	0.00481
Eu	0.00021	0.00560	0.00082	0.00456	0.00002	0.00450	0.00072	0.00430
Os	0.00007	0.00003	0.00012	0.00004	0.00006	0.00014	≈0.00000	≈0.00000
Pb	0.00005	0.00008	0.00019	0.00010	0.00011	0.00016	0.00003	0.00012
Sn	0.00416	≈0.00000	0.00356	0.00516	0.00306	0.00452	0.00350	≈0.00000
Re	0.00016	0.00061	≈0.00000	≈0.00000	≈0.00000	≈0.00000	0.00017	≈0.00000
C	35.95	21.86	32.85	27.88	40.17	37.19	33.39	30.34
H	3.95	0.06	4.42	0.11	5.15	0.06	4.50	0.07
N	1.70	0.71	1.44	0.85	1.19	1.08	1.67	1.04
O	43.14	26.49	44.97	29.16	43.64	20.30	44.87	24.78
∑	**100.000**	**100.002**	**100.000**	**98.836**	**0.9994895**	**99.999**	**100.001**	**100.010**

Table 51: EDXRF analysis of ISS feedstock, carbonisates, oil, and aqueous phase

	ISS			
	Feedstock	**Carbonisate**	**Oil**	**Aqueous phase**
	[wt%]	**[wt%]**	**[wt%]**	**[wt%]**
Na	0.811000	1.203000	≈0.000000	≈0.000000
Mg	1.368000	2.074000	0.270000	0.055450
Al	0.366000	0.607000	0.084280	≈0.000000
Si	1.136000	1.849000	0.308000	0.073200
P	0.338000	0.519000	0.086780	0.071720
Cl	0.336000	0.496000	0.024840	0.016010
K	0.016670	0.030580	0.017460	0.004360
Ca	6.091000	10.425000	0.422000	0.225000
Ti	0.050240	0.085420	0.017630	0.003370
V	0.005790	0.009780	0.000320	≈0.000000
Cr	**9.095000**	**15.104000**	**0.314000**	**0.058590**
Mn	0.125000	0.211000	0.002520	≈0.000000
Fe	7.389000	12.197000	0.233000	0.038380
Cu	0.007150	0.013730	0.004340	0.001940
Zn	0.015750	0.028140	0.001940	0.000730
As	≈0.000000	≈0.000000	0.000030	≈0.000000
Br	≈0.000000	≈0.000000	0.000110	≈0.000000
Rb	0.000990	0.000360	≈0.000000	≈0.000000
Sr	0.004200	0.006830	≈0.000000	≈0.000000
Sn	0.003700	0.004510	0.003920	0.004810
Se	≈0.000000	0.000190	≈0.000000	≈0.000000
Zr	0.000800	0.001160	≈0.000000	≈0.000000
La	0.010780	0.018920	≈0.000000	≈0.000000
Re	≈0.000000	≈0.000000	0.000260	0.000160
Hg	0.008180	0.001890	≈0.000000	≈0.000000
Os	≈0.000000	≈0.000000	≈0.000000	≈0.000000
Te	≈0.000000	≈0.000000	≈0.000000	0.005960
Pb	≈0.000000	≈0.000000	0.000810	≈0.000000
Bi	0.008710	0.003010	0.002840	≈0.000000
C	20.60	13.70	83.23	2.99
H	3.40	0.10	7.63	11.33
N	1.70	0.60	4.34	4.89
S	3.01	5.30	0.80	1.97
O	44.10	35.41	2.21	78.26
∑	**99.999960**	**100.001520**	**100.000080**	**99.999680**

Table 52: Matrix of the considered utilization pathways of RSS; Comparison of mLR and LC (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

RSS			Gate fee	mid						low						high					
			WEO (2016)	Current Policies		New Policies		450		Current Policies		New Policies		450		Current Policies		New Policies		450	
Heating	TCR product | Downstream processes		Utilization	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR
Natural gas	carbonisate		BASE*	210.7	306	214.3	296	223	267.4	297.7	356.7	301.3	346.7	309.9	318.2	138.3	263.6	141.9	253.6	150.5	225.1
			CCS	210.7	304.3	214.3	300.9	223	316.3	297.7	355.1	301.3	351.7	309.9	367.1	138.3	262	141.9	258.6	150.5	274
Steam coal	carbonisate		BASE*	182.9	289.6	185.6	279.2	215.2	262.9	269.8	340.4	272.5	329.9	302.2	313.7	110.4	247.3	113.1	236.8	142.8	220.6
Feedstock	carbonisate		BASE*	104.1	243.6	104.1	231.6	104.1	198	218.1	310.3	218.1	298.2	218.1	264.6	9.02	188.1	9.02	176	9.02	142.5
			CCS	104.1	242	104.1	236.5	104.1	246.8	218.1	308.7	218.1	303.1	218.1	313.5	9.02	186.5	9.02	181	9.02	191.3
Product carbonisate	carbonisate		BASE*	299	455.1	299.4	433.6	304.2	374.3	483.6	526.4	484.1	504.9	488.9	445.6	145.1	395.7	145.6	374.1	150.4	314.8
Product syngas	carbonisate		BASE*	185.7	234.7	185.7	219.6	185.7	187.2	306.9	285.5	306.9	270.3	306.9	237.9	84.68	192.5	84.68	177.3	84.68	144.9
			CCS	185.7	232.5	185.7	226.5	185.7	255.3	306.9	283.2	306.9	277.2	306.9	306	84.68	190.2	84.68	184.2	84.68	213
Natural gas	gas		BASE**	210.7	306	214.3	300.9	223	316.3	297.7	356.7	301.3	351.7	309.9	367.1	138.3	263.6	141.9	258.6	150.5	274
		PSA	H_2+off gas	242.4	323.2	246	319.7	254.6	333.9	329.4	374.3	333	370.8	341.6	385	170	280.6	173.6	277.1	182.2	291.3
Steam coal	gas		BASE**	182.9	289.6	185.6	279.2	215.2	262.9	269.8	340.4	272.5	329.9	302.2	313.7	110.4	247.3	113.1	236.8	142.8	220.6
		PSA	H_2+off gas	214.5	306.8	217.2	297.8	246.9	280.5	301.5	357.9	304.2	348.9	333.9	331.6	142.1	264.2	144.8	255.2	174.5	237.9
Feedstock	gas		BASE**	104.1	243.6	104.1	236.5	104.1	246.8	218.1	310.3	218.1	303.1	218.1	313.5	9.02	188.1	9.02	181	9.02	191.3
		PSA	H_2+off gas	135.8	260.5	135.8	254.9	135.8	264	249.8	327.5	249.8	321.9	249.8	331.1	40.7	204.6	40.7	199	40.7	208.2
Product carbonisate	gas		BASE**	299	455.1	299.4	433.6	304.2	374.3	483.6	526.4	484.1	504.9	488.9	445.6	145.1	395.7	145.6	374.1	150.4	314.8
		PSA	H_2+off gas	366.3	467.5	366.7	449.1	371.5	387.4	550.9	541.9	551.3	523.5	556.1	461.8	212.4	405.5	212.9	387.2	217.7	325.4
Natural gas	gas/oil		BASE**	210.7	306	214.3	300.9	223	316.3	297.7	356.7	301.3	351.7	309.9	367.1	138.3	263.6	141.9	258.6	150.5	274
		CHP	only gas (no consumers for heat)	226.7	271.3	230.6	267.6	239.7	297.4	319.2	325.5	323	321.8	332.1	351.6	149.7	226.1	153.5	222.4	162.7	252.2
			only gas (40 €/MWh for heat)	169.9	231.9	173.7	228.1	182.8	258	262.3	286.1	266.1	282.3	275.3	312.2	92.83	186.7	96.65	183	105.8	212.8
			gas+oil (no consumers for heat)	356.7	277.4	350	276.7	339.7	311.6	447.7	322.9	441	322.2	430.8	357.1	280.8	239.5	274.1	238.9	263.9	273.7
			gas+oil (40 €/MWh for heat)	267.3	227.9	260.6	227.3	250.4	262.1	358.4	273.4	351.6	272.7	341.4	307.6	191.4	190	184.7	189.4	174.5	224.2
Steam coal	gas/oil		BASE**	182.9	289.6	185.6	279.2	215.2	262.9	269.8	340.4	272.5	329.9	302.2	313.7	110.4	247.3	113.1	236.8	142.8	220.6
		CHP	only gas (no consumers for heat)	197.1	253.9	200	244.4	231.5	240.7	289.5	308.1	292.4	298.6	324	294.9	120.1	208.7	123	199.2	154.5	195.5
			only gas (40 €/MWh for heat)	140.2	214.5	143.1	204.9	174.6	201.2	232.6	268.7	235.5	259.1	267.1	255.4	63.19	133.8	66.07	124.3	97.62	156.1
			gas+oil (no consumers for heat)	327.5	262.8	319.8	256.5	331.7	256.4	418.5	308.3	410.9	302	422.7	301.9	251.6	224.9	243.9	218.6	255.8	218.5
			gas+oil (40 €/MWh for heat)	238.1	213.3	230.5	207	242.3	206.9	329.2	258.8	321.5	252.5	333.4	252.4	162.2	175.5	154.6	169.1	166.4	169
Feedstock	gas/oil		BASE**	104.1	243.6	104.1	236.5	104.1	246.8	218.1	310.3	218.1	303.1	218.1	313.5	9.02	188.1	9.02	181	9.02	191.3
		CHP	only gas (no consumers for heat)	113.4	204.8	113.4	198.8	113.4	223.3	234.6	275.9	234.6	269.9	234.6	294.4	12.34	145.6	12.34	139.6	12.34	164.1
			only gas (40 €/MWh for heat)	56.47	129.9	56.47	123.9	56.47	148.4	177.7	236.5	177.7	230.5	177.7	255	-44.6	106.1	-44.6	100.1	-44.6	124.6
			gas+oil (no consumers for heat)	245	221.6	234.5	219.1	215.3	249.4	364.4	281.3	353.9	278.7	334.7	309.1	145.5	171.9	135	169.4	115.7	199.7
			gas+oil (40 €/MWh for heat)	155.6	172.2	145.1	169.6	125.9	199.9	275.1	231.8	264.6	229.2	245.3	259.6	56.1	122.4	45.61	119.9	26.38	150.2
Product carbonisate	gas/oil		BASE**	299	455.1	299.4	433.6	304.2	374.3	483.6	526.4	484.1	504.9	488.9	445.6	145.1	395.7	145.6	374.1	150.4	314.8
		CHP	only gas (no consumers for heat)	348.2	395.3	348.7	374.3	354.2	337.3	559.3	477.8	559.8	456.8	565.3	419.8	172.3	326.5	172.8	305.5	178.3	268.5
			only gas (40 €/MWh for heat)	218.3	356.4	218.8	335.4	224.3	298.4	429.4	439	429.9	418	435.4	381	42.33	287.6	42.83	266.6	48.33	229.6
			gas+oil (no consumers for heat)	635.4	152.2	612.4	152.2	574.6	152.2	839.5	152.2	816.5	152.2	778.7	152.2	465.3	152.2	442.3	152.2	404.5	152.2
			gas+oil (40 €/MWh for heat)	435.1	152.2	412.1	152.2	374.3	152.2	639.2	152.2	616.2	152.2	578.4	152.2	265	152.2	242	152.2	204.2	152.2
Natural gas	gas/oil		BASE**	210.7	306	214.3	300.9	223	316.3	297.7	356.7	301.3	351.7	309.9	367.1	138.3	263.6	141.9	258.6	150.5	274
		CHP/PSA	only gas (no consumers for heat)	261.4	313.4	265.6	310.6	275.6	337.8	363	374.8	367.2	372	377.3	399.2	176.7	262.2	180.9	259.5	190.9	286.7
			only gas (40 €/MWh for heat)	217.3	279.5	221.5	276.7	231.5	303.9	318.9	340.9	323.1	338.1	333.2	365.3	132.6	228.3	136.8	225.6	146.8	252.8
			gas+oil (no consumers for heat)	398.1	316.9	391	317	380.2	347.7	494.1	365.8	487	365.9	476.3	396.6	318	276.2	310.9	276.3	300.1	307
			gas+oil (40 €/MWh for heat)	320.9	271.3	313.8	271.4	303	302.1	417	320.2	409.9	320.3	399.1	351	240.8	230.6	233.7	230.7	222.9	261.4
Steam coal	gas/oil		BASE**	182.9	289.6	185.6	279.2	215.2	262.9	269.8	340.4	272.5	329.9	302.2	313.7	110.4	247.3	113.1	236.8	142.8	220.6
		CHP/PSA	only gas (no consumers for heat)	228.8	293.7	231.9	284.5	266.6	275.3	330.4	355.1	333.6	345.9	368.3	336.7	144.1	242.6	147.2	233.4	181.9	224.2
			only gas (40 €/MWh for heat)	184.7	259.8	187.8	250.6	222.5	241.4	286.3	321.2	289.5	312	324.2	302.8	99.95	208.7	103.1	199.5	137.8	190.3
			gas+oil (no consumers for heat)	367.2	301.2	359.2	295.4	371.7	289.4	463.3	350.1	455.2	344.2	467.8	338.2	287.2	260.5	279.1	254.6	291.6	248.6
			gas+oil (40 €/MWh for heat)	290.1	255.7	282	249.8	294.5	243.8	386.1	304.5	378.1	298.7	390.6	292.7	210	214.9	201.9	209.1	214.4	203.1
Feedstock	gas/oil		BASE**	104.1	243.6	104.1	236.5	104.1	246.8	218.1	310.3	218.1	303.1	218.1	313.5	9.02	188.1	9.02	181	9.02	191.3
		CHP/PSA	only gas (no consumers for heat)	136.7	238.1	136.7	232.8	136.7	253.9	270	318.6	270	313.3	270	334.4	25.56	171	25.56	165.7	25.56	186.9
			only gas (40 €/MWh for heat)	92.56	204.2	92.56	198.9	92.56	220	225.9	284.7	225.9	279.4	225.9	300.5	-18.5	137.1	-18.5	131.8	-18.5	153
			gas+oil (no consumers for heat)	280.2	257	269.1	255	248.8	280.9	406.2	321.1	395.1	319.2	374.9	345	175.2	203.5	164.1	201.6	143.8	227.5
			gas+oil (40 €/MWh for heat)	203	211.4	191.9	209.5	171.7	235.3	329	275.5	318	273.6	297.7	299.4	97.99	158	86.91	156.1	66.63	181.9
Product carbonisate	gas/oil		BASE**	299	455.1	299.4	433.6	304.2	374.3	483.6	526.4	484.1	504.9	488.9	445.6	145.1	395.7	145.6	374.1	150.4	314.8
		CHP/PSA	only gas (no consumers for heat)	470.7	534.9	471.3	511.7	478.2	450.3	737	652.1	737.6	628.9	744.5	567.5	248.7	437.2	249.4	414.1	256.3	352.7
			only gas (40 €/MWh for heat)	355.1	489.4	355.7	466.2	362.7	404.8	621.4	606.6	622.1	583.4	629	522	133.2	391.7	133.8	368.6	140.8	307.2
			gas+oil (no consumers for heat)	772.1	194	746	196.5	703.2	182.9	1003	199.4	977.2	201.9	934.4	188.2	579.4	189.6	553.3	192.1	510.5	178.4
			gas+oil (40 €/MWh for heat)	586.3	191.4	560.2	193.9	517.4	180.2	817.6	196.8	791.5	199.3	748.7	185.6	393.6	186.9	367.5	189.4	324.7	175.7

Table 53: Matrix of the considered utilization pathways of RSS; Difference mLR-LC as an indicator of profitability (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

RSS			Gate fee	mid			low			high		
			WEO scenarios (2016)	Current Policies	New Policies	450	Current Policies	New Policies	450	Current Policies	New Policies	450
Heating	TCR product | Downstream processes		Utilization	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC
Natural gas	carbonisate		BASE*	95.253	81.62	44.46	59.03	45.45	8.28	125.34	111.76	74.6
			CCS	93.59	86.58	93.32	57.43	50.4	57.15	123.74	116.72	123.46
Steam coal	carbonisate		BASE*	106.79	93.59	47.67	70.62	57.42	11.49	136.94	123.74	77.81
Feedstock	carbonisate		BASE*	139.56	127.48	93.91	92.12	80.04	46.46	179.1	167.02	133.45
			CCS	137.97	132.44	142.77	90.52	84.99	95.32	177.5	171.98	182.31
Product carbonisate	carbonisate		BASE*	156.13	134.14	70.01	42.82	20.83	-43.3	**250.56**	**228.56**	164.43
Product syngas	carbonisate		BASE*	49.05	33.92	1.49	-21.44	-36.57	-69	107.79	92.66	60.23
			CCS	46.83	40.83	69.61	-23.67	-29.67	-0.89	105.56	99.56	128.34
Natural gas	gas		BASE**	95.253	86.58	93.32	59.03	50.4	57.15	125.34	116.72	123.46
		PSA	H_2+off gas sell	80.77	73.68	79.27	44.92	37.84	43.43	110.64	103.56	109.16
Steam coal	gas		BASE**	106.79	93.59	47.67	70.62	57.42	11.49	136.94	123.74	77.81
		PSA	H_2+off gas sell	92.27	80.59	33.59	56.42	44.74	-2.26	122.14	110.46	63.47
Feedstock	gas		BASE**	139.56	132.44	142.77	92.12	84.99	95.32	179.1	171.98	182.31
		PSA	H_2+off gas sell	124.75	119.14	128.29	77.72	72.12	81.27	163.93	158.33	167.48
Product carbonisate	gas		BASE**	156.13	134.14	70.01	42.82	20.83	-43.3	**250.56**	**228.56**	164.43
		PSA	H_2+off gas sell	101.2	82.44	15.88	-9.02	-27.78	-94.34	193.06	174.3	107.74
Natural gas	gas/oil		BASE**	95.253	86.58	93.32	59.03	50.4	57.15	125.34	116.72	123.46
		CHP	only gas (no consumers for heat)	44.54	36.99	57.67	6.32	-1.23	19.45	76.4	68.84	89.53
			only gas (40 €/MWh for heat)	62	54.45	75.13	23.78	16.22	36.91	93.85	86.3	106.98
			gas+oil (no consumers for heat)	-79.25	-73.21	-28.15	-124.83	-118.78	-73.73	-41.27	-35.22	9.83
			gas+oil (40 €/MWh for heat)	-39.38	-33.34	11.72	-84.96	-78.91	-33.86	-1.41	4.65	49.69
Steam coal	gas/oil		BASE**	106.79	93.59	47.67	70.62	57.42	11.49	136.94	123.74	77.81
		CHP	only gas (no consumers for heat)	56.8	44.38	9.12	18.58	6.16	-29.1	88.65	76.22	40.98
			only gas (40 €/MWh for heat)	74.25	61.83	26.59	36.03	23.61	-11.63	70.61	58.18	58.43
			gas+oil (no consumers for heat)	-64.63	-63.3	-75.27	-110.21	-108.88	-120.85	-26.66	-25.33	-37.3
			gas+oil (40 €/MWh for heat)	-24.77	-23.44	-35.41	-70.34	-69.02	-80.99	13.21	14.54	2.57
Feedstock	gas/oil		BASE**	139.56	132.44	142.77	92.12	84.99	95.32	179.1	171.98	182.31
		CHP	only gas (no consumers for heat)	91.43	85.46	109.93	41.3	35.32	59.79	133.21	127.24	151.71
			only gas (40 €/MWh for heat)	73.39	67.42	91.89	58.75	52.78	77.25	150.67	144.69	169.16
			gas+oil (no consumers for heat)	-23.34	-15.41	34.16	-83.13	-75.19	-25.62	26.48	34.41	83.98
			gas+oil (40 €/MWh for heat)	16.53	24.46	74.03	-43.26	-35.32	14.24	66.34	74.27	123.84
Product carbonisate	gas/oil		BASE**	156.13	134.14	70.01	42.82	20.83	-43.3	**250.56**	**228.56**	164.43
		CHP	only gas (no consumers for heat)	47.06	25.57	-16.92	-81.51	-103	-145.49	154.21	132.72	90.22
			only gas (40 €/MWh for heat)	138.16	116.67	74.17	9.59	-11.91	-54.41	**245.29**	223.8	181.31
			gas+oil (no consumers for heat)	-483.17	-460.13	-422.36	-687.25	-664.21	-626.43	-313.1	-290.07	-252.29
			gas+oil (40 €/MWh for heat)	-282.87	-259.83	-222.05	-486.95	-463.91	-426.13	-112.8	-89.77	-51.99
Natural gas	gas/oil		BASE**	95.253	86.58	93.32	59.03	50.4	57.15	125.34	116.72	123.46
		CHP/PSA	only gas (no consumers for heat)	52.03	45.05	62.21	11.75	4.78	21.94	85.59	78.62	95.77
			only gas (40 €/MWh for heat)	62.23	55.25	72.41	21.96	14.98	32.14	95.79	88.82	105.97
			gas+oil (no consumers for heat)	-81.14	-73.93	-32.5	-128.35	-121.14	-79.71	-41.81	-34.6	6.84
			gas+oil (40 €/MWh for heat)	-49.53	-42.34	-0.89	-96.74	-89.53	-48.1	-10.2	-2.99	38.45
Steam coal	gas/oil		BASE**	106.79	93.59	47.67	70.62	57.42	11.49	136.94	123.74	77.81
		CHP/PSA	only gas (no consumers for heat)	64.95	52.59	8.67	24.67	12.32	-31.61	98.51	86.15	42.23
			only gas (40 €/MWh for heat)	75.15	62.79	18.87	34.88	22.52	-21.41	108.71	96.36	52.44
			gas+oil (no consumers for heat)	-66.01	-63.79	-82.31	-113.21	-111	-129.51	-26.66	-24.45	-42.96
			gas+oil (40 €/MWh for heat)	-34.4	-32.18	-50.7	-81.6	-79.39	-97.9	4.95	7.16	-11.35
Feedstock	gas/oil		BASE**	139.56	132.44	142.77	92.12	84.99	95.32	179.1	171.98	182.31
		CHP/PSA	only gas (no consumers for heat)	101.44	96.13	117.28	48.61	43.3	64.45	145.46	140.15	161.3
			only gas (40 €/MWh for heat)	111.64	106.33	127.48	58.81	53.5	74.65	155.66	150.35	171.5
			gas+oil (no consumers for heat)	-23.23	-14.08	32.04	-85.16	-75.99	-29.88	28.36	37.53	83.64
			gas+oil (40 €/MWh for heat)	8.37	17.53	63.65	-53.55	-44.38	1.73	59.97	69.14	115.24
Product carbonisate	gas/oil		BASE**	156.13	134.14	70.01	42.82	20.83	-43.3	**250.56**	**228.56**	164.43
		CHP/PSA	only gas (no consumers for heat)	64.23	40.45	-27.92	-84.91	-108.68	-177.05	188.51	164.72	96.35
			only gas (40 €/MWh for heat)	134.27	110.49	42.13	-14.86	-38.64	-107.01	**258.55**	**234.76**	166.41
			gas+oil (no consumers for heat)	-578.04	-549.44	-520.3	-803.89	-775.29	-746.16	-389.83	-361.23	-332.1
			gas+oil (40 €/MWh for heat)	-394.96	-366.36	-337.23	-620.81	-592.21	-563.08	-206.75	-178.15	-149.02

Table 54: Matrix of the considered utilization pathways of DSS. Comparison of mLR and LC (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

DSS			Gate fee	mid						low						high					
			WEO (2016)	Current Policies		New Policies		450		Current Policies		New Policies		450		Current Policies		New Policies		450	
Heating	TCR product | Downstream processes		Utilization	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR
Natural gas	carbonisate		BASE*	199.2	242.5	202.6	235.3	210.7	214.9	313.4	182.9	313.8	171.2	314.9	148.2	130.7	205.2	134.1	198	142.2	177.6
			CCS	199.2	241.8	202.6	239.7	210.7	254	313.4	181.8	313.8	177.7	314.9	205.3	130.7	204.5	134.1	202.4	142.2	216.7
Steam coal	carbonisate		BASE*	172.8	228.2	175.4	220.4	203.5	210.9	255	272.9	257.6	265.2	285.6	255.7	104.3	190.9	106.9	183.1	135	173.6
Feedstock	carbonisate		BASE*	89.53	182.8	89.53	173.7	89.53	148.9	204.5	245.4	204.5	236.3	204.5	211.5	-6.31	130.6	-6.31	121.5	-6.31	96.68
			CCS	89.53	182.1	89.53	178.1	89.53	188	204.5	244.7	204.5	240.7	204.5	250.6	-6.31	129.9	-6.31	125.9	-6.31	135.8
Product carbonisate	carbonisate		BASE*	341.8	405.6	343.4	387.4	360.3	342	541.8	477.1	543.4	459	560.3	413.6	175.2	345.9	176.7	327.8	193.6	282.4
Product syngas	carbonisate		BASE*	193.4	154	193.8	142.3	194.9	119.3	313.4	182.9	313.8	171.2	314.9	148.2	93.35	129.9	93.79	118.3	94.85	95.25
			CCS	193.4	152.9	193.8	148.8	194.9	176.4	313.4	181.8	313.8	177.7	314.9	205.3	93.35	128.8	93.79	124.7	94.85	152.4
Natural gas	gas		BASE**	199.2	242.5	202.6	239.7	210.7	254	313.4	182.9	313.8	177.7	314.9	205.3	130.7	205.2	134.1	202.4	142.2	216.7
		PSA	H_2+off gas	227.9	284	231.3	283.3	239.4	290.5	310.1	329.3	313.5	328.5	321.6	335.8	159.4	246.3	162.8	245.6	170.9	252.8
Steam coal	gas		BASE**	172.8	228.2	175.4	220.4	203.5	210.9	255	272.9	257.6	265.2	285.6	255.7	104.3	190.9	106.9	183.1	135	173.6
		PSA	H_2+off gas	201.5	269.5	204.1	263.9	232.2	247.4	283.7	314.8	286.3	309.1	314.3	292.6	133	231.8	135.6	226.2	163.7	209.7
Feedstock	gas		BASE**	89.53	182.8	89.53	178.1	89.53	188	204.5	245.4	204.5	240.7	204.5	250.6	-6.31	130.6	-6.31	125.9	-6.31	135.8
		PSA	H_2+off gas	118.2	223.7	118.2	221.1	118.2	223.8	233.2	287	233.2	284.3	233.2	287.1	22.39	170.9	22.39	168.3	22.39	171.1
Product carbonisate	gas		BASE**	341.8	405.6	343.4	387.4	360.3	342	541.8	477.1	543.4	459	560.3	413.6	175.2	345.9	176.7	327.8	193.6	282.4
		PSA	H_2+off gas	411.7	483.5	413.2	470.4	430.1	408.2	611.7	561.9	613.2	548.8	630.1	486.6	245	418.1	246.5	405.1	263.4	342.9
Natural gas	gas/oil		BASE**	199.2	242.5	202.6	239.7	210.7	254	313.4	182.9	313.8	177.7	314.9	205.3	130.7	205.2	134.1	202.4	142.2	216.7
		CHP	only gas (no consumers for heat)	207.8	215.4	211.5	213.5	220.3	238.5	296.4	264	300.1	262.1	308.9	287.1	134	174.9	137.7	173	146.5	198
			only gas (40 €/MWh for heat)	167.5	185.6	171.1	183.7	179.9	208.7	256.1	234.2	259.7	232.2	268.5	257.3	93.63	145.1	97.3	143.2	106.1	168.2
			gas+oil (no consumers for heat)	308.3	225.3	303.6	225.1	297.1	252.7	395.3	267.7	390.7	267.4	384.2	295	235.7	190.1	231	189.8	224.5	217.4
			gas+oil (40 €/MWh for heat)	241.4	183.6	236.8	183.4	230.3	211	328.5	225.9	323.8	225.7	317.3	253.3	168.9	148.4	164.2	148.1	157.7	175.7
Steam coal	gas/oil		BASE**	172.8	228.2	175.4	220.4	203.5	210.9	255	272.9	257.6	265.2	285.6	255.7	104.3	190.9	106.9	183.1	135	173.6
		CHP	only gas (no consumers for heat)	179.4	199.8	182.2	192.6	212.4	192	268	248.4	270.8	241.2	301	240.6	105.6	159.3	108.4	152.1	138.6	151.6
			only gas (40 €/MWh for heat)	139.1	170	141.8	162.8	172.1	162.2	227.7	218.6	230.4	211.4	260.7	210.8	65.22	129.5	67.97	122.3	98.22	121.7
			gas+oil (no consumers for heat)	280.3	211.8	274.8	206.4	289.4	207.5	367.4	254.1	361.9	248.7	376.4	249.8	207.8	176.5	202.2	171.1	216.8	172.3
			gas+oil (40 €/MWh for heat)	213.5	170	208	164.7	222.5	165.8	300.6	212.4	295	207	309.6	208.1	140.9	134.8	135.4	129.4	150	130.5
Feedstock	gas/oil		BASE**	89.53	182.8	89.53	178.1	89.53	188	204.5	245.4	204.5	240.7	204.5	250.6	-6.31	130.6	-6.31	125.9	-6.31	135.8
		CHP	only gas (no consumers for heat)	89.63	150.6	89.63	146.6	89.63	166.9	213.6	218.5	213.6	214.6	213.6	234.9	-13.7	93.9	-13.7	89.96	-13.7	110.2
			only gas (40 €/MWh for heat)	49.25	120.7	49.25	116.8	49.25	137.1	173.2	188.7	173.2	184.8	173.2	205	-54.1	64.09	-54.1	60.15	-54.1	80.39
			gas+oil (no consumers for heat)	192.1	168.9	183.8	166.9	168.7	190.3	313.9	228.1	305.7	226.1	290.5	249.5	90.57	119.5	82.3	117.5	67.16	141
			gas+oil (40 €/MWh for heat)	125.3	127.2	117	125.2	101.9	148.6	247.1	186.4	238.8	184.4	223.7	207.8	23.73	77.8	15.47	75.8	0.33	99.24
Product carbonisate	gas/oil		BASE**	341.8	405.6	343.4	387.4	360.3	342	541.8	477.1	543.4	459	560.3	413.6	175.2	345.9	176.7	327.8	193.6	282.4
		CHP	only gas (no consumers for heat)	396	376	397.9	357.1	418.4	328.4	638.7	465	640.6	446.1	661.1	417.4	193.7	301.9	195.6	283	216.1	254.3
			only gas (40 €/MWh for heat)	285.4	344.7	287.3	325.8	307.8	297.1	528.1	433.7	530	414.8	550.5	386.1	83.11	270.6	84.98	251.7	105.5	223
			gas+oil (no consumers for heat)	654.4	115.4	634.2	115.4	613.5	115.4	886	115.4	865.8	115.4	845.1	115.4	461.4	115.4	441.2	115.4	420.5	115.4
			gas+oil (40 €/MWh for heat)	476.7	115.4	456.5	115.4	435.8	115.4	708.2	115.4	688	115.4	667.3	115.4	283.7	115.4	263.5	115.4	242.8	115.4
Natural gas	gas/oil		BASE**	199.2	242.5	202.6	239.7	210.7	254	313.4	182.9	313.8	177.7	314.9	205.3	130.7	205.2	134.1	202.4	142.2	216.7
		CHP/PSA	only gas (no consumers for heat)	246.3	275.9	250.3	276.1	259.8	293.4	342.4	330.5	346.4	330.7	355.9	347.9	166.2	230.5	170.2	230.7	179.7	247.9
			only gas (40 €/MWh for heat)	209.9	246.3	213.8	246.5	223.4	263.8	306	300.9	310	301.1	319.5	318.3	129.8	200.9	133.7	201.1	143.3	218.3
			gas+oil (no consumers for heat)	344.8	281.7	339.9	283.3	333	302.2	436.6	327.5	431.7	329.1	424.8	348	268.3	243.6	263.4	245.1	256.5	264
			gas+oil (40 €/MWh for heat)	281.4	239.4	276.5	240.9	269.6	259.8	373.2	285.2	368.3	286.7	361.4	305.6	204.9	201.2	200	202.7	193.1	221.6
Steam coal	gas/oil		BASE**	172.8	228.2	175.4	220.4	203.5	210.9	255	272.9	257.6	265.2	285.6	255.7	104.3	190.9	106.9	183.1	135	173.6
		CHP/PSA	only gas (no consumers for heat)	215.5	258.4	218.5	252.9	251.3	242.8	311.6	313	314.6	307.4	347.4	297.3	135.3	213	138.3	207.4	171.2	197.3
			only gas (40 €/MWh for heat)	179	228.8	182	223.3	214.8	213.2	275.2	283.4	278.2	277.9	311	267.8	98.91	183.4	101.9	177.9	134.7	167.7
			gas+oil (no consumers for heat)	315.4	267	309.5	263.2	324.9	254.4	407.1	312.9	401.3	309	416.7	300.2	238.9	228.9	233	225	248.4	216.2
			gas+oil (40 €/MWh for heat)	251.9	224.7	246.1	220.8	261.5	212	343.7	270.5	337.9	266.6	353.2	257.8	175.5	186.5	169.6	182.6	185	173.9
Feedstock	gas/oil		BASE**	89.53	182.8	89.53	178.1	89.53	188	204.5	245.4	204.5	240.7	204.5	250.6	-6.31	130.6	-6.31	125.9	-6.31	135.8
		CHP/PSA	only gas (no consumers for heat)	118	203.1	118	201.1	118	212.9	252.5	279.5	252.5	277.4	252.5	289.3	5.92	139.5	5.92	137.5	5.92	149.3
			only gas (40 €/MWh for heat)	81.59	173.5	81.59	171.5	81.59	183.4	216.1	249.9	216.1	247.8	216.1	259.7	-30.5	109.9	-30.5	107.9	-30.5	119.7
			gas+oil (no consumers for heat)	222.3	220.6	213.6	220.2	197.7	234.6	350.8	284.7	342	284.3	326.1	298.7	115.3	167.2	106.6	166.8	90.63	181.2
			gas+oil (40 €/MWh for heat)	158.9	178.2	150.2	177.9	134.2	192.2	287.3	242.3	278.6	242	262.7	256.3	51.9	124.8	43.18	124.5	27.22	138.8
Product carbonisate	gas/oil		BASE**	341.8	405.6	343.4	387.4	360.3	342	541.8	477.1	543.4	459	560.3	413.6	175.2	345.9	176.7	327.8	193.6	282.4
		CHP/PSA	only gas (no consumers for heat)	571	610	573.4	593.1	599.5	526.1	880.1	746.4	882.5	729.6	908.6	662.5	313.5	496.3	315.8	479.5	342	412.4
			only gas (40 €/MWh for heat)	453.9	563.6	456.3	546.8	482.4	479.7	763	700	765.4	683.2	791.5	616.1	196.3	449.9	198.7	433.1	224.8	366
			gas+oil (no consumers for heat)	815.9	233.1	792.5	238.6	768.5	210	1084	245.7	1061	251.2	1037	222.6	592.4	222.6	569	228.1	545	199.5
			gas+oil (40 €/MWh for heat)	630.6	227.4	607.2	232.9	583.3	204.3	898.8	240	875.4	245.5	851.5	216.9	407.1	216.9	383.7	222.4	359.8	193.8

Table 55: Matrix of the considered utilization pathways of DSS; Difference mLR-LC as an indicator of profitability (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

DSS			Gate fee	mid			low			high		
			WEO (2016)	Current Policies	New Policies	450	Current Policies	New Policies	450	Current Policies	New Policies	450
Heating	TCR product | Downstream processes		Utilization	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC
Natural gas	carbonisate		BASE*	43.32	32.66	4.14	-130.46	-142.56	-166.63	74.51	63.85	35.34
			CCS	42.58	37.07	43.26	-131.54	-136.12	-109.51	73.77	68.26	74.46
Steam coal	carbonisate		BASE*	55.33	45.05	7.46	17.9	7.62	-29.98	86.52	76.24	38.65
Feedstock	carbonisate		BASE*	93.26	84.15	59.34	40.89	31.78	6.97	136.91	127.8	102.99
			CCS	92.52	88.56	98.46	40.15	36.19	46.09	136.17	132.21	142.11
Product carbonisate	carbonisate		BASE*	63.75	44.05	-18.26	-64.69	-84.39	-146.7	**170.79**	151.09	88.79
Product syngas	carbonisate		BASE*	-39.36	-51.46	-75.52	-130.46	-142.56	-166.63	36.56	24.46	0.4
			CCS	-40.44	-45.02	-18.41	-131.54	-136.12	-109.51	35.48	30.9	57.51
Natural gas	gas		BASE**	43.32	37.07	43.26	-130.46	-136.12	-109.51	74.51	68.26	74.46
		PSA	H_2+off gas	56.15	51.98	51.08	19.19	15.03	14.12	86.94	82.78	81.88
Steam coal	gas		BASE**	55.33	45.05	7.46	17.9	7.62	-29.98	86.52	76.24	38.65
		PSA	H_2+off gas	68	59.8	15.23	31.05	22.84	-21.72	98.8	90.61	46.04
Feedstock	gas		BASE**	93.26	88.56	98.46	40.89	36.19	46.09	136.91	132.21	142.11
		PSA	H_2+off gas	105.46	102.82	105.58	53.75	51.11	53.87	148.55	145.91	148.67
Product carbonisate	gas		BASE**	63.75	44.05	-18.26	-64.69	-84.39	-146.7	**170.79**	151.09	88.79
		PSA	H_2+off gas	71.82	57.2	-21.9	-49.77	-64.4	-143.5	**173.15**	158.52	79.42
Natural gas	gas/oil		BASE**	43.32	37.07	43.26	-130.46	-136.12	-109.51	74.51	68.26	74.46
		CHP	only gas (no consumers for heat)	7.55	1.95	18.23	-32.46	-38.06	-21.78	40.88	35.3	51.58
			only gas (40 €/MWh for heat)	18.11	12.52	28.8	-21.9	-27.49	-11.21	51.45	45.86	62.14
			gas+oil (no consumers for heat)	-82.94	-78.52	-44.38	-127.68	-123.27	-89.12	-45.66	-41.23	-7.09
			gas+oil (40 €/MWh for heat)	-57.81	-53.38	-19.24	-102.55	-98.13	-63.99	-20.52	-16.1	18.05
Steam coal	gas/oil		BASE**	55.33	45.05	7.46	17.9	7.62	-29.98	86.52	76.24	38.65
		CHP	only gas (no consumers for heat)	20.38	10.45	-20.39	-19.64	-29.56	-60.4	53.72	43.78	12.95
			only gas (40 €/MWh for heat)	30.94	21.01	-9.83	-9.07	-19	-49.84	64.28	54.35	23.52
			gas+oil (no consumers for heat)	-68.59	-68.38	-81.85	-113.34	-113.13	-126.6	-31.3	-31.1	-44.56
			gas+oil (40 €/MWh for heat)	-43.46	-43.25	-56.72	-88.2	-88	-101.46	-6.17	-5.96	-19.43
Feedstock	gas/oil		BASE**	93.26	88.56	98.46	40.89	36.19	46.09	136.91	132.21	142.11
		CHP	only gas (no consumers for heat)	60.92	56.99	77.23	4.94	1.01	21.25	107.58	103.64	123.88
			only gas (40 €/MWh for heat)	71.49	67.56	87.8	15.51	11.58	31.82	118.15	114.21	134.45
			gas+oil (no consumers for heat)	-23.24	-16.97	21.61	-85.85	-79.58	-40.99	28.93	35.21	73.79
			gas+oil (40 €/MWh for heat)	1.89	8.16	46.74	-60.71	-54.45	-15.87	54.07	60.33	98.91
Product carbonisate	gas/oil		BASE**	63.75	44.05	-18.26	-64.69	-84.39	-146.7	**170.79**	151.09	88.79
		CHP	only gas (no consumers for heat)	-19.94	-40.72	-89.93	-173.7	-194.48	-243.69	108.18	87.39	38.19
			only gas (40 €/MWh for heat)	59.34	38.56	-10.66	-94.41	-115.19	-164.41	**187.47**	166.68	117.47
			gas+oil (no consumers for heat)	-538.99	-518.8	-498.09	-770.55	-750.36	-729.65	-346.03	-325.83	-305.13
			gas+oil (40 €/MWh for heat)	-361.24	-341.05	-320.34	-592.8	-572.61	-551.9	-168.27	-148.08	-127.38
Natural gas	gas/oil		BASE**	43.32	37.07	43.26	-130.46	-136.12	-109.51	74.51	68.26	74.46
		CHP/PSA	only gas (no consumers for heat)	29.62	25.85	33.59	-11.96	-15.74	-7.99	64.28	60.5	68.24
			only gas (40 €/MWh for heat)	36.47	32.68	40.43	-5.11	-8.9	-1.16	71.12	67.34	75.08
			gas+oil (no consumers for heat)	-63.06	-56.62	-30.86	-109.03	-102.61	-76.84	-24.74	-18.31	7.46
			gas+oil (40 €/MWh for heat)	-42.03	-35.59	-9.83	-88	-81.58	-55.81	-3.7	2.72	28.49
Steam coal	gas/oil		BASE**	55.33	45.05	7.46	17.9	7.62	-29.98	86.52	76.24	38.65
		CHP/PSA	only gas (no consumers for heat)	42.97	34.44	-8.49	1.38	-7.14	-50.07	77.62	69.11	26.18
			only gas (40 €/MWh for heat)	49.8	41.29	-1.64	8.22	-0.29	-43.22	84.46	75.94	33.01
			gas+oil (no consumers for heat)	-48.31	-46.34	-70.47	-94.28	-92.31	-116.45	-9.99	-8.02	-32.15
			gas+oil (40 €/MWh for heat)	-27.28	-25.3	-49.44	-73.26	-71.28	-95.42	11.03	13.02	-11.12
Feedstock	gas/oil		BASE**	93.26	88.56	98.46	40.89	36.19	46.09	136.91	132.21	142.11
		CHP/PSA	only gas (no consumers for heat)	85.11	83.05	94.91	26.93	24.86	36.73	133.6	131.54	143.41
			only gas (40 €/MWh for heat)	91.95	89.89	101.76	33.77	31.71	43.57	140.44	138.38	150.24
			gas+oil (no consumers for heat)	-1.71	6.63	36.95	-66.04	-57.71	-27.39	51.91	60.24	90.56
			gas+oil (40 €/MWh for heat)	19.32	27.65	57.98	-45.01	-36.68	-6.36	72.93	81.27	111.59
Product carbonisate	gas/oil		BASE**	63.75	44.05	-18.26	-64.69	-84.39	-146.7	**170.79**	151.09	88.79
		CHP/PSA	only gas (no consumers for heat)	38.95	19.74	-73.43	-133.72	-152.91	-246.09	**182.83**	163.64	70.46
			only gas (40 €/MWh for heat)	109.66	90.47	-2.71	-63	-82.2	-175.37	**253.55**	**234.35**	141.17
			gas+oil (no consumers for heat)	-582.81	-553.95	-558.52	-838.41	-809.55	-814.12	-369.8	-340.95	-345.52
			gas+oil (40 €/MWh for heat)	-403.24	-374.38	-378.95	-658.84	-629.98	-634.55	-190.24	-161.38	-165.95

Table 56: Matrix of the considered utilization pathways of woody biomass; Comparison of mLR and LC (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

Woody Biomass			Gate fee	mid						low						high					
			WEO (2016)	Current Policies		New Policies		450		Current Policies		New Policies		450		Current Policies		New Policies		450	
Heating	TCR product | Downstream processes		Utilization	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR
Natural gas	carbonisate		BASE*	355.1	315.2	358	309.7	365.1	286.8	329.1	303.5	332	298.1	339.1	275.1	455.6	360.4	458.5	354.9	465.5	331.9
			BBQ briquetts	355.1	315.5	358	311.8	365.1	293.3	329.1	303.8	332	300.1	339.1	281.6	455.6	360.7	458.5	356.9	465.5	338.5
			CCS	355.1	314.9	358	315.8	365.1	336.3	329.1	303.2	332	304.2	339.1	324.6	455.6	360.1	458.5	361	465.5	381.4
Steam coal	carbonisate		BASE*	332.4	305	334.6	299.2	358.8	284	306.3	293.3	308.6	287.5	332.8	272.3	432.8	350.2	435	344.4	459.2	329.1
			BBQ briquetts	332.4	305.3	334.6	301.2	358.8	290.5	306.3	293.6	308.6	289.5	332.8	278.8	432.8	350.5	435	346.4	459.2	335.6
			CCS	332.4	304.7	334.6	305.3	358.8	333.5	306.3	293	308.6	293.6	332.8	321.8	432.8	349.9	435	350.5	459.2	378.6
Feedstock	carbonisate		BASE*	324.2	301.3	324.2	294.5	324.2	268.4	290.3	286.1	290.3	279.3	290.3	253.2	454.9	360.1	454.9	353.3	454.9	327.2
			Biochar	324.2	440.9	324.2	435.8	324.2	414.1	290.3	425.6	290.3	420.6	290.3	398.9	454.9	499.6	454.9	494.5	454.9	472.9
			BBQ briquetts	324.2	301.6	324.2	296.6	324.2	274.9	290.3	286.4	290.3	281.4	290.3	259.7	454.9	360.4	454.9	355.3	454.9	333.7
			CCS	324.2	301	324.2	300.6	324.2	317.9	290.3	285.8	290.3	285.4	290.3	302.7	454.9	359.8	454.9	359.4	454.9	376.7
Product carbonisate	carbonisate		BASE*	393	238.4	393	231.5	393	202.4	358.4	233.3	358.4	226.4	358.4	197.2	526.7	258.2	526.7	251.3	526.7	222.2
			Biochar	393	249.4	393	242.7	393	213.8	358.4	244.3	358.4	237.5	358.4	208.7	526.7	269.2	526.7	262.5	526.7	233.6
			BBQ briquetts	393	238.4	393	231.7	393	202.9	358.4	233.3	358.4	226.6	358.4	197.7	526.7	258.2	526.7	251.5	526.7	222.7
			CCS	393	238.4	393	232	393	206.3	358.4	233.3	358.4	226.9	358.4	201.1	526.7	258.2	526.7	251.8	526.7	226.1
Product syngas	carbonisate		BASE*	463.2	414.5	463.2	405.3	463.2	377.2	421.9	391.5	421.9	382.3	421.9	354.2	622.6	503.5	622.6	494.3	622.6	466.2
			Biochar	463.2	635.9	463.2	629.5	463.2	608.4	421.9	612.9	421.9	606.4	421.9	585.4	622.6	724.9	622.6	718.4	622.6	697.4
			BBQ briquetts	463.2	415	463.2	408.5	463.2	387.5	421.9	392	421.9	385.5	421.9	364.5	622.6	504	622.6	497.5	622.6	476.5
			CCS	463.2	414	463.2	415	463.2	455.8	421.9	391	421.9	392	421.9	432.7	622.6	503	622.6	504	622.6	544.7
Natural gas	gas	no PSA	BASE**	355.1	315.5	358	315.8	365.1	336.3	329.1	303.8	332	304.2	339.1	324.6	455.6	360.7	458.5	361	465.5	381.4
		PSA	H_2+off gas	418.1	395.5	421.1	400.3	428.1	404.7	392.1	383	395.1	387.9	402.1	392.3	518.6	443.4	521.5	448.2	528.6	452.7
Steam coal	gas	no PSA	BASE**	332.4	305.3	334.6	305.3	358.8	333.5	306.3	293.6	308.6	293.6	332.8	321.8	432.8	350.5	435	350.5	459.2	378.6
		PSA	H_2+off gas	395.4	384.6	397.6	389.1	421.8	401.7	369.4	372.2	371.6	376.7	395.8	389.3	495.8	432.5	498.1	437	522.3	449.7
Feedstock	gas	no PSA	BASE**	324.2	440.9	324.2	435.8	324.2	414.1	290.3	425.6	290.3	420.6	290.3	398.9	454.9	499.6	454.9	494.5	454.9	472.9
		PSA	H_2+off gas	387.2	519.9	387.2	519.3	387.2	481.4	353.4	503.8	353.4	503.1	353.4	465.3	517.9	582.3	517.9	581.7	517.9	543.8
Product carbonisate	gas	no PSA	BASE**	393	249.4	393	242.7	393	213.8	358.4	244.3	358.4	237.5	358.4	208.7	526.7	269.2	526.7	262.5	526.7	233.6
		PSA	H_2+off gas	476.9	333.2	476.9	332.3	476.9	281.9	442.3	326.3	442.3	325.5	442.3	275.1	610.6	359.5	610.6	358.7	610.6	308.3
Natural gas	gas/oil	no CHP	BASE**	355.1	315.5	358	315.8	365.1	336.3	329.1	303.8	332	304.2	339.1	324.6	455.6	360.7	458.5	361	465.5	381.4
		CHP	only gas (no consumers for heat)	395.3	300.7	398.5	298.6	406	295.7	367.3	288	370.5	290.4	378.1	329.3	503.4	349.4	506.6	351.8	514.1	390.7
			only gas (40 €/MWh for heat)	325.3	277.4	328.4	275.4	336	272.5	297.3	264.8	300.5	267.2	308	306.1	433.4	326.2	436.5	328.5	444.1	367.5
			gas+oil (no consumers for heat)	444.7	279.1	444.1	279.3	444.6	280.2	417.2	268.4	416.6	272.8	417.1	315	550.9	320.5	550.2	324.9	550.8	367.1
			gas+oil (40 €/MWh for heat)	375.4	259.7	374.7	259.9	375.2	260.9	347.9	249	347.2	253.5	347.8	295.6	481.5	301.1	480.9	305.6	481.4	347.7
Steam coal	gas/oil	no CHP	BASE**	332.4	305.3	334.6	305.3	358.8	333.5	306.3	293.6	308.6	293.6	332.8	321.8	432.8	350.5	435	350.5	459.2	378.6
		CHP	only gas (no consumers for heat)	370.9	289.6	373.2	287.2	399.3	292.6	342.9	277	345.3	279	371.3	326.3	479	338.4	481.3	340.4	507.4	387.6
			only gas (40 €/MWh for heat)	300.8	266.4	303.2	264	329.2	269.4	272.8	253.8	275.2	255.8	301.3	303	408.9	315.2	411.3	317.2	437.3	364.4
			gas+oil (no consumers for heat)	420.7	269.7	419.3	269.6	437.9	277.6	393.2	259	391.8	263.2	410.5	312.4	526.8	311.1	525.4	315.3	544.1	364.5
			gas+oil (40 €/MWh for heat)	351.3	250.4	349.9	250.2	368.6	258.3	323.8	239.7	322.4	243.8	341.1	293	457.5	291.7	456.1	295.9	474.8	345.1
Feedstock	gas/oil	no CHP	BASE**	324.2	440.9	324.2	435.8	324.2	414.1	290.3	425.6	290.3	420.6	290.3	398.9	454.9	499.6	454.9	494.5	454.9	472.9
		CHP	only gas (no consumers for heat)	362.1	435.4	362.1	432	362.1	425.6	325.7	419	325.7	415.6	325.7	409.2	502.7	498.9	502.7	495.4	502.7	489.1
			only gas (40 €/MWh for heat)	292	412.2	292	408.8	292	402.4	255.6	395.8	255.6	392.3	255.6	386	432.6	475.7	432.6	472.2	432.6	465.8
			gas+oil (no consumers for heat)	412	413.5	408.3	412.4	401.4	410.5	376.3	399.6	372.5	398.5	365.6	396.6	550.2	467.3	546.4	466.3	539.5	464.3
			gas+oil (40 €/MWh for heat)	342.7	394.1	338.9	393.1	332	391.1	306.9	380.2	303.2	379.1	296.3	377.2	480.8	447.9	477	446.9	470.2	445
Product carbonisate	gas/oil	no CHP	BASE**	393	249.4	393	242.7	393	213.8	358.4	244.3	358.4	237.5	358.4	208.7	526.7	269.2	526.7	262.5	526.7	233.6
		CHP	only gas (no consumers for heat)	451.8	217.3	451.8	212.6	451.8	203.9	413.6	211.6	413.6	206.9	413.6	198.2	599.4	239.3	599.4	234.5	599.4	225.9
			only gas (40 €/MWh for heat)	356.2	208.9	356.2	204.2	356.2	195.5	318	203.3	318	198.6	318	189.9	503.8	230.9	503.8	226.2	503.8	217.5
			gas+oil (no consumers for heat)	517.5	155.8	512.4	155.7	503	155.4	480.2	154.2	475.1	154.1	465.8	153.9	661.5	161.7	656.4	161.5	647.1	161.3
			gas+oil (40 €/MWh for heat)	423.4	153.7	418.3	153.5	408.9	153.3	386.1	152.1	381	152	371.7	151.8	567.4	159.5	562.3	159.4	553	159.2
Natural gas	gas/oil		BASE**	355.1	315.5	358	315.8	365.1	336.3	329.1	303.8	332	304.2	339.1	324.6	455.6	360.7	458.5	361	465.5	381.4
		CHP/PSA	only gas (no consumers for heat)	532.5	461.8	536.4	470.5	545.9	494.2	497.5	444.1	501.5	452.8	510.9	476.5	667.5	530.1	671.4	538.8	680.9	562.6
			only gas (40 €/MWh for heat)	458.5	429.1	462.4	437.8	471.9	461.5	423.5	411.4	427.5	420.1	436.9	443.8	593.5	497.4	597.4	506.1	606.9	529.9
			gas+oil (no consumers for heat)	561.5	409.9	560.7	420.2	561.4	446.3	528.9	395.8	528.1	406	528.7	432.1	687.7	464.6	686.9	474.9	687.5	500.9
			gas+oil (40 €/MWh for heat)	478.7	380.3	477.9	390.6	478.6	416.6	446.1	366.1	445.3	376.4	445.9	402.5	604.9	435	604.1	445.2	604.7	471.3
Steam coal	gas/oil		BASE**	332.4	305.3	334.6	305.3	358.8	333.5	306.3	293.6	308.6	293.6	332.8	321.8	432.8	350.5	435	350.5	459.2	378.6
		CHP/PSA	only gas (no consumers for heat)	501.9	446.3	504.9	454.5	537.4	489.9	467	428.6	469.9	436.8	502.5	472.2	636.9	514.6	639.9	522.8	672.4	558.3
			only gas (40 €/MWh for heat)	427.9	413.6	430.9	421.8	463.4	457.2	393	395.9	395.9	404.1	428.5	439.6	562.9	481.9	565.9	490.1	598.4	525.6
			gas+oil (no consumers for heat)	533	397.5	531.3	407.4	553.5	442.8	500.3	383.4	498.6	393.3	520.8	428.7	659.1	452.2	657.4	462.1	679.6	497.5
			gas+oil (40 €/MWh for heat)	450.1	367.9	448.4	377.8	470.7	413.2	417.5	353.7	415.8	363.6	438	399	576.3	422.6	574.6	432.5	596.8	467.9
Feedstock	gas/oil		BASE**	324.2	440.9	324.2	435.8	324.2	414.1	290.3	425.6	290.3	420.6	290.3	398.9	454.9	499.6	454.9	494.5	454.9	472.9
		CHP/PSA	only gas (no consumers for heat)	490.9	627.8	490.9	629.1	490.9	595.7	445.4	604.8	445.4	606	445.4	572.7	666.6	716.7	666.6	718	666.6	684.6
			only gas (40 €/MWh for heat)	416.9	595.1	416.9	596.4	416.9	563	371.4	572.1	371.4	573.3	371.4	540	592.6	684	592.6	685.3	592.6	651.9
			gas+oil (no consumers for heat)	522.7	567.9	518.2	571.5	510	544.8	480.2	549.5	475.7	553.1	467.5	526.4	686.8	639	682.3	642.6	674.2	616
			gas+oil (40 €/MWh for heat)	439.9	538.3	435.4	541.8	427.2	515.2	397.4	519.8	392.9	523.4	384.7	496.8	604	609.4	599.5	613	591.3	586.3
Product carbonisate	gas/oil		BASE**	393	249.4	393	242.7	393	213.8	358.4	244.3	358.4	237.5	358.4	208.7	526.7	269.2	526.7	262.5	526.7	233.6
		CHP/PSA	only gas (no consumers for heat)	679	402.1	679	404	679	353.9	626.5	390.8	626.5	392.6	626.5	342.6	881.8	445.9	881.8	447.8	881.8	397.7
			only gas (40 €/MWh for heat)	567.9	384.1	567.9	386	567.9	335.9	515.4	372.8	515.4	374.7	515.4	324.6	770.7	428	770.7	429.8	770.7	379.8
			gas+oil (no consumers for heat)	707.2	286	700.7	293.1	688.8	257.9	659.8	281.4	653.3	288.5	641.4	253.2	890.7	304	884.2	311.1	872.3	275.9
			gas+oil (40 €/MWh for heat)	586.8	278	580.3	285.1	568.4	249.9	539.3	273.4	532.8	280.5	520.9	245.2	770.3	296	763.8	303.1	751.9	267.9

Table 57: Matrix of the considered utilization pathways of woody biomass; Difference mLR-LC as an indicator of profitability (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

Woody Biomass			Gate fee	mid			low			high		
			WEO (2016)	Current Policies	New Policies	450	Current Policies	New Policies	450	Current Policies	New Policies	450
Heating	TCR product | Downstream processes		Utilization	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC
Natural gas	carbonisate		BASE*	-39.87	-48.29	-78.29	-25.56	-33.97	-63.96	-95.19	-103.6	-133.59
			BBQ briquetts	-39.56	-46.25	-71.78	-25.25	-31.93	-57.45	-94.88	-101.56	-127.08
			CCS	-40.18	-42.19	-28.78	-25.86	-27.87	-14.46	-95.49	-97.5	-84.09
Steam coal	carbonisate		BASE*	-27.35	-35.36	-74.82	-13.03	-21.05	-60.5	-82.66	-90.68	-130.13
			BBQ briquetts	-27.04	-33.32	-68.31	-12.72	-19.01	-53.99	-82.35	-88.64	-123.62
			CCS	-27.66	-29.26	-25.32	-13.34	-14.95	-11	-82.97	-84.58	-80.63
Feedstock	carbonisate		BASE*	-22.85	-29.65	-55.78	-4.22	-11.03	-37.15	-94.81	-101.61	-127.73
			Biochar	116.68	111.61	89.95	135.3	130.23	108.58	44.72	39.65	18
			BBQ briquetts	-22.54	-27.61	-49.27	-3.92	-8.99	-30.64	-94.5	-99.57	-121.22
			CCS	-23.16	-23.55	-6.27	-4.53	-4.92	12.35	-95.11	-95.5	-78.23
Product Carbonisate	carbonisate		BASE*	-154.58	-161.46	-190.64	-125.08	-131.97	-161.14	-268.51	-275.39	-304.57
			Biochar	-143.58	-150.32	-179.15	-114.08	-120.83	-149.65	-257.51	-264.25	-293.08
			BBQ briquetts	-154.55	-161.3	-190.13	-125.06	-131.8	-160.63	-268.48	-275.23	-304.06
			CCS	-154.6	-160.98	-186.74	-125.11	-131.48	-157.24	-268.53	-274.91	-300.67
Product Syngas	carbonisate		BASE*	-48.64	-57.86	-85.96	-30.4	-39.61	-67.72	-119.12	-128.33	-156.44
			Biochar	**172.77**	**166.31**	145.29	**191.02**	**184.55**	163.54	102.3	95.84	74.82
			BBQ briquetts	-48.15	-54.62	-75.63	-29.91	-36.37	-57.39	-118.63	-125.09	-146.11
			CCS	-49.13	-48.17	-7.4	-30.89	-29.93	10.84	-119.61	-118.64	-77.88
Natural gas	gas	no PSA	BASE**	-39.56	-42.19	-28.78	-25.25	-27.87	-14.46	-94.88	-97.5	-84.09
		PSA	H_2+off gas	-22.67	-20.76	-23.37	-9.07	-7.18	-9.78	-75.19	-73.28	-75.89
Steam coal	gas	no PSA	BASE**	-27.04	-29.26	-25.32	-12.72	-14.95	-11	-82.35	-84.58	-80.63
		PSA	H_2+off gas	-10.78	-8.5	-20.08	2.81	5.1	-6.49	-63.3	-61.01	-72.6
Feedstock	gas	no PSA	BASE**	116.68	111.61	89.95	135.3	130.23	108.58	44.72	39.65	18
		PSA	H_2+off gas	132.72	132.09	94.23	150.4	149.78	111.91	64.39	63.77	25.9
Product Carbonisate	gas	no PSA	BASE**	-143.58	-150.32	-179.15	-114.08	-120.83	-149.65	-257.51	-264.25	-293.08
		PSA	H_2+off gas	-143.72	-144.55	-194.95	-115.93	-116.76	-167.15	-251.07	-251.9	-302.29
Natural gas	gas/oil	no CHP	BASE**	-39.56	-42.19	-28.78	-25.25	-27.87	-14.46	-94.88	-97.5	-84.09
		CHP	only gas (no consumers for heat)	-94.67	-99.86	-110.37	-79.32	-80.13	-48.76	-154.01	-154.82	-123.44
			only gas (40 €/MWh for heat)	-47.85	-53.04	-63.55	-32.5	-33.31	-1.93	-107.19	-108	-76.62
			gas+oil (no consumers for heat)	-165.61	-164.79	-164.36	-148.84	-143.73	-102.16	-230.4	-225.28	-183.71
			gas+oil (40 €/MWh for heat)	-115.62	-114.81	-114.38	-98.85	-93.74	-52.17	-180.42	-175.31	-133.74
Steam coal	gas/oil	no CHP	BASE**	-27.04	-29.26	-25.32	-12.72	-14.95	-11	-82.35	-84.58	-80.63
		CHP	only gas (no consumers for heat)	-81.24	-85.99	-106.66	-65.89	-66.27	-45.05	-140.58	-140.95	-119.73
			only gas (40 €/MWh for heat)	-34.42	-39.17	-59.84	-19.07	-19.44	1.78	-93.76	-94.13	-72.91
			gas+oil (no consumers for heat)	-150.94	-149.66	-160.3	-134.17	-128.6	-98.1	-215.72	-210.15	-179.65
			gas+oil (40 €/MWh for heat)	-100.96	-99.67	-110.33	-84.19	-78.61	-48.12	-165.75	-160.17	-129.68
Feedstock	gas/oil	no CHP	BASE**	116.68	111.61	89.95	135.3	130.23	108.58	44.72	39.65	18
		CHP	only gas (no consumers for heat)	73.37	69.93	63.56	93.35	89.91	83.54	-3.81	-7.26	-13.63
			only gas (40 €/MWh for heat)	120.2	116.76	110.39	140.18	136.74	130.37	43.01	39.56	33.19
			gas+oil (no consumers for heat)	1.45	4.16	9.12	23.27	25.98	30.94	-82.83	-80.12	-75.16
			gas+oil (40 €/MWh for heat)	51.43	54.14	59.11	73.25	75.96	80.92	-32.86	-30.15	-25.18
Product Carbonisate	gas/oil	no CHP	BASE**	-143.58	-150.32	-179.15	-114.08	-120.83	-149.65	-257.51	-264.25	-293.08
		CHP	only gas (no consumers for heat)	-234.56	-239.26	-247.96	-202.04	-206.75	-215.44	-360.19	-364.9	-373.59
			only gas (40 €/MWh for heat)	-147.27	-151.98	-160.67	-114.75	-119.46	-128.16	-272.91	-277.61	-286.31
			gas+oil (no consumers for heat)	-361.71	-356.72	-347.59	-325.96	-320.97	-311.84	-499.84	-494.86	-485.72
			gas+oil (40 €/MWh for heat)	-269.74	-264.76	-255.62	-233.99	-229	-219.87	-407.87	-402.88	-393.75
Natural gas	gas/oil		BASE**	-39.56	-42.19	-28.78	-25.25	-27.87	-14.46	-94.88	-97.5	-84.09
		CHP/PSA	only gas (no consumers for heat)	-70.72	-65.96	-51.65	-53.46	-48.7	-34.39	-137.39	-132.64	-118.32
			only gas (40 €/MWh for heat)	-29.42	-24.66	-10.34	-12.16	-7.41	6.92	-96.1	-91.34	-77.02
			gas+oil (no consumers for heat)	-151.6	-140.54	-115.11	-133.1	-122.03	-96.6	-223.08	-212.02	-186.59
			gas+oil (40 €/MWh for heat)	-98.43	-87.37	-61.94	-79.93	-68.86	-43.44	-169.91	-158.85	-133.43
Steam coal	gas/oil		BASE**	-27.04	-29.26	-25.32	-12.72	-14.95	-11	-82.35	-84.58	-80.63
		CHP/PSA	only gas (no consumers for heat)	-55.62	-50.39	-47.46	-38.36	-33.13	-30.22	-122.29	-117.06	-114.14
			only gas (40 €/MWh for heat)	-14.32	-9.09	-6.17	2.94	8.17	11.09	-81	-75.77	-72.84
			gas+oil (no consumers for heat)	-135.41	-123.83	-110.63	-116.92	-105.33	-92.13	-206.9	-195.31	-182.11
			gas+oil (40 €/MWh for heat)	-82.25	-70.66	-57.47	-63.74	-52.16	-38.97	-153.73	-142.14	-128.95
Feedstock	gas/oil		BASE**	116.68	111.61	89.95	135.3	130.23	108.58	44.72	39.65	18
		CHP/PSA	only gas (no consumers for heat)	136.91	138.15	104.81	159.35	160.6	127.26	50.16	51.4	18.06
			only gas (40 €/MWh for heat)	**178.2**	**179.44**	146.1	**200.66**	**201.9**	**168.56**	91.46	92.7	59.37
			gas+oil (no consumers for heat)	45.22	53.27	34.81	69.29	77.34	58.88	-47.78	-39.73	-58.18
			gas+oil (40 €/MWh for heat)	98.38	106.44	87.98	122.46	130.51	112.05	5.39	13.44	-5.02
Product Carbonisate	gas/oil		BASE**	-143.58	-150.32	-179.15	-114.08	-120.83	-149.65	-257.51	-264.25	-293.08
		CHP/PSA	only gas (no consumers for heat)	-276.88	-275.01	-325.09	-235.73	-233.86	-283.94	-435.88	-434.02	-484.09
			only gas (40 €/MWh for heat)	-183.71	-181.84	-231.92	-142.55	-140.68	-190.76	-342.71	-340.85	-390.92
			gas+oil (no consumers for heat)	-421.22	-407.62	-430.99	-378.4	-364.79	-388.17	-586.67	-573.07	-596.44
			gas+oil (40 €/MWh for heat)	-308.79	-295.19	-318.57	-265.97	-252.37	-275.75	-474.24	-460.65	-484.02

Table 58: Matrix of the considered utilization pathways of algae; Comparison of mLR and LC (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

Algae			Gate fee	mid						low						high					
			WEO (2016)	Current Policies		New Policies		450		Current Policies		New Policies		450		Current Policies		New Policies		450	
Heating	TCR product | Downstream processes		Utilization	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR
Natural gas	carbonisate		BASE*	250.6	274.1	253.9	268.4	261.8	249.2	280.6	290.9	283.9	285.2	291.8	266	220.6	257.4	223.9	251.7	231.8	232.4
			CCS	250.6	274.3	253.9	272.4	261.8	279	280.6	291	283.9	289.1	291.8	295.8	220.6	257.5	223.9	255.6	231.8	262.3
Steam coal	carbonisate		BASE*	224.9	259.8	227.4	253.6	254.7	245.2	254.9	276.6	257.4	270.4	284.7	262	194.9	243	197.4	236.9	224.7	228.5
Feedstock	carbonisate		BASE*	165.2	226.5	165.2	218.9	165.2	195.3	208.1	250.4	208.1	242.8	208.1	219.2	122.4	202.5	122.4	195	122.4	171.3
			CCS	165.2	226.6	165.2	222.8	165.2	225.1	208.1	250.5	208.1	246.8	208.1	249	122.4	202.7	122.4	198.9	122.4	201.1
Product carbonisate	carbonisate		BASE*	360.5	292.9	362.6	281.6	384.5	248.6	414.1	304.1	416.1	292.8	438.1	259.9	307	281.7	309	270.4	331	237.4
Product syngas	carbonisate		BASE*	303.6	242.9	303.6	231.9	303.6	208	354.4	263.8	354.4	252.9	354.4	228.9	252.8	221.9	252.8	211	252.8	187
			CCS	303.6	243.1	303.6	238.6	303.6	258.5	354.4	264	354.4	259.5	354.4	279.4	252.8	222.2	252.8	217.7	252.8	237.5
Natural gas	gas		BASE**	250.6	274.3	253.9	272.4	261.8	279	280.6	291	283.9	289.1	291.8	295.8	220.6	257.5	223.9	255.6	231.8	262.3
		PSA	H_2+off gas	295.5	326.6	298.8	327.7	306.7	325.3	325.5	343.7	328.8	344.8	336.7	342.4	265.5	309.5	268.8	310.6	276.7	308.2
Steam coal	gas		BASE**	224.9	259.8	227.4	253.6	254.7	245.2	254.9	276.6	257.4	270.4	284.7	262	194.9	243	197.4	236.9	224.7	228.5
		PSA	H_2+off gas	269.8	311.8	272.3	308.6	299.6	291.4	299.8	329	302.3	325.8	329.6	308.6	239.8	294.7	242.3	291.5	269.6	274.3
Feedstock	gas		BASE**	165.2	226.6	165.2	222.8	165.2	225.1	208.1	250.5	208.1	246.8	208.1	249	122.4	202.7	122.4	198.9	122.4	201.1
		PSA	H_2+off gas	210.1	277.9	210.1	277.1	210.1	270.1	253	302.3	253	301.6	253	294.6	167.3	253.4	167.3	252.6	167.3	245.7
Product carbonisate	gas		BASE**	360.5	292.9	362.6	281.6	384.5	248.6	414.1	304.1	416.1	292.8	438.1	259.9	307	281.7	309	270.4	331	237.4
		PSA	H_2+off gas	440.8	355	442.8	349.1	464.8	300.7	494.4	368.4	496.4	362.5	518.4	314.1	387.2	341.6	389.2	335.7	411.2	287.3
Natural gas	gas/oil		BASE**	250.6	274.3	253.9	272.4	261.8	279	280.6	291	283.9	289.1	291.8	295.8	220.6	257.5	223.9	255.6	231.8	262.3
		CHP	only gas (no consumers for heat)	276.6	261.7	280.3	261.1	288.9	280.9	309.5	280.2	313.1	279.6	321.7	299.4	243.8	243.2	247.4	242.6	256.1	262.4
			only gas (40 €/MWh for heat)	223.9	232.5	227.5	231.9	236.2	251.7	256.7	250.9	260.4	250.3	269	270.2	191.1	214	194.7	213.4	203.4	233.2
			gas+oil (no consumers for heat)	348.6	255.2	346.4	257.2	344.2	281.3	380.6	271.1	378.4	273.1	376.2	297.1	316.6	239.4	314.3	241.4	312.2	265.5
			gas+oil (40 €/MWh for heat)	277.8	222	275.6	224	273.4	248	309.8	237.8	307.6	239.8	305.4	263.9	245.8	206.1	243.5	208.1	241.4	232.2
Steam coal	gas/oil		BASE**	224.9	259.8	227.4	253.6	254.7	245.2	254.9	276.6	257.4	270.4	284.7	262	194.9	243	197.4	236.9	224.7	228.5
		CHP	only gas (no consumers for heat)	248.6	245.8	251.3	240.5	281.2	243.9	281.4	264.2	284.1	258.9	314	262.4	215.8	227.3	218.5	222	248.4	225.5
			only gas (40 €/MWh for heat)	195.9	216.5	198.6	211.3	228.5	214.7	228.7	235	231.4	229.7	261.3	233.2	163.1	198.1	165.8	192.8	195.7	196.3
			gas+oil (no consumers for heat)	321.2	241.5	318.1	239.1	336.7	245.7	353.3	257.4	350.1	254.9	368.7	261.6	289.2	225.7	286.1	223.2	304.6	229.9
			gas+oil (40 €/MWh for heat)	250.4	208.3	247.3	205.8	265.8	212.5	282.4	224.1	279.3	221.6	297.9	228.3	218.4	192.4	215.3	190	233.8	196.6
Feedstock	gas/oil		BASE**	165.2	226.6	165.2	222.8	165.2	225.1	208.1	250.5	208.1	246.8	208.1	249	122.4	202.7	122.4	198.9	122.4	201.1
		CHP	only gas (no consumers for heat)	183.3	209.2	183.3	206.5	183.3	221.5	230.2	235.5	230.2	232.9	230.2	247.8	136.4	182.8	136.4	180.2	136.4	195.1
			only gas (40 €/MWh for heat)	130.6	180	130.6	177.3	130.6	192.3	177.5	206.3	177.5	203.7	177.5	218.6	83.72	153.6	83.72	151	83.72	165.9
			gas+oil (no consumers for heat)	257.5	210.2	251.7	210.4	241.1	230.3	303.3	232.8	297.5	233.1	286.9	252.9	211.8	187.5	206	187.8	195.4	207.7
			gas+oil (40 €/MWh for heat)	186.7	176.9	180.9	177.2	170.3	197	232.5	199.5	226.7	199.8	216.1	219.7	141	154.3	135.2	154.5	124.6	174.4
Product carbonisate	gas/oil		BASE**	360.5	292.9	362.6	281.6	384.5	248.6	414.1	304.1	416.1	292.8	438.1	259.9	307	281.7	309	270.4	331	237.4
		CHP	only gas (no consumers for heat)	430.7	269.2	433.1	258.7	459	243.9	494	282.6	496.3	272.2	522.3	257.4	367.5	255.7	369.8	245.2	395.8	230.5
			only gas (40 €/MWh for heat)	329.1	254.9	331.5	244.4	357.4	229.7	392.3	268.4	394.7	257.9	420.7	243.1	265.9	241.4	268.2	230.9	294.2	216.2
			gas+oil (no consumers for heat)	559.5	134.4	550.8	134.4	555.6	134.4	619.9	134.4	611.2	134.4	616	134.4	499.1	134.4	490.4	134.4	495.2	134.4
			gas+oil (40 €/MWh for heat)	426	134.4	417.3	134.4	422.1	134.4	486.3	134.4	477.7	134.4	482.5	134.4	365.6	134.4	356.9	134.4	361.7	134.4
Natural gas	gas/oil		BASE**	250.6	274.3	253.9	272.4	261.8	279	280.6	291	283.9	289.1	291.8	295.8	220.6	257.5	223.9	255.6	231.8	262.3
		CHP/PSA	only gas (no consumers for heat)	358.1	375.2	362.5	378.2	372.9	386.7	397.6	399.3	402	402.3	412.4	410.8	333.4	362.6	323	354.1	333.4	362.6
			only gas (40 €/MWh for heat)	310.6	342.7	315	345.7	325.4	354.2	350.1	366.8	354.5	369.8	364.9	378.3	285.9	330.1	275.5	321.6	285.9	330.1
			gas+oil (no consumers for heat)	417	335.4	414.4	340.5	412	352.5	453.5	354.5	450.9	359.6	448.4	371.7	375.5	333.4	377.9	321.3	375.5	333.4
			gas+oil (40 €/MWh for heat)	349.4	298.2	346.9	303.2	344.4	315.3	385.9	317.3	383.4	322.4	380.9	334.5	307.9	296.2	310.4	284.1	307.9	296.2
Steam coal	gas/oil		BASE**	224.9	259.8	227.4	253.6	254.7	245.2	254.9	276.6	257.4	270.4	284.7	262	194.9	243	197.4	236.9	224.7	228.5
		CHP/PSA	only gas (no consumers for heat)	324.4	354.4	327.6	351.7	363.6	341.8	363.8	378.5	367.1	375.8	403.1	365.9	284.9	330.3	288.2	327.6	324.1	317.6
			only gas (40 €/MWh for heat)	276.9	321.9	280.1	319.2	316.1	309.3	316.3	346	319.6	343.3	355.6	333.4	237.4	297.8	240.7	295.1	276.6	285.2
			gas+oil (no consumers for heat)	385.8	318.9	382.2	318.8	403.3	311.8	422.3	338	418.7	337.9	439.8	330.9	349.3	299.7	345.7	299.6	366.8	292.6
			gas+oil (40 €/MWh for heat)	318.2	281.6	314.7	281.6	335.8	274.5	354.7	300.8	351.2	300.7	372.3	293.7	281.8	262.5	278.2	262.4	299.3	255.4
Feedstock	gas/oil		BASE**	165.2	226.6	165.2	222.8	165.2	225.1	208.1	250.5	208.1	246.8	208.1	249	122.4	202.7	122.4	198.9	122.4	201.1
		CHP/PSA	only gas (no consumers for heat)	245.8	306.6	245.8	306.9	245.8	309.1	302.2	341.1	302.2	341.4	302.2	343.5	189.4	272.2	189.4	272.5	189.4	274.6
			only gas (40 €/MWh for heat)	198.3	274.2	198.3	274.4	198.3	276.6	254.7	308.6	254.7	308.9	254.7	311	141.9	239.7	141.9	240	141.9	242.2
			gas+oil (no consumers for heat)	313.2	280.9	306.6	283.9	294.5	290.9	365.3	308.3	358.7	311.2	346.6	318.3	261.1	253.6	254.5	256.6	242.4	263.6
			gas+oil (40 €/MWh for heat)	245.7	243.7	239.1	246.7	227	253.7	297.8	271.1	291.2	274	279.1	281.1	193.5	216.4	186.9	219.3	174.9	226.4
Product carbonisate	gas/oil		BASE**	360.5	292.9	362.6	281.6	384.5	248.6	414.1	304.1	416.1	292.8	438.1	259.9	307	281.7	309	270.4	331	237.4
		CHP/PSA	only gas (no consumers for heat)	698.6	522.5	702.1	515.5	740.6	459.2	792.4	550.2	795.9	543.2	834.4	487	604.8	494.7	608.4	487.7	646.8	431.5
			only gas (40 €/MWh for heat)	585.8	494.3	589.3	487.3	627.8	431.1	679.6	522.1	683.1	515.1	721.6	458.8	492	466.6	495.5	459.6	534	403.3
			gas+oil (no consumers for heat)	769.7	234.7	758.4	241.2	764.6	210.5	848.1	238.6	836.9	245.1	843.1	214.4	691.2	230.8	679.9	237.4	686.2	206.6
			gas+oil (40 €/MWh for heat)	624.4	229.7	613.2	236.2	619.4	205.5	702.9	233.6	691.6	240.1	697.9	209.4	545.9	225.8	534.7	232.4	540.9	201.6

Table 59: Matrix of the considered utilization pathways of algae; Difference mLR-LC as an indicator of profitability (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

Algae			Gate fee	mid			low			high		
			WEO (2016)	Current Policies	New Policies	450	Current Policies	New Policies	450	Current Policies	New Policies	450
Heating	TCR product | Downstream processes		Utilization	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC
Natural gas	carbonisate		BASE*	23.58	14.56	-12.59	10.34	1.32	-25.83	36.83	27.8	0.66
			CCS	23.72	18.5	17.23	10.48	5.26	3.99	36.96	31.75	30.47
Steam coal	carbonisate		BASE*	34.91	26.24	-9.46	21.67	13	-22.7	48.15	39.49	3.78
Feedstock	carbonisate		BASE*	61.25	53.69	30.04	42.34	34.77	11.13	80.18	72.61	48.96
			CCS	61.39	57.63	59.86	42.48	38.72	40.94	80.31	76.55	78.78
Product carbonisate	carbonisate		BASE*	-67.66	-80.96	-135.9	-109.99	-123.29	-178.24	-25.32	-38.62	-93.57
Product syngas	carbonisate		BASE*	-60.72	-71.63	-95.62	-90.62	-101.53	-125.52	-30.83	-41.74	-65.73
			CCS	-60.49	-64.96	-45.11	-90.39	-94.86	-75.01	-30.6	-35.07	-15.22
Natural gas	gas		BASE**	23.72	18.5	17.23	10.48	5.26	3.99	36.96	31.75	30.47
		PSA	H_2+off gas	31.13	28.91	18.59	18.26	16.05	5.72	43.99	41.78	31.45
Steam coal	gas		BASE**	34.91	26.24	-9.46	21.67	13	-22.7	48.15	39.49	3.78
		PSA	H_2+off gas	42	36.32	-8.19	29.13	23.45	-21.06	54.86	49.18	4.67
Feedstock	gas		BASE**	61.39	57.63	59.86	42.48	38.72	40.94	80.31	76.55	78.78
		PSA	H_2+off gas	67.72	66.92	60	49.34	48.55	41.62	**86.09**	**85.29**	78.37
Product carbonisate	gas		BASE**	-67.66	-80.96	-135.9	-109.99	-123.29	-178.24	-25.32	-38.62	-93.57
		PSA	H_2+off gas	-85.78	-93.69	-164.1	-125.95	-133.86	-204.27	-45.59	-53.52	-123.93
Natural gas	gas/oil		BASE**	23.72	18.5	17.23	10.48	5.26	3.99	36.96	31.75	30.47
		CHP	only gas (no consumers for heat)	-14.95	-19.16	-8.03	-29.3	-33.52	-22.38	-0.6	-4.81	6.32
			only gas (40 €/MWh for heat)	8.56	4.34	15.47	-5.8	-10.02	1.12	22.9	18.69	29.82
			gas+oil (no consumers for heat)	-93.39	-89.12	-62.93	-109.57	-105.3	-79.11	-77.21	-72.94	-46.75
			gas+oil (40 €/MWh for heat)	-55.84	-51.57	-25.38	-72.02	-67.75	-41.56	-39.65	-35.39	-9.19
Steam coal	gas/oil		BASE**	34.91	26.24	-9.46	21.67	13	-22.7	48.15	39.49	3.78
		CHP	only gas (no consumers for heat)	-2.82	-10.82	-37.25	-17.17	-25.17	-51.6	11.53	3.53	-22.9
			only gas (40 €/MWh for heat)	20.68	12.68	-13.75	6.33	-1.67	-28.09	35.03	27.03	0.6
			gas+oil (no consumers for heat)	-79.69	-79.05	-90.94	-95.88	-95.22	-107.11	-63.51	-62.87	-74.75
			gas+oil (40 €/MWh for heat)	-42.14	-41.5	-53.38	-58.32	-57.67	-69.56	-25.95	-25.31	-37.2
Feedstock	gas/oil		BASE**	61.39	57.63	59.86	42.48	38.72	40.94	80.31	76.55	78.78
		CHP	only gas (no consumers for heat)	25.87	23.24	38.17	5.37	2.74	17.67	46.37	43.73	58.67
			only gas (40 €/MWh for heat)	49.37	46.74	61.67	28.87	26.24	41.17	69.87	67.23	**82.17**
			gas+oil (no consumers for heat)	-47.35	-41.3	-10.84	-70.47	-64.42	-33.95	-24.23	-18.18	12.28
			gas+oil (40 €/MWh for heat)	-9.8	-3.75	26.72	-32.92	-26.87	3.6	13.32	19.37	49.84
Product carbonisate	gas/oil		BASE**	-67.66	-80.96	-135.9	-109.99	-123.29	-178.24	-25.32	-38.62	-93.57
		CHP	only gas (no consumers for heat)	-161.55	-174.38	-215.08	-211.32	-224.15	-264.85	-111.77	-124.61	-165.31
			only gas (40 €/MWh for heat)	-74.22	-87.05	-127.76	-123.99	-136.83	-177.53	-24.45	-37.28	-77.98
			gas+oil (no consumers for heat)	-425.04	-416.38	-421.16	-485.43	-476.77	-481.55	-364.65	-355.99	-360.77
			gas+oil (40 €/MWh for heat)	-291.51	-282.85	-287.63	-351.9	-343.24	-348.02	-231.12	-222.46	-227.24
Natural gas	gas/oil		BASE**	23.72	18.5	17.23	10.48	5.26	3.99	36.96	31.75	30.47
		CHP/PSA	only gas (no consumers for heat)	17.1	15.7	13.78	1.73	0.33	-1.59	29.15	31.06	29.15
			only gas (40 €/MWh for heat)	32.11	30.7	28.79	16.74	15.32	13.42	44.16	46.07	44.16
			gas+oil (no consumers for heat)	-81.58	-73.94	-59.42	-98.92	-91.28	-76.76	-42.07	-56.59	-42.07
			gas+oil (40 €/MWh for heat)	-51.27	-43.63	-29.11	-68.62	-60.97	-46.45	-11.76	-26.29	-11.76
Steam coal	gas/oil		BASE**	34.91	26.24	-9.46	21.67	13	-22.7	48.15	39.49	3.78
		CHP/PSA	only gas (no consumers for heat)	30.06	24.07	-21.82	14.7	8.7	-37.19	45.44	39.45	-6.46
			only gas (40 €/MWh for heat)	45.07	39.07	-6.82	29.7	23.71	-22.19	60.44	54.44	8.55
			gas+oil (no consumers for heat)	-66.92	-63.43	-91.58	-84.26	-80.77	-108.92	-49.57	-46.08	-74.23
			gas+oil (40 €/MWh for heat)	-36.6	-33.12	-61.27	-53.94	-50.46	-78.61	-19.26	-15.78	-43.93
Feedstock	gas/oil		BASE**	61.39	57.63	59.86	42.48	38.72	40.94	80.31	76.55	78.78
		CHP/PSA	only gas (no consumers for heat)	60.82	61.11	63.26	38.86	39.15	41.3	**82.78**	**83.07**	**85.22**
			only gas (40 €/MWh for heat)	75.83	76.12	78.27	53.87	54.16	56.31	**97.78**	**98.07**	**100.22**
			gas+oil (no consumers for heat)	-32.25	-22.69	-3.59	-57.03	-47.47	-28.37	-7.47	2.09	21.2
			gas+oil (40 €/MWh for heat)	-1.94	7.62	26.72	-26.71	-17.15	1.95	22.84	32.4	51.5
Product carbonisate	gas/oil		BASE**	-67.66	-80.96	-135.9	-109.99	-123.29	-178.24	-25.32	-38.62	-93.57
		CHP/PSA	only gas (no consumers for heat)	-176.13	-186.66	-281.4	-242.16	-252.69	-347.41	-110.11	-120.64	-215.37
			only gas (40 €/MWh for heat)	-91.47	-102	-196.72	-157.49	-168.02	-262.75	-25.44	-35.97	-130.71
			gas+oil (no consumers for heat)	-534.96	-517.18	-554.15	-609.56	-591.78	-628.74	-460.35	-442.58	-479.55
			gas+oil (40 €/MWh for heat)	-394.71	-376.93	-413.9	-469.31	-451.53	-488.5	-320.11	-302.33	-339.29

Table 60: Matrix of the considered utilization pathways of oMSW; Comparison of mLR and LC (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

oMSW			Gate fee	mid						low						high					
			WEO (2016)	Current Policies		New Policies		450		Current Policies		New Policies		450		Current Policies		New Policies		450	
Heating	TCR product | Downstream processes		Utilization	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR
Natural gas	carbonisate		BASE*	245.6	295.6	248.9	286.6	256.7	261.7	275	312.1	278.3	303.1	286.1	278.2	216.2	279.1	219.5	270	227.2	245.2
			CCS	245.6	293.6	248.9	288.8	256.7	292.3	275	310.1	278.3	305.3	286.1	308.9	216.2	277	219.5	272.3	227.2	275.8
Steam coal	carbonisate		BASE*	220.5	281.5	222.9	272	249.7	257.8	249.9	298	252.3	288.5	279.1	274.3	191.1	265	193.5	255.5	220.3	241.3
Feedstock	carbonisate		BASE*	165	250.3	165	239.4	165	210.2	204.8	272.7	204.8	261.8	204.8	232.6	125.2	227.9	125.2	217.1	125.2	187.8
			CCS	165	248.3	165	241.7	165	240.8	204.8	270.6	204.8	264	204.8	263.2	125.2	225.9	125.2	219.3	125.2	218.5
Product carbonisate	carbonisate		BASE*	431.1	467.5	432.7	446.5	450.6	394.2	497.3	490.3	498.9	469.2	516.8	417	364.9	444.8	366.6	423.7	384.4	371.5
Product syngas	carbonisate		BASE*	253.8	220.7	253.8	206.6	253.8	177.8	296.2	234.9	296.2	220.7	296.2	192	211.3	206.6	211.3	192.4	211.3	163.7
			CCS	253.8	217.7	253.8	209.8	253.8	222.1	296.2	231.9	296.2	224	296.2	236.2	211.3	203.6	211.3	195.7	211.3	207.9
Natural gas	gas		BASE**	245.6	295.6	248.9	288.8	256.7	292.3	275	312.1	278.3	305.3	286.1	308.9	216.2	279.1	219.5	272.3	227.2	275.8
		PSA	H_2+off gas	277.2	326.4	280.4	321.7	288.2	320.4	306.6	343.1	309.8	338.4	317.6	337.1	247.8	309.7	251	305	258.8	303.7
Steam coal	gas		BASE**	220.5	281.5	222.9	272	249.7	257.8	249.9	298	252.3	288.5	279.1	274.3	191.1	265	193.5	255.5	220.3	241.3
		PSA	H_2+off gas	252	312.1	254.5	304.8	281.3	285.9	281.4	328.8	283.9	321.5	310.7	302.6	222.6	295.4	225.1	288.1	251.8	269.2
Feedstock	gas		BASE**	165	250.3	165	241.7	165	240.8	204.8	272.7	204.8	264	204.8	263.2	125.2	227.9	125.2	219.3	125.2	218.5
		PSA	H_2+off gas	196.6	280.6	196.6	274.1	196.6	268.4	236.4	303.2	236.4	296.7	236.4	291	156.7	258	156.7	251.5	156.7	245.8
Product carbonisate	gas		BASE**	431.1	467.5	432.7	446.5	450.6	394.2	497.3	490.3	498.9	469.2	516.8	417	364.9	444.8	366.6	423.7	384.4	371.5
		PSA	H_2+off gas	502.1	513.7	503.7	497.5	521.6	434.8	568.3	538.5	569.9	522.3	587.8	459.5	435.9	489	437.6	472.8	455.4	410
Natural gas	gas/oil		BASE**	245.6	295.6	248.9	288.8	256.7	292.3	275	312.1	278.3	305.3	286.1	308.9	216.2	279.1	219.5	272.3	227.2	275.8
		CHP	only gas (no consumers for heat)	265	271.1	249.5	265.2	276.8	280.2	296.5	288.9	299.9	282.9	308.2	297.9	233.6	253.4	237.1	247.4	245.4	262.4
			only gas (40 €/MWh for heat)	217.8	238.1	221.3	232.2	229.6	247.2	249.2	255.9	252.7	249.9	261	264.9	186.4	220.4	189.8	214.4	198.1	229.4
			gas+oil (no consumers for heat)	367	265.6	362	263.4	354.9	284.9	397.8	280.8	392.8	278.7	385.6	300.1	336.2	250.4	331.2	248.2	324.1	269.6
			gas+oil (40 €/MWh for heat)	290.3	221	285.3	218.8	278.1	240.3	321	236.2	316.1	234.1	308.9	255.5	259.5	205.8	254.5	203.6	247.4	225
Steam coal	gas/oil		BASE**	220.5	281.5	222.9	272	249.7	257.8	249.9	298	252.3	288.5	279.1	274.3	191.1	265	193.5	255.5	220.3	241.3
		CHP	only gas (no consumers for heat)	238.1	256	240.8	247.1	269.4	243.3	269.6	273.7	272.2	264.9	300.8	261	206.7	238.2	209.3	229.4	237.9	225.5
			only gas (40 €/MWh for heat)	190.9	223	193.5	214.1	222.1	210.3	222.4	240.7	225	231.9	253.6	228	159.5	205.2	162.1	196.4	190.7	192.5
			gas+oil (no consumers for heat)	340.6	252.6	334.9	247.7	347.6	249.2	371.4	267.8	365.6	262.9	378.4	264.4	309.9	237.3	304.1	232.4	316.8	234
			gas+oil (40 €/MWh for heat)	263.9	208	258.1	203	270.9	204.6	294.7	223.2	288.9	218.3	301.6	219.8	233.1	192.7	227.4	187.8	240.1	189.4
Feedstock	gas/oil		BASE**	165	250.3	165	241.7	165	240.8	204.8	272.7	204.8	264	204.8	263.2	125.2	227.9	125.2	219.3	125.2	218.5
		CHP	only gas (no consumers for heat)	178.8	222.5	178.8	214.5	178.8	224.9	221.4	246.5	221.4	238.6	221.4	248.9	136.3	198.4	136.3	190.5	136.3	200.8
			only gas (40 €/MWh for heat)	131.6	189.5	131.6	181.6	131.6	191.9	174.2	213.5	174.2	205.6	174.2	215.9	89.05	165.4	89.05	157.5	89.05	167.8
			gas+oil (no consumers for heat)	282.6	223.8	274.2	220	258.9	237.4	324.3	244.5	315.9	240.6	300.6	258	240.9	203.2	232.5	199.3	217.2	216.7
			gas+oil (40 €/MWh for heat)	205.9	179.2	197.5	175.4	182.2	192.8	247.6	199.9	239.2	196	223.9	213.4	164.2	158.6	155.8	154.7	140.5	172.1
Product carbonisate	gas/oil		BASE**	431.1	467.5	432.7	446.5	450.6	394.2	497.3	490.3	498.9	469.2	516.8	417	364.9	444.8	366.6	423.7	384.4	371.5
		CHP	only gas (no consumers for heat)	510.2	434.5	512.1	413.1	533	379.7	587.6	461.5	589.5	440.2	610.4	406.8	432.9	407.5	434.8	386.1	455.6	352.7
			only gas (40 €/MWh for heat)	394	404.5	395.9	383.2	416.8	349.8	471.4	431.5	473.3	410.2	494.2	376.8	316.6	377.5	318.5	356.1	339.4	322.7
			gas+oil (no consumers for heat)	741.6	138.6	723.5	138.6	706.8	138.6	815.2	138.6	797.1	138.6	780.4	138.6	668.1	138.6	650	138.6	633.3	138.6
			gas+oil (40 €/MWh for heat)	558.4	138.6	540.2	138.6	523.5	138.6	631.9	138.6	613.8	138.6	597.1	138.6	484.8	138.6	466.7	138.6	450	138.6
Natural gas	gas/oil		BASE**	245.6	295.6	248.9	288.8	256.7	292.3	275	312.1	278.3	305.3	286.1	308.9	216.2	279.1	219.5	272.3	227.2	275.8
		CHP/PSA	only gas (no consumers for heat)	309.9	335	313.8	330.5	323.1	337.9	345.1	355.7	349	351.3	358.3	358.7	274.7	314.3	278.6	309.8	287.9	317.2
			only gas (40 €/MWh for heat)	273	305.8	276.9	301.3	286.2	308.7	308.2	326.5	312	322	321.3	329.4	237.8	285	241.7	280.5	251	287.9
			gas+oil (no consumers for heat)	401.6	309.8	396.3	309	388.6	322.2	434.5	326.5	429.2	325.8	421.6	339	368.7	293	363.4	292.3	355.7	305.5
			gas+oil (40 €/MWh for heat)	332.9	266.4	327.6	265.6	319.9	278.8	365.8	283.1	360.5	282.4	352.8	295.6	299.9	249.6	294.7	248.9	287	262.1
Steam coal	gas/oil		BASE**	220.5	281.5	222.9	272	249.7	257.8	249.9	298	252.3	288.5	279.1	274.3	191.1	265	193.5	255.5	220.3	241.3
		CHP/PSA	only gas (no consumers for heat)	279.8	317.3	282.7	309.6	314.8	296.4	315	338	317.9	330.3	349.9	317.1	244.6	296.6	247.6	288.9	279.6	275.7
			only gas (40 €/MWh for heat)	242.9	288	245.8	280.3	277.8	267.1	278.1	308.7	281	301	313	287.9	207.7	267.3	210.6	259.6	242.6	246.4
			gas+oil (no consumers for heat)	373.4	295.5	367.2	291.8	380.9	284	406.4	312.2	400.2	308.5	413.8	300.7	340.5	278.7	334.3	275	347.9	267.3
			gas+oil (40 €/MWh for heat)	304.7	252.1	298.5	248.4	312.1	240.6	337.6	268.8	331.4	265.1	345	257.3	271.8	235.3	265.6	231.6	279.2	223.9
Feedstock	gas/oil		BASE**	165	250.3	165	241.7	165	240.8	204.8	272.7	204.8	264	204.8	263.2	125.2	227.9	125.2	219.3	125.2	218.5
		CHP/PSA	only gas (no consumers for heat)	213.4	278.2	213.4	271.4	213.4	273.4	261.1	306.3	261.1	299.5	261.1	301.4	165.8	250.1	165.8	243.4	165.8	245.3
			only gas (40 €/MWh for heat)	176.5	248.9	176.5	242.2	176.5	244.1	224.2	277	224.2	270.2	224.2	272.2	128.9	220.9	128.9	214.1	128.9	216
			gas+oil (no consumers for heat)	311.4	263.9	302.4	261.3	286.1	270.1	355.9	286.5	347	284	330.6	292.7	266.8	241.2	257.8	238.6	241.5	247.4
			gas+oil (40 €/MWh for heat)	242.6	220.5	233.7	217.9	217.3	226.7	287.2	243.1	278.3	240.5	261.9	249.3	198	197.8	189.1	195.2	172.8	204
Product carbonisate	gas/oil		BASE**	431.1	467.5	432.7	446.5	450.6	394.2	497.3	490.3	498.9	469.2	516.8	417	364.9	444.8	366.6	423.7	384.4	371.5
		CHP/PSA	only gas (no consumers for heat)	731.2	695.7	733.8	673.3	762.1	601.4	836.1	740.4	838.7	717.9	867	646.1	626.3	651.1	628.9	628.6	657.2	556.8
			only gas (40 €/MWh for heat)	621.1	653.8	623.7	631.3	652	559.5	726	698.5	728.6	676	756.9	604.2	516.2	609.1	518.8	586.6	547.1	514.8
			gas+oil (no consumers for heat)	901.8	219.2	880.3	223.9	860.5	199.9	988.8	222.7	967.3	227.4	947.6	203.4	814.8	215.7	793.3	220.4	773.5	196.4
			gas+oil (40 €/MWh for heat)	720.1	214.5	698.6	219.1	678.9	195.1	807.1	218	785.6	222.6	765.9	198.7	633.1	210.9	611.6	215.6	591.9	191.6

Table 61: Matrix of the considered utilization pathways of oMSW; Difference mLR-LC as an indicator of profitability (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

oMSW			Gate fee	mid			low			high		
			WEO (2016)	Current Policies	New Policies	450	Current Policies	New Policies	450	Current Policies	New Policies	450
Heating	TCR product | Downstream processes		Utilization	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC
Natural gas	carbonisate		BASE*	49.98	37.67	5.05	37.1	24.78	-7.84	62.87	50.56	17.94
			CCS	47.92	39.9	35.68	35.03	27.01	22.79	60.81	52.79	48.56
Steam coal	carbonisate		BASE*	61	49.05	8.1	48.12	36.16	-4.79	73.89	61.94	20.99
Feedstock	carbonisate		BASE*	85.32	74.43	45.22	67.86	56.98	27.76	**102.78**	91.9	62.68
			CCS	83.25	76.66	75.84	65.8	59.21	58.38	**100.72**	**94.12**	93.3
Product carbonisate	carbonisate		BASE*	36.42	13.72	-56.38	-7.01	-29.71	-99.8	79.83	57.13	-12.96
Product syngas	carbonisate		BASE*	-33.04	-47.16	-75.92	-61.37	-75.5	-104.26	-4.71	-18.83	-47.59
			CCS	-36.02	-43.95	-31.7	-64.35	-72.28	-60.03	-7.68	-15.62	-3.37
Natural gas	gas		BASE**	49.98	39.9	35.68	37.1	27.01	22.79	62.87	52.79	48.56
		PSA	H_2+off gas	49.22	41.3	32.23	36.51	28.58	19.51	61.94	54.01	44.94
Steam coal	gas		BASE**	61	49.05	8.1	48.12	36.16	-4.79	73.89	61.94	20.99
		PSA	H_2+off gas	60.1	50.29	4.61	47.39	37.57	-8.11	72.81	63.01	17.32
Feedstock	gas		BASE**	85.32	76.66	75.84	67.86	59.21	58.38	**102.78**	**94.12**	93.3
		PSA	H_2+off gas	84.08	77.56	71.85	66.86	60.34	54.63	**101.3**	**94.77**	89.06
Product carbonisate	gas		BASE**	36.42	13.72	-56.38	-7.01	-29.71	-99.8	79.83	57.13	-12.96
		PSA	H_2+off gas	11.61	-6.24	-86.8	-29.82	-47.67	-128.23	53.04	35.19	-45.38
Natural gas	gas/oil		BASE**	49.98	39.9	35.68	37.1	27.01	22.79	62.87	52.79	48.56
		CHP	only gas (no consumers for heat)	6.11	15.67	3.37	-7.58	-17.01	-10.31	19.79	10.35	17.06
			only gas (40 €/MWh for heat)	20.34	10.9	17.62	6.66	-2.78	3.92	34.03	24.6	31.3
			gas+oil (no consumers for heat)	-101.36	-98.58	-69.99	-116.92	-114.13	-85.55	-85.82	-83.04	-54.45
			gas+oil (40 €/MWh for heat)	-69.26	-66.48	-37.89	-84.8	-82.02	-53.43	-53.71	-50.94	-22.35
Steam coal	gas/oil		BASE**	61	49.05	8.1	48.12	36.16	-4.79	73.89	61.94	20.99
		CHP	only gas (no consumers for heat)	17.81	6.37	-26.12	4.13	-7.31	-39.8	31.5	20.06	-12.43
			only gas (40 €/MWh for heat)	32.05	20.61	-11.88	18.36	6.92	-25.57	45.73	34.29	1.8
			gas+oil (no consumers for heat)	-88.07	-87.2	-98.38	-103.62	-102.75	-113.92	-72.53	-71.65	-82.82
			gas+oil (40 €/MWh for heat)	-55.96	-55.09	-66.26	-71.51	-70.63	-81.81	-40.42	-39.54	-50.72
Feedstock	gas/oil		BASE**	85.32	76.66	75.84	67.86	59.21	58.38	**102.78**	**94.12**	93.3
		CHP	only gas (no consumers for heat)	43.63	35.7	46.02	25.1	17.17	27.49	62.16	54.24	64.56
			only gas (40 €/MWh for heat)	57.86	49.94	60.26	39.33	31.4	41.72	76.39	68.47	78.79
			gas+oil (no consumers for heat)	-58.75	-54.25	-21.56	-79.8	-75.3	-42.61	-37.69	-33.19	-0.5
			gas+oil (40 €/MWh for heat)	-26.64	-22.14	10.55	-47.7	-43.2	-10.49	-5.6	-1.09	31.6
Product carbonisate	gas/oil		BASE**	36.42	13.72	-56.38	-7.01	-29.71	-99.8	79.83	57.13	-12.96
		CHP	only gas (no consumers for heat)	-75.74	-99.01	-153.28	-126.09	-149.35	-203.64	-25.39	-48.65	-102.94
			only gas (40 €/MWh for heat)	10.52	-12.74	-67.02	-39.83	-63.09	-117.38	60.88	37.61	-16.67
			gas+oil (no consumers for heat)	-603.07	-584.94	-568.24	-676.61	-658.48	-641.78	-529.53	-511.39	-494.69
			gas+oil (40 €/MWh for heat)	-419.79	-401.66	-384.96	-493.33	-475.2	-458.5	-346.25	-328.11	-311.41
Natural gas	gas/oil		BASE**	49.98	39.9	35.68	37.1	27.01	22.79	62.87	52.79	48.56
		CHP/PSA	only gas (no consumers for heat)	25.11	16.75	14.85	10.65	2.29	0.39	39.57	31.2	29.31
			only gas (40 €/MWh for heat)	32.78	24.41	22.52	18.32	9.96	8.06	47.24	38.88	36.98
			gas+oil (no consumers for heat)	-91.82	-87.27	-66.41	-107.99	-103.44	-82.58	-75.64	-71.1	-50.23
			gas+oil (40 €/MWh for heat)	-66.5	-61.95	-41.09	-82.66	-78.13	-57.26	-50.32	-45.78	-24.91
Steam coal	gas/oil		BASE**	61	49.05	8.1	48.12	36.16	-4.79	73.89	61.94	20.99
		CHP/PSA	only gas (no consumers for heat)	37.48	26.85	-18.36	23.02	12.39	-32.82	51.94	41.3	-3.9
			only gas (40 €/MWh for heat)	45.14	34.51	-10.69	30.68	20.05	-25.15	59.61	48.98	3.77
			gas+oil (no consumers for heat)	-77.98	-75.49	-96.85	-94.16	-91.67	-113.03	-61.81	-59.32	-80.68
			gas+oil (40 €/MWh for heat)	-52.66	-50.16	-71.54	-68.83	-66.34	-87.7	-36.49	-34	-55.36
Feedstock	gas/oil		BASE**	85.32	76.66	75.84	67.86	59.21	58.38	**102.78**	**94.12**	93.3
		CHP/PSA	only gas (no consumers for heat)	64.75	57.99	59.91	45.17	38.4	40.33	84.34	77.57	79.5
			only gas (40 €/MWh for heat)	72.42	65.65	67.58	52.84	46.07	47.99	92	85.24	87.16
			gas+oil (no consumers for heat)	-47.48	-41.15	-16.01	-69.38	-63.05	-37.91	-25.57	-19.24	5.89
			gas+oil (40 €/MWh for heat)	-22.16	-15.83	9.31	-44.05	-37.73	-12.6	-0.25	6.07	31.22
Product carbonisate	gas/oil		BASE**	36.42	13.72	-56.38	-7.01	-29.71	-99.8	79.83	57.13	-12.96
		CHP/PSA	only gas (no consumers for heat)	-35.45	-60.52	-160.63	-95.67	-120.74	-220.85	24.76	-0.31	-100.42
			only gas (40 €/MWh for heat)	32.69	7.62	-92.48	-27.53	-52.6	-152.7	92.9	67.83	-32.27
			gas+oil (no consumers for heat)	-682.56	-656.44	-660.66	-766.05	-739.93	-744.15	-599.07	-572.94	-577.17
			gas+oil (40 €/MWh for heat)	-505.62	-479.49	-483.72	-589.11	-562.99	-567.21	-422.13	-396	-400.23

Table 62: Matrix of the considered utilization pathways of SWF; Comparison of mLR and LC (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

SWF			Gate fee	mid						low						high					
			WEO (2016)	Current Policies		New Policies		450		Current Policies		New Policies		450		Current Policies		New Policies		450	
Heating	TCR product | Downstream processes		Utilization	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR
Natural gas	carbonisate		BASE*	264.9	368.5	268.4	358.4	276.9	324	293.4	384.1	297	374	305.5	339.6	179.2	321.8	182.7	311.6	191.2	277.2
			CCS	264.9	367.1	268.4	362	276.9	361.3	293.4	382.7	297	377.6	305.5	376.8	179.2	320.4	182.7	315.3	191.2	314.5
Steam coal	carbonisate		BASE*	237.4	353.5	240.1	342.9	269.3	319.8	266	369.1	268.6	358.5	297.9	335.4	151.7	306.8	154.3	296.2	183.6	273.1
Feedstock	carbonisate		BASE*	179.5	322	179.5	309.9	179.5	270.9	215.8	341.8	215.8	329.7	215.8	290.7	70.54	262.5	70.54	250.5	70.54	211.4
			CCS	179.5	320.6	179.5	313.5	179.5	308.1	215.8	340.4	215.8	333.3	215.8	327.9	70.54	261.1	70.54	254.1	70.54	248.7
Product carbonisate	carbonisate		BASE*	286.9	366.1	287.9	351.4	299.2	305	326.9	376.8	327.9	362.2	339.2	315.8	166.9	333.8	167.9	319.2	179.2	272.7
Product syngas	carbonisate		BASE*	270.6	391.1	270.6	375.5	270.6	334.1	311.6	416.7	311.6	401.1	311.6	359.7	147.5	314.4	147.5	298.8	147.5	257.3
			CCS	270.6	389.1	270.6	380.7	270.6	387.6	311.6	414.7	311.6	406.3	311.6	413.2	147.5	312.4	147.5	304	147.5	310.8
Natural gas	gas		BASE**	264.9	368.5	268.4	362	276.9	361.3	293.4	384.1	297	377.6	305.5	376.8	179.2	321.8	182.7	315.3	191.2	314.5
		PSA	H_2+off gas	319.5	508.4	323.1	505.8	331.6	479.2	348.1	524.7	351.6	522.1	360.1	495.5	233.8	459.5	237.4	456.8	245.9	430.3
Steam coal	gas		BASE**	237.4	353.5	240.1	342.9	269.3	319.8	266	369.1	268.6	358.5	297.9	335.4	151.7	306.8	154.3	296.2	183.6	273.1
		PSA	H_2+off gas	292	492.7	294.7	485.9	324	437.6	320.6	509	323.3	502.2	352.5	453.9	206.3	443.8	209	437	238.3	388.7
Feedstock	gas		BASE**	179.5	322	179.5	313.5	179.5	308.1	215.8	341.8	215.8	333.3	215.8	327.9	70.54	262.5	70.54	254.1	70.54	248.7
		PSA	H_2+off gas	234.1	459.7	234.1	455	234.1	423.6	270.5	480.4	270.5	475.7	270.5	444.3	125.2	397.5	125.2	392.8	125.2	361.4
Product carbonisate	gas		BASE**	286.9	366.1	287.9	351.4	299.2	305	326.9	376.8	327.9	362.2	339.2	315.8	166.9	333.8	167.9	319.2	179.2	272.7
		PSA	H_2+off gas	363.4	542.6	364.4	533.3	375.7	451	403.4	555.3	404.4	546	415.7	463.7	243.4	504.3	244.4	495	255.7	412.7
Natural gas	gas/oil		BASE**	264.9	368.5	268.4	362	276.9	361.3	293.4	384.1	297	377.6	305.5	376.8	179.2	321.8	182.7	315.3	191.2	314.5
		CHP	only gas (no consumers for heat)	297	320.1	300.7	315.7	309.8	336.2	327.3	336.7	331.1	332.3	340.1	352.8	206	270.3	209.8	266	218.8	286.5
			only gas (40 €/MWh for heat)	208.7	282.6	212.5	278.2	221.5	298.8	239.1	299.2	242.8	294.8	251.9	315.4	117.8	232.9	121.5	228.5	130.5	249
			gas+oil (no consumers for heat)	432.5	287.7	426.5	288.7	417.5	318.3	462.3	300	456.3	300.9	447.4	330.5	342.9	251.1	336.9	252.1	328	281.7
			gas+oil (40 €/MWh for heat)	331	257.4	325	258.4	316.1	288	360.8	269.6	354.8	270.6	345.9	300.2	241.4	220.8	235.4	221.7	226.5	251.4
Steam coal	gas/oil		BASE**	237.4	353.5	240.1	342.9	269.3	319.8	266	369.1	268.6	358.5	297.9	335.4	151.7	306.8	154.3	296.2	183.6	273.1
		CHP	only gas (no consumers for heat)	267.8	304.1	270.6	295.4	301.7	292.3	298.1	320.7	301	312	332	308.9	176.8	254.4	179.7	245.6	210.7	242.5
			only gas (40 €/MWh for heat)	179.6	266.7	182.4	257.9	213.5	254.8	209.9	283.2	212.7	274.5	243.8	271.4	88.58	216.9	91.41	208.2	122.5	205.1
			gas+oil (no consumers for heat)	403.8	276	396.8	272.8	409.6	276.1	433.6	288.2	426.7	285	439.5	288.3	314.2	239.4	307.2	236.1	320	239.5
			gas+oil (40 €/MWh for heat)	302.3	245.7	295.3	242.4	308.1	245.8	332.1	257.9	325.2	254.7	338	258	212.7	209.1	205.8	205.8	218.5	209.2
Feedstock	gas/oil		BASE**	179.5	322	179.5	313.5	179.5	308.1	215.8	341.8	215.8	333.3	215.8	327.9	70.54	262.5	70.54	254.1	70.54	248.7
		CHP	only gas (no consumers for heat)	206.4	270.5	206.4	264.1	206.4	279.7	244.9	291.6	244.9	285.2	244.9	300.8	90.7	207.3	90.7	200.9	90.7	216.5
			only gas (40 €/MWh for heat)	118.1	233.1	118.1	226.6	118.1	242.2	156.7	254.1	156.7	247.7	156.7	263.3	2.46	102.9	2.46	96.42	2.46	112
			gas+oil (no consumers for heat)	343.3	251.3	333.5	250.7	315.7	276.7	381.2	266.8	371.5	266.2	353.7	292.2	229.4	204.7	219.7	204.1	201.9	230.1
			gas+oil (40 €/MWh for heat)	241.8	221	232	220.4	214.2	246.4	279.7	236.5	270	235.9	252.2	261.9	127.9	174.4	118.2	173.8	100.4	199.8
Product carbonisate	gas/oil		BASE**	286.9	366.1	287.9	351.4	299.2	305	326.9	376.8	327.9	362.2	339.2	315.8	166.9	333.8	167.9	319.2	179.2	272.7
		CHP	only gas (no consumers for heat)	334.9	290.4	336	278.1	348.3	258.2	378.4	302.2	379.6	289.9	391.9	270	204.3	255.2	205.4	242.9	217.7	223
			only gas (40 €/MWh for heat)	208.3	268.4	209.4	256.1	221.7	236.2	251.8	280.1	252.9	267.8	265.2	247.9	77.67	233.1	78.8	220.8	91.1	200.9
			gas+oil (no consumers for heat)	527.3	156.3	514.5	156.3	501.2	156.3	569.8	156.3	557.1	156.3	543.7	156.3	399.5	156.3	386.8	156.3	373.4	156.3
			gas+oil (40 €/MWh for heat)	382.6	156.3	369.8	156.3	356.5	156.3	425.1	156.3	412.4	156.3	399	156.3	254.8	156.3	242.1	156.3	228.7	156.3
Natural gas	gas/oil		BASE**	264.9	368.5	268.4	362	276.9	361.3	293.4	384.1	297	377.6	305.5	376.8	179.2	321.8	182.7	315.3	191.2	314.5
		CHP/PSA	only gas (no consumers for heat)	359.4	468.1	363.3	468.5	372.6	467.8	390.6	486	394.5	486.4	403.8	485.7	265.7	414.3	269.6	414.7	278.9	414
			only gas (40 €/MWh for heat)	259.8	422.1	263.7	422.6	273	421.8	291	440	294.9	440.5	304.2	439.8	166.1	368.3	170	368.8	179.3	368
			gas+oil (no consumers for heat)	486.5	420.3	480.3	425.8	471	434.2	517.6	433.9	511.3	439.5	502	447.9	393.4	379.2	387.1	384.7	377.8	393.1
			gas+oil (40 €/MWh for heat)	358.9	377.5	352.6	383.1	343.4	391.5	389.9	391.2	383.7	396.8	374.4	405.2	265.7	336.5	259.5	342	250.2	350.4
Steam coal	gas/oil		BASE**	237.4	353.5	240.1	342.9	269.3	319.8	266	369.1	268.6	358.5	297.9	335.4	151.7	306.8	154.3	296.2	183.6	273.1
		CHP/PSA	only gas (no consumers for heat)	329.4	450.8	332.3	446.7	364.2	422.3	360.6	468.7	363.5	464.7	395.5	440.2	235.7	397	238.6	392.9	270.6	368.5
			only gas (40 €/MWh for heat)	229.8	404.9	232.7	400.8	264.7	376.3	261	422.8	263.9	418.7	295.9	394.3	136.1	351.1	139	347	171	322.6
			gas+oil (no consumers for heat)	456.7	407.1	449.4	408.2	462.7	390.1	487.7	420.8	480.5	421.9	493.8	403.8	363.5	366	356.3	367.1	369.6	349
			gas+oil (40 €/MWh for heat)	329	364.4	321.8	365.5	335.1	347.4	360.1	378.1	352.9	379.2	366.1	361	235.9	323.3	228.6	324.4	241.9	306.3
Feedstock	gas/oil		BASE**	179.5	322	179.5	313.5	179.5	308.1	215.8	341.8	215.8	333.3	215.8	327.9	70.54	262.5	70.54	254.1	70.54	248.7
		CHP/PSA	only gas (no consumers for heat)	266.1	414.5	266.1	412.7	266.1	406.6	305.8	437.3	305.8	435.5	305.8	429.4	147	346.1	147	344.3	147	338.3
			only gas (40 €/MWh for heat)	166.5	368.5	166.5	366.7	166.5	360.7	206.2	391.3	206.2	389.5	206.2	383.5	47.45	300.2	47.45	298.4	47.45	292.3
			gas+oil (no consumers for heat)	393.7	379.3	383.6	383.2	365.1	387.5	433.2	396.7	423.1	400.6	404.6	404.9	275.3	327.1	265.2	330.9	246.7	335.3
			gas+oil (40 €/MWh for heat)	266.1	336.6	256	340.4	237.5	344.8	305.6	354	295.5	357.8	276.9	362.2	147.7	284.4	137.6	288.2	119.1	292.6
Product carbonisate	gas/oil		BASE**	286.9	366.1	287.9	351.4	299.2	305	326.9	376.8	327.9	362.2	339.2	315.8	166.9	333.8	167.9	319.2	179.2	272.7
		CHP/PSA	only gas (no consumers for heat)	427.3	484.4	428.4	478.7	441.3	426.5	472.7	499	473.8	493.3	486.7	441.1	291.1	440.6	292.3	434.8	305.1	382.6
			only gas (40 €/MWh for heat)	282.5	453	283.6	447.3	296.5	395.1	327.9	467.6	329	461.9	341.9	409.7	146.3	409.2	147.5	403.5	160.3	351.2
			gas+oil (no consumers for heat)	611.1	322.9	597.6	329.4	583.5	297.4	656.2	325.6	642.7	332.2	628.6	300.1	476	314.7	462.5	321.2	448.4	289.2
			gas+oil (40 €/MWh for heat)	426	316.4	412.5	323	398.4	290.9	471	319.2	457.6	325.7	443.4	293.6	290.9	308.2	277.4	314.8	263.3	282.7

Table 63: Matrix of the considered utilization pathways of SWF; Difference mLR-LC as an indicator of profitability (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

SWF			Gate fee	mid			low			high		
			WEO (2016)	Current Policies	New Policies	450	Current Policies	New Policies	450	Current Policies	New Policies	450
Heating	TCR product | Downstream processes		Utilization	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC
Natural gas	carbonisate		BASE*	103.64	89.95	47.07	90.65	76.96	34.08	142.61	128.93	86.04
			CCS	102.24	93.59	84.34	89.25	80.6	71.35	141.21	132.57	123.31
Steam coal	carbonisate		BASE*	116.14	102.86	50.53	103.15	89.87	37.54	155.11	141.84	89.5
Feedstock	carbonisate		BASE*	142.46	130.39	91.36	125.95	113.89	74.86	192	179.93	140.9
			CCS	141.06	134.02	128.63	124.56	117.52	112.13	190.6	183.56	178.17
Product carbonisate	carbonisate		BASE*	79.18	63.53	5.77	49.93	34.28	-23.47	166.92	151.27	93.52
Product syngas	carbonisate		BASE*	120.52	104.93	63.49	105.07	89.48	48.04	166.85	151.26	109.82
			CCS	118.52	110.14	117	103.07	94.7	101.55	164.85	156.47	163.33
Natural gas	gas		BASE**	103.64	93.59	84.34	90.65	80.6	71.35	142.61	132.57	123.31
		PSA	H_2+off gas	188.9	182.68	147.64	176.63	170.42	135.37	225.67	219.45	184.42
Steam coal	gas		BASE**	116.14	102.86	50.53	103.15	89.87	37.54	155.11	141.84	89.5
		PSA	H_2+off gas	200.7	191.22	113.64	188.44	178.96	101.37	237.47	227.99	150.41
Feedstock	gas		BASE**	142.46	134.02	128.63	125.95	117.52	112.13	192	183.56	178.17
		PSA	H_2+off gas	225.53	220.84	189.44	209.95	205.25	173.85	**272.28**	**267.58**	236.19
Product carbonisate	gas		BASE**	79.18	63.53	5.77	49.93	34.28	-23.47	166.92	151.27	93.52
		PSA	H_2+off gas	179.19	168.83	75.23	151.95	141.59	47.99	**260.91**	**250.55**	156.95
Natural gas	gas/oil		BASE**	103.64	93.59	84.34	90.65	80.6	71.35	142.61	132.57	123.31
		CHP	only gas (no consumers for heat)	23.09	14.96	26.48	9.34	1.21	12.73	64.33	56.2	67.71
			only gas (40 €/MWh for heat)	73.86	65.73	77.25	60.12	51.99	63.5	115.1	106.98	118.49
			gas+oil (no consumers for heat)	-144.74	-137.81	-99.26	-162.39	-155.47	-116.92	-91.77	-84.84	-46.29
			gas+oil (40 €/MWh for heat)	-73.54	-66.61	-28.08	-91.2	-84.27	-45.73	-20.58	-13.66	24.89
Steam coal	gas/oil		BASE**	116.14	102.86	50.53	103.15	89.87	37.54	155.11	141.84	89.5
		CHP	only gas (no consumers for heat)	36.31	24.75	-9.42	22.57	11	-23.17	77.56	65.99	31.81
			only gas (40 €/MWh for heat)	87.09	75.53	41.34	73.34	61.78	27.61	128.33	116.77	82.59
			gas+oil (no consumers for heat)	-127.75	-124.07	-133.51	-145.41	-141.73	-151.17	-74.78	-71.11	-80.55
			gas+oil (40 €/MWh for heat)	-56.55	-52.89	-62.33	-74.21	-70.54	-79.98	-3.6	0.08	-9.36
Feedstock	gas/oil		BASE**	142.46	134.02	128.63	125.95	117.52	112.13	192	183.56	178.17
		CHP	only gas (no consumers for heat)	64.17	57.74	73.35	46.69	40.27	55.87	116.59	110.16	125.77
			only gas (40 €/MWh for heat)	114.94	108.52	124.12	97.47	91.05	106.65	100.39	93.96	109.57
			gas+oil (no consumers for heat)	-91.98	-82.85	-39.07	-114.42	-105.29	-61.5	-24.66	-15.53	28.26
			gas+oil (40 €/MWh for heat)	-20.78	-11.67	32.13	-43.23	-34.11	9.68	46.54	55.66	99.45
Product carbonisate	gas/oil		BASE**	79.18	63.53	5.77	49.93	34.28	-23.47	166.92	151.27	93.52
		CHP	only gas (no consumers for heat)	-44.49	-57.9	-90.12	-76.27	-89.68	-121.9	50.84	37.44	5.22
			only gas (40 €/MWh for heat)	60.1	46.7	14.47	28.32	14.92	-17.31	155.44	142.03	109.81
			gas+oil (no consumers for heat)	-370.93	-358.18	-344.83	-413.5	-400.75	-387.4	-243.22	-230.47	-217.12
			gas+oil (40 €/MWh for heat)	-226.23	-213.48	-200.13	-268.8	-256.05	-242.7	-98.52	-85.77	-72.42
Natural gas	gas/oil		BASE**	103.64	93.59	84.34	90.65	80.6	71.35	142.61	132.57	123.31
		CHP/PSA	only gas (no consumers for heat)	108.66	105.22	95.22	95.36	91.93	81.93	148.53	145.11	135.1
			only gas (40 €/MWh for heat)	162.3	158.88	148.87	149.01	145.59	135.57	202.18	198.75	188.75
			gas+oil (no consumers for heat)	-66.27	-54.5	-36.78	-83.64	-71.87	-54.14	-14.2	-2.42	15.29
			gas+oil (40 €/MWh for heat)	18.66	30.43	48.14	1.29	13.07	30.79	70.72	82.51	100.22
Steam coal	gas/oil		BASE**	116.14	102.86	50.53	103.15	89.87	37.54	155.11	141.84	89.5
		CHP/PSA	only gas (no consumers for heat)	121.45	114.45	58.04	108.15	101.16	44.75	161.32	154.32	97.91
			only gas (40 €/MWh for heat)	175.09	168.11	111.69	161.8	154.81	98.39	214.97	207.98	151.56
			gas+oil (no consumers for heat)	-49.58	-41.22	-72.67	-66.93	-58.57	-90.02	2.5	10.86	-20.59
			gas+oil (40 €/MWh for heat)	35.35	43.71	12.26	17.99	26.36	-5.1	87.43	95.79	64.34
Feedstock	gas/oil		BASE**	142.46	134.02	128.63	125.95	117.52	112.13	192	183.56	178.17
		CHP/PSA	only gas (no consumers for heat)	148.38	146.6	140.55	131.48	129.7	123.65	199.06	197.28	191.23
			only gas (40 €/MWh for heat)	202.02	200.24	194.19	185.13	183.35	177.3	**252.71**	**250.93**	**244.88**
			gas+oil (no consumers for heat)	-14.4	-0.47	22.4	-36.47	-22.54	0.34	51.8	65.72	88.6
			gas+oil (40 €/MWh for heat)	70.53	84.45	107.34	48.46	62.39	85.27	136.72	150.64	173.53
Product carbonisate	gas/oil		BASE**	79.18	63.53	5.77	49.93	34.28	-23.47	166.92	151.27	93.52
		CHP/PSA	only gas (no consumers for heat)	57.15	50.26	-14.82	26.38	19.49	-45.59	149.46	142.57	77.49
			only gas (40 €/MWh for heat)	170.55	163.67	98.58	139.78	132.9	67.82	**262.86**	**255.98**	190.89
			gas+oil (no consumers for heat)	-288.24	-268.22	-286.17	-330.55	-310.53	-328.47	-161.32	-141.29	-159.24
			gas+oil (40 €/MWh for heat)	-109.59	-89.56	-107.51	-151.89	-131.87	-149.82	17.34	37.36	19.42

Table 64: Matrix of the considered utilization pathways of LLR; Comparison of mLR and LC (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

LLR			Gate fee	mid						low						high					
			WEO (2016)	Current Policies		New Policies		450		Current Policies		New Policies		450		Current Policies		New Policies		450	
Heating	TCR product | Downstream processes		Utilization	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR
Natural gas	carbonisate		BASE*	264.9	377.2	268.4	366.2	276.9	326.1	293.4	390	297	379	305.5	338.9	179.2	338.9	182.7	327.8	191.2	287.8
Steam coal	carbonisate		BASE*	237.4	364.9	240.1	353.5	269.3	322.7	266	377.7	268.6	366.3	297.9	335.5	151.7	326.6	154.3	315.1	183.6	284.4
Feedstock	carbonisate		BASE*	181.9	340.1	181.9	327.5	181.9	283.6	216.8	355.7	216.8	343.1	216.8	299.2	77.27	293.3	77.27	280.7	77.27	236.8
			CCS	181.9	340.5	181.9	329.2	181.9	294.4	216.8	356.1	216.8	344.8	216.8	310	77.27	293.7	77.27	282.4	77.27	247.6
Product carbonisate	carbonisate		BASE*	277.4	373.2	280	359	309.4	314.1	311.8	381.4	314.5	367.2	343.9	322.3	173.9	348.6	176.6	334.4	205.9	289.5
Product syngas	carbonisate		BASE*	261.4	407.7	261.4	391.9	261.4	345.1	301.1	429.7	301.1	413.8	301.1	367.1	142.5	341.8	142.5	326	142.5	279.3
			CCS	261.4	408.2	261.4	394.2	261.4	360.2	301.1	430.2	301.1	416.2	301.1	382.1	142.5	342.4	142.5	328.4	142.5	294.3
Natural gas	gas		BASE**	264.9	377.2	268.4	366.2	276.9	326.1	293.4	390	297	379	305.5	338.9	179.2	338.9	182.7	327.8	191.2	287.8
		PSA	H_2+off gas	329.9	447.2	333.5	440.5	342	386	358.5	460.7	362.1	454	370.6	399.6	244.2	406.5	247.8	399.8	256.3	345.4
Steam coal	gas		BASE**	237.4	364.9	240.1	353.5	269.3	322.7	266	377.7	268.6	366.3	297.9	335.5	151.7	326.6	154.3	315.1	183.6	284.4
		PSA	H_2+off gas	302.4	434.1	305.1	427	334.4	382.4	331	447.7	333.7	440.6	363	396	216.7	393.5	219.4	386.4	248.7	341.8
Feedstock	gas		BASE**	181.9	340.5	181.9	329.2	181.9	294.4	216.8	356.1	216.8	344.8	216.8	310	77.27	293.7	77.27	282.4	77.27	247.6
		PSA	H_2+off gas	247	408.2	247	401.2	247	351.8	281.9	424.7	281.9	417.7	281.9	368.3	142.3	358.5	142.3	351.5	142.3	302.2
Product carbonisate	gas		BASE**	277.4	373.2	280	359	309.4	314.1	311.8	381.4	314.5	367.2	343.9	322.3	173.9	348.6	176.6	334.4	205.9	289.5
		PSA	H_2+off gas	355.9	442.8	358.6	433.9	387.9	372.5	390.4	452.4	393	443.4	422.4	382	252.4	414.1	255.1	405.2	284.5	343.8
Natural gas	gas/oil		BASE**	264.9	377.2	268.4	366.2	276.9	326.1	293.4	390	297	379	305.5	338.9	179.2	338.9	182.7	327.8	191.2	287.8
		CHP	only gas (no consumers for heat)	309	324	312.7	315.7	321.6	301	338.9	337.4	342.6	329.1	351.5	314.4	219.3	283.8	223	275.5	231.9	260.8
			only gas (40 €/MWh for heat)	213	295.2	216.7	286.9	225.6	272.2	242.9	308.7	246.6	300.3	255.5	285.6	123.2	255	127	246.7	135.9	232
			gas+oil (no consumers for heat)	431.3	247.4	425.3	246.4	416.4	244.8	461.1	255.9	455.1	254.9	446.2	253.3	341.9	222	336	221	327.1	219.4
			gas+oil (40 €/MWh for heat)	306.1	225.1	300.1	224	291.2	222.5	335.9	233.5	329.9	232.5	321	231	216.8	199.7	210.8	198.6	201.9	197.1
Steam coal	gas/oil		BASE**	237.4	364.9	240.1	353.5	269.3	322.7	266	377.7	268.6	366.3	297.9	335.5	151.7	326.6	154.3	315.1	183.6	284.4
		CHP	only gas (no consumers for heat)	280.2	311.1	283	302.4	313.7	297.4	310.1	324.5	312.9	315.8	343.6	310.8	190.5	270.9	193.3	262.1	223.9	257.2
			only gas (40 €/MWh for heat)	184.2	282.4	187	273.6	217.7	268.7	214.1	295.8	216.9	287	247.6	282.1	94.45	242.1	97.25	233.4	127.9	228.5
			gas+oil (no consumers for heat)	402.6	239.3	395.7	238	408.5	242.6	432.4	247.7	425.5	246.5	438.2	251.1	313.3	213.9	306.4	212.6	319.1	217.2
			gas+oil (40 €/MWh for heat)	277.5	216.9	270.5	215.6	283.3	220.2	307.2	225.4	300.3	224.1	313.1	228.7	188.1	191.5	181.2	190.2	194	194.8
Feedstock	gas/oil		BASE**	181.9	340.5	181.9	329.2	181.9	294.4	216.8	356.1	216.8	344.8	216.8	310	77.27	293.7	77.27	282.4	77.27	247.6
		CHP	only gas (no consumers for heat)	222.1	285.4	222.1	276.9	222.1	267.7	258.7	301.8	258.7	293.2	258.7	284.1	112.6	236.4	112.6	227.8	112.6	218.6
			only gas (40 €/MWh for heat)	126.1	256.7	126.1	248.1	126.1	239	162.7	273.1	162.7	264.5	162.7	255.4	16.55	102.9	16.55	94.27	16.55	85.14
			gas+oil (no consumers for heat)	344.8	223.2	335.1	222.5	317.4	228	381.2	233.6	371.5	232.9	353.7	238.3	235.8	192.2	226.1	191.5	208.3	197
			gas+oil (40 €/MWh for heat)	219.6	200.9	210	200.2	192.2	205.6	256	211.2	246.3	210.5	228.5	215.9	110.6	169.9	100.9	169.2	83.15	174.6
Product carbonisate	gas/oil		BASE**	277.4	373.2	280	359	309.4	314.1	311.8	381.4	314.5	367.2	343.9	322.3	173.9	348.6	176.6	334.4	205.9	289.5
		CHP	only gas (no consumers for heat)	331.9	302.1	334.7	291.1	365.8	276.8	368.3	310.8	371.2	299.8	402.2	285.5	222.5	276.1	225.3	265	256.4	250.7
			only gas (40 €/MWh for heat)	214.9	285.1	217.7	274	248.7	259.7	251.3	293.7	254.2	282.7	285.2	268.4	105.5	259	108.3	247.9	139.3	233.7
			gas+oil (no consumers for heat)	480.6	166.7	471.6	166.7	480.9	166.7	516.8	166.7	507.9	166.7	517.1	166.7	371.8	166.7	362.9	166.7	372.1	166.7
			gas+oil (40 €/MWh for heat)	328.2	166.7	319.2	166.7	328.5	166.7	364.4	166.7	355.5	166.7	364.7	166.7	219.4	166.7	210.5	166.7	219.7	166.7
Natural gas	gas/oil		BASE**	264.9	377.2	268.4	366.2	276.9	326.1	293.4	390	297	379	305.5	338.9	179.2	338.9	182.7	327.8	191.2	287.8
		CHP/PSA	only gas (no consumers for heat)	384.5	426.3	388.5	421.8	398.3	385.7	417.2	442.1	421.3	437.5	431	401.4	286.2	379.1	290.3	374.6	300	338.5
			only gas (40 €/MWh for heat)	292	394	296.1	389.5	305.8	353.3	324.8	409.7	328.9	405.2	338.6	369	193.8	346.8	197.8	342.3	207.6	306.1
			gas+oil (no consumers for heat)	511.1	339.4	504.6	342.4	495	320.3	543.2	349.6	536.7	352.6	527.1	330.6	414.6	308.7	408.1	311.7	398.5	289.6
			gas+oil (40 €/MWh for heat)	388.3	313	381.8	316	372.2	294	420.5	323.2	414	326.2	404.4	304.2	291.8	282.3	285.4	285.3	275.8	263.3
Steam coal	gas/oil		BASE**	237.4	364.9	240.1	353.5	269.3	322.7	266	377.7	268.6	366.3	297.9	335.5	151.7	326.6	154.3	315.1	183.6	284.4
		CHP/PSA	only gas (no consumers for heat)	353	411.2	356	406.2	389.6	381.5	385.7	426.9	388.8	421.9	422.3	397.2	254.7	364	257.7	359	291.3	334.3
			only gas (40 €/MWh for heat)	260.5	378.8	263.6	373.8	297.1	349.1	293.3	394.6	296.3	389.6	329.9	364.9	162.2	331.7	165.3	326.7	198.8	301.9
			gas+oil (no consumers for heat)	480.1	329.5	472.7	332.2	486.4	317.6	512.3	339.7	504.8	342.4	518.6	327.9	383.6	298.8	376.2	301.5	390	286.9
			gas+oil (40 €/MWh for heat)	357.4	303.1	349.9	305.8	363.7	291.3	389.5	313.4	382.1	316.1	395.8	301.5	260.9	272.4	253.4	275.1	267.2	260.6
Feedstock	gas/oil		BASE**	181.9	340.5	181.9	329.2	181.9	294.4	216.8	356.1	216.8	344.8	216.8	310	77.27	293.7	77.27	282.4	77.27	247.6
		CHP/PSA	only gas (no consumers for heat)	289.4	381.1	289.4	376.1	289.4	345.8	329.4	400.3	329.4	395.3	329.4	365	169.4	323.5	169.4	318.5	169.4	288.2
			only gas (40 €/MWh for heat)	196.9	348.7	196.9	343.8	196.9	313.4	236.9	367.9	236.9	363	236.9	332.6	76.94	291.1	76.94	286.2	76.94	255.8
			gas+oil (no consumers for heat)	417.7	310.1	407.2	313.3	388.1	298.5	456.9	322.6	446.5	325.8	427.3	311	299.9	272.6	289.5	275.8	270.3	261
			gas+oil (40 €/MWh for heat)	294.9	283.7	284.5	286.9	265.3	272.1	334.2	296.2	323.7	299.4	304.6	284.6	177.2	246.2	166.7	249.5	147.5	234.6
Product carbonisate	gas/oil		BASE**	277.4	373.2	280	359	309.4	314.1	311.8	381.4	314.5	367.2	343.9	322.3	173.9	348.6	176.6	334.4	205.9	289.5
		CHP/PSA	only gas (no consumers for heat)	428.5	414.1	431.7	407.4	466.4	367.6	469.3	425.5	472.4	418.9	507.1	379.1	306.2	379.6	309.3	372.9	344.1	333.1
			only gas (40 €/MWh for heat)	313.4	392.1	316.6	385.4	351.3	345.6	354.2	403.6	357.4	396.9	392.1	357.1	191.1	357.6	194.3	350.9	229	311.1
			gas+oil (no consumers for heat)	584.3	255.7	574.5	260.9	584.6	237.1	624.2	257.6	614.3	262.8	624.5	238.9	464.8	250.2	454.9	255.4	465.1	231.6
			gas+oil (40 €/MWh for heat)	432.2	251.6	422.4	256.8	432.5	233	472.1	253.4	462.2	258.7	472.4	234.8	312.7	246.1	302.8	251.3	313	227.4

Table 65: Matrix of the considered utilization pathways of LLR; Difference mLR-LC as an indicator of profitability (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

LLR			Gate fee	mid			low			high		
			WEO (2016)	Current Policies	New Policies	450	Current Policies	New Policies	450	Current Policies	New Policies	450
Heating	TCR product | Downstream processes		Utilization	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC
Natural gas	carbonisate		BASE*	112.33	97.76	49.21	96.54	81.97	33.42	159.69	145.13	96.58
Steam coal	carbonisate		BASE*	127.52	113.43	53.41	111.73	97.65	37.62	174.89	160.81	100.78
Feedstock	carbonisate		BASE*	158.18	145.57	101.71	138.9	126.29	82.43	**216.01**	203.4	159.54
			CCS	158.55	147.26	112.53	139.27	127.99	93.25	**216.38**	205.09	170.36
Product carbonisate	carbonisate		BASE*	95.86	79.01	4.73	69.58	52.72	-21.55	174.71	157.86	83.58
Product syngas	carbonisate		BASE*	146.28	130.46	83.72	128.59	112.77	66.04	199.31	183.49	136.76
			CCS	146.79	132.81	98.73	129.11	115.13	81.05	199.83	185.85	151.77
Natural gas	gas		BASE**	112.33	97.76	49.21	96.54	81.97	33.42	159.69	145.13	96.58
		PSA	H_2+off gas	117.24	107.01	44.06	102.21	91.99	29.04	162.28	152.06	89.12
Steam coal	gas		BASE**	127.52	113.43	53.41	111.73	97.65	37.62	174.89	160.81	100.78
		PSA	H_2+off gas	131.68	121.92	48.06	116.67	106.91	33.04	176.73	166.97	93.11
Feedstock	gas		BASE**	158.55	147.26	112.53	139.27	127.99	93.25	**216.38**	205.09	170.36
		PSA	H_2+off gas	161.21	154.18	104.82	142.88	135.85	86.49	**216.21**	**209.18**	159.82
Product carbonisate	gas		BASE**	95.86	79.01	4.73	69.58	52.72	-21.55	174.71	157.86	83.58
		PSA	H_2+off gas	86.92	75.3	-15.46	62	50.38	-40.39	161.69	150.07	59.31
Natural gas	gas/oil		BASE**	112.33	97.76	49.21	96.54	81.97	33.42	159.69	145.13	96.58
		CHP	only gas (no consumers for heat)	14.96	2.94	-20.66	-1.56	-13.58	-37.18	64.51	52.49	28.89
			only gas (40 €/MWh for heat)	82.24	70.21	46.62	65.73	53.69	30.1	131.79	119.77	96.17
			gas+oil (no consumers for heat)	-183.85	-178.89	-171.54	-205.16	-200.19	-192.84	-119.92	-114.96	-107.61
			gas+oil (40 €/MWh for heat)	-81.04	-76.07	-68.72	-102.35	-97.38	-90.03	-17.12	-12.14	-4.79
Steam coal	gas/oil		BASE**	127.52	113.43	53.41	111.73	97.65	37.62	174.89	160.81	100.78
		CHP	only gas (no consumers for heat)	30.85	19.33	-16.27	14.34	2.81	-32.79	80.4	68.89	33.28
			only gas (40 €/MWh for heat)	98.14	86.61	51.01	81.62	70.1	34.5	147.69	136.16	100.57
			gas+oil (no consumers for heat)	-163.35	-157.72	-165.87	-184.66	-179.04	-187.17	-99.42	-93.81	-101.94
			gas+oil (40 €/MWh for heat)	-60.54	-54.92	-63.05	-81.84	-76.22	-84.36	3.39	9.01	0.88
Feedstock	gas/oil		BASE**	158.55	147.26	112.53	139.27	127.99	93.25	**216.38**	205.09	170.36
		CHP	only gas (no consumers for heat)	63.31	54.72	45.59	43.14	34.56	25.42	123.8	115.22	106.09
			only gas (40 €/MWh for heat)	130.59	122.01	112.88	110.43	101.84	92.71	86.31	77.72	68.59
			gas+oil (no consumers for heat)	-121.59	-112.6	-89.4	-147.6	-138.61	-115.42	-43.55	-34.56	-11.36
			gas+oil (40 €/MWh for heat)	-18.78	-9.79	13.41	-44.8	-35.8	-12.6	59.26	68.25	91.44
Product carbonisate	gas/oil		BASE**	95.86	79.01	4.73	69.58	52.72	-21.55	174.71	157.86	83.58
		CHP	only gas (no consumers for heat)	-29.75	-43.64	-88.97	-57.53	-71.42	-116.75	53.59	39.7	-5.64
			only gas (40 €/MWh for heat)	70.19	56.3	10.98	42.41	28.52	-16.8	153.53	139.64	94.32
			gas+oil (no consumers for heat)	-313.92	-304.94	-314.19	-350.17	-341.19	-350.44	-205.17	-196.18	-205.43
			gas+oil (40 €/MWh for heat)	-161.52	-152.54	-161.78	-197.77	-188.79	-198.03	-52.76	-43.78	-53.02
Natural gas	gas/oil		BASE**	112.33	97.76	49.21	96.54	81.97	33.42	159.69	145.13	96.58
		CHP/PSA	only gas (no consumers for heat)	41.85	33.26	-12.62	24.82	16.24	-29.66	92.94	84.36	38.48
			only gas (40 €/MWh for heat)	101.95	93.36	47.48	84.92	76.33	30.45	153.04	144.46	98.57
			gas+oil (no consumers for heat)	-171.7	-162.21	-174.63	-193.62	-184.13	-196.55	-105.93	-96.44	-108.86
			gas+oil (40 €/MWh for heat)	-75.32	-65.82	-78.24	-97.23	-87.75	-100.17	-9.55	-0.06	-12.48
Steam coal	gas/oil		BASE**	127.52	113.43	53.41	111.73	97.65	37.62	174.89	160.81	100.78
		CHP/PSA	only gas (no consumers for heat)	58.24	50.17	-8.09	41.21	33.14	-25.12	109.33	101.26	43
			only gas (40 €/MWh for heat)	118.34	110.28	52.02	101.31	93.25	34.98	169.43	161.37	103.1
			gas+oil (no consumers for heat)	-150.6	-140.44	-168.79	-172.53	-162.37	-190.72	-84.83	-74.67	-103.03
			gas+oil (40 €/MWh for heat)	-54.22	-44.06	-72.41	-76.14	-65.98	-94.33	11.55	21.71	-6.64
Feedstock	gas/oil		BASE**	158.55	147.26	112.53	139.27	127.99	93.25	**216.38**	205.09	170.36
		CHP/PSA	only gas (no consumers for heat)	91.72	86.77	56.41	70.93	65.98	35.62	154.09	149.14	118.78
			only gas (40 €/MWh for heat)	151.82	146.87	116.51	131.03	126.08	95.72	**214.2**	**209.24**	178.88
			gas+oil (no consumers for heat)	-107.62	-93.92	-89.56	-134.39	-120.68	-116.32	-27.34	-13.63	-9.27
			gas+oil (40 €/MWh for heat)	-11.24	2.45	6.83	-38	-24.3	-19.94	69.04	82.75	87.11
Product carbonisate	gas/oil		BASE**	95.86	79.01	4.73	69.58	52.72	-21.55	174.71	157.86	83.58
		CHP/PSA	only gas (no consumers for heat)	-14.44	-24.3	-98.81	-43.72	-53.58	-128.09	73.41	63.56	-10.95
			only gas (40 €/MWh for heat)	78.66	68.81	-5.7	49.38	39.53	-34.98	166.52	156.66	82.15
			gas+oil (no consumers for heat)	-328.61	-313.52	-347.53	-366.6	-351.53	-385.52	-214.62	-199.54	-233.54
			gas+oil (40 €/MWh for heat)	-180.63	-165.56	-199.56	-218.63	-203.55	-237.55	-66.64	-51.57	-85.57

Table 66: Matrix of the considered utilization pathways of ISS; Comparison of mLR and LC (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

ISS			Gate fee	mid						low						high					
			WEO (2016)	Current Policies		New Policies		450		Current Policies		New Policies		450		Current Policies		New Policies		450	
Heating	TCR product | Downstream processes		Utilization	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR
Natural gas	carbonisate		BASE*	247.2	190.8	250.5	189.3	258.5	180.6	273.9	203.4	277.2	201.9	285.1	193.2	167.2	153.2	170.5	151.7	178.5	143
Steam coal	carbonisate		BASE*	221.6	178.8	224	176.9	251.4	177.3	248.2	191.3	250.7	189.4	278	189.8	141.6	141.2	144	139.3	171.4	139.7
Feedstock	carbonisate		BASE*	148.9	144.6	148.9	141.5	148.9	129.1	193.8	165.7	193.8	162.7	193.8	150.3	14.03	81.22	14.03	78.15	14.03	65.73
			CCS	148.9	140.3	148.9	140.2	148.9	146.4	193.8	161.4	193.8	161.3	193.8	167.5	14.03	76.91	14.03	76.81	14.03	82.98
Product carbonisate	carbonisate		BASE*	549.4	210.5	552.4	205.1	585.1	180.4	623.4	215.8	626.4	210.4	659.2	185.7	327.2	194.6	330.1	189.2	362.9	164.6
Product syngas	carbonisate		BASE*	289.9	45.67	290.9	42.41	293.2	35.26	330.7	47.3	331.7	44.04	334	36.89	167.4	40.77	168.4	37.52	170.7	30.36
			CCS	289.9	39.08	290.9	40.35	293.2	61.67	330.7	40.71	331.7	41.99	334	63.3	167.4	34.18	168.4	35.46	170.7	56.77
Natural gas	gas		BASE**	247.2	190.8	250.5	189.3	258.5	180.6	273.9	203.4	277.2	201.9	285.1	193.2	167.2	153.2	170.5	151.7	178.5	143
		PSA	H_2+off gas	278.8	248.6	282.1	250.3	290	229.8	305.5	261.4	308.8	263.1	316.7	242.6	198.8	210.3	202.1	211.9	210	191.4
Steam coal	gas		BASE**	221.6	178.8	224	176.9	251.4	177.3	248.2	191.3	250.7	189.4	278	189.8	141.6	141.2	144	139.3	171.4	139.7
		PSA	H_2+off gas	253.1	236.3	255.6	237.6	282.9	226.4	279.8	249.1	282.3	250.4	309.6	239.2	173.1	197.9	175.6	199.2	202.9	188
Feedstock	gas		BASE**	148.9	144.6	148.9	141.5	148.9	146.4	193.8	165.7	193.8	162.7	193.8	167.5	14.03	81.22	14.03	78.15	14.03	82.98
		PSA	H_2+off gas	180.5	201.5	180.5	201.5	180.5	194.5	225.4	223	225.4	223.1	225.4	216.1	45.61	136.8	45.61	136.8	45.61	129.8
Product carbonisate	gas		BASE**	549.4	210.5	552.4	205.1	585.1	180.4	623.4	215.8	626.4	210.4	659.2	185.7	327.2	194.6	330.1	189.2	362.9	164.6
		PSA	H_2+off gas	637.1	341.7	640.1	345.3	672.8	290.1	711.2	352.6	714.1	356.2	746.9	301	414.9	309	417.9	312.6	450.6	257.4
Natural gas	gas/oil		BASE**	247.2	190.8	250.5	189.3	258.5	180.6	273.9	203.4	277.2	201.9	285.1	193.2	167.2	153.2	170.5	151.7	178.5	143
		CHP	only gas (no consumers for heat)	264.7	168.6	268.3	168	277	166.9	294	182.5	297.6	181.9	306.3	180.8	176.8	126.8	180.5	126.2	189.2	125.1
			only gas (40 €/MWh for heat)	229.1	143	232.7	142.4	241.4	141.4	258.3	157	262	156.3	270.7	155.3	141.2	101.2	144.8	100.6	153.5	99.55
			gas+oil (no consumers for heat)	276.2	167.3	278.7	167.1	285.1	166.6	305.3	180.9	307.7	180.6	314.2	180.2	189	126.7	191.5	126.5	197.9	126
			gas+oil (40 €/MWh for heat)	236.5	139.6	238.9	139.3	245.4	138.9	265.5	153.1	267.9	152.8	274.4	152.4	149.3	98.99	151.7	98.7	158.2	98.28
Steam coal	gas/oil		BASE**	221.6	178.8	224	176.9	251.4	177.3	248.2	191.3	250.7	189.4	278	189.8	141.6	141.2	144	139.3	171.4	139.7
		CHP	only gas (no consumers for heat)	236.5	155.2	239.2	154.1	269.2	163.2	265.8	169.1	268.5	168.1	298.5	177.1	148.6	113.4	151.4	112.3	181.4	121.4
			only gas (40 €/MWh for heat)	200.9	129.6	203.6	128.6	233.6	137.6	230.2	143.6	232.9	142.5	262.9	151.6	113	87.83	115.8	86.77	145.7	95.84
			gas+oil (no consumers for heat)	248.3	154.3	249.8	153.6	277.4	163	277.3	167.9	278.9	167.2	306.5	176.6	161.1	113.7	162.6	113	190.2	122.4
			gas+oil (40 €/MWh for heat)	208.5	126.6	210	125.9	237.6	135.3	237.6	140.1	239.1	139.4	266.7	148.8	121.3	85.97	122.8	85.27	150.4	94.68
Feedstock	gas/oil		BASE**	148.9	144.6	148.9	141.5	148.9	146.4	193.8	165.7	193.8	162.7	193.8	167.5	14.03	81.22	14.03	78.15	14.03	82.98
		CHP	only gas (no consumers for heat)	156.7	117.2	156.7	114.9	156.7	128.6	206.1	140.7	206.1	138.4	206.1	152.1	8.59	46.76	8.59	44.39	8.59	58.15
			only gas (40 €/MWh for heat)	121.1	91.66	121.1	89.3	121.1	103.1	170.4	115.2	170.4	112.8	170.4	126.5	-27	21.19	-27	18.83	-27	32.59
			gas+oil (no consumers for heat)	169.1	117.4	167.9	115.5	165.7	129.8	218.1	140.3	216.9	138.3	214.7	152.7	22.07	49.01	20.88	47.05	18.72	61.41
			gas+oil (40 €/MWh for heat)	129.3	89.69	128.1	87.73	125.9	102.1	178.3	112.5	177.1	110.5	174.9	124.9	-17.7	21.26	-18.9	19.29	-21.1	33.66
Product carbonisate	gas/oil		BASE**	549.4	210.5	552.4	205.1	585.1	180.4	623.4	215.8	626.4	210.4	659.2	185.7	327.2	194.6	330.1	189.2	362.9	164.6
		CHP	only gas (no consumers for heat)	708	154.5	712	150.7	755.6	146.4	806.6	161.9	810.6	158.1	854.2	153.8	412.3	132.5	416.3	128.7	459.9	124.4
			only gas (40 €/MWh for heat)	588.1	148.6	592.1	144.8	635.7	140.5	686.7	155.9	690.7	152.2	734.3	147.9	292.4	126.6	296.4	122.8	340	118.5
			gas+oil (no consumers for heat)	735.2	76.21	735.2	76.21	770.5	76.21	831.3	76.21	831.3	76.21	866.7	76.21	446.9	76.21	446.8	76.21	482.2	76.21
			gas+oil (40 €/MWh for heat)	603.7	76.21	603.6	76.21	639	76.21	699.8	76.21	699.8	76.21	735.1	76.21	315.3	76.21	315.3	76.21	350.6	76.21
Natural gas	gas/oil		BASE**	247.2	190.8	250.5	189.3	258.5	180.6	273.9	203.4	277.2	201.9	285.1	193.2	167.2	153.2	170.5	151.7	178.5	143
		CHP/PSA	only gas (no consumers for heat)	324.4	260.2	328.5	263.3	338.4	245.6	357.6	277.2	361.7	280.3	371.6	262.6	224.8	209.2	228.9	212.3	238.8	194.6
			only gas (40 €/MWh for heat)	292.5	233.7	296.6	236.8	306.5	219.1	325.7	250.7	329.8	253.8	339.7	236.1	192.9	182.7	197	185.8	206.9	168.1
			gas+oil (no consumers for heat)	331.5	253.6	334.2	256.9	341.5	240.1	363.9	269.7	366.6	272.9	373.8	256.1	234.4	205.4	237.1	208.7	244.3	191.9
			gas+oil (40 €/MWh for heat)	295.5	225	298.2	228.2	305.5	211.4	327.9	241	330.6	244.3	337.8	227.5	198.4	176.8	201.1	180.1	208.3	163.2
Steam coal	gas/oil		BASE**	221.6	178.8	224	176.9	251.4	177.3	248.2	191.3	250.7	189.4	278	189.8	141.6	141.2	144	139.3	171.4	139.7
		CHP/PSA	only gas (no consumers for heat)	292.4	243.8	295.5	246.4	329.5	241.1	325.6	260.8	328.7	263.4	362.7	258.1	192.8	192.8	195.9	195.4	229.9	190.1
			only gas (40 €/MWh for heat)	260.6	217.3	263.7	219.9	297.7	214.6	293.8	234.3	296.9	236.9	330.9	231.6	161	166.3	164.1	168.9	198.1	163.6
			gas+oil (no consumers for heat)	300.4	238.2	302.1	240.9	332.8	235.8	332.8	254.2	334.5	257	365.2	251.8	203.2	190	204.9	192.8	235.7	187.6
			gas+oil (40 €/MWh for heat)	264.4	209.5	266.1	212.3	296.8	207.2	296.8	225.6	298.5	228.4	329.2	223.2	167.2	161.4	168.9	164.1	199.7	159
Feedstock	gas/oil		BASE**	148.9	144.6	148.9	141.5	148.9	146.4	193.8	165.7	193.8	162.7	193.8	167.5	14.03	81.22	14.03	78.15	14.03	82.98
		CHP/PSA	only gas (no consumers for heat)	202	197.5	202	198.5	202	197.3	257.9	226.2	257.9	227.2	257.9	225.9	34.06	111.5	34.06	112.5	34.06	111.3
			only gas (40 €/MWh for heat)	170.1	171	170.1	172	170.1	170.8	226.1	199.7	226.1	200.7	226.1	199.4	2.21	85.02	2.21	86.02	2.21	84.8
			gas+oil (no consumers for heat)	212.1	194.4	210.8	195.7	208.4	195	266.7	221.5	265.4	222.7	263	222.1	48.32	113.2	47	114.5	44.59	113.8
			gas+oil (40 €/MWh for heat)	176.1	165.8	174.8	167	172.4	166.4	230.7	192.8	229.4	194.1	227	193.5	12.32	84.55	11	85.82	8.59	85.18
Product carbonisate	gas/oil		BASE**	549.4	210.5	552.4	205.1	585.1	180.4	623.4	215.8	626.4	210.4	659.2	185.7	327.2	194.6	330.1	189.2	362.9	164.6
		CHP/PSA	only gas (no consumers for heat)	1293	601.7	1300	614.4	1372	533.5	1457	634.2	1463	646.8	1536	565.9	803.3	504.4	809.9	517	882.1	436.1
			only gas (40 €/MWh for heat)	1137	574.7	1143	587.3	1216	506.5	1300	607.2	1307	619.8	1379	538.9	646.5	477.4	653.1	490	725.4	409.1
			gas+oil (no consumers for heat)	1219	393.4	1219	409.6	1273	341.4	1365	407.7	1365	423.8	1418	355.6	782.9	350.5	782.8	366.7	836.3	298.5
			gas+oil (40 €/MWh for heat)	1058	380.3	1057	396.5	1111	328.3	1203	394.6	1203	410.8	1256	342.6	621.2	337.4	621.1	353.6	674.6	285.4

Table 67: Matrix of the considered utilization pathways of ISS; Difference mLR-LC as an indicator of profitability (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

ISS			Gate fee	mid			low			high		
			WEO (2016)	Current Policies	New Policies	450	Current Policies	New Policies	450	Current Policies	New Policies	450
Heating	TCR product | Downstream processes		Utilization	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC
Natural gas	carbonisate		BASE*	-56.39	-61.21	-77.84	-70.53	-75.34	-91.97	-13.99	-18.81	-35.44
Steam coal	carbonisate		BASE*	-42.79	-47.17	-74.08	-56.93	-61.31	-88.21	-0.39	-4.78	-31.68
Feedstock	carbonisate		BASE*	-4.29	-7.35	-19.77	-28.11	-31.17	-43.59	67.19	64.12	51.7
			CCS	-8.59	-8.69	-2.52	-32.41	-32.51	-26.34	62.88	62.78	68.95
Product carbonisate	carbonisate		BASE*	-338.89	-347.26	-404.71	-407.68	-416.05	-473.5	-132.52	-140.89	-198.34
Product syngas	carbonisate		BASE*	-244.22	-248.44	-257.89	-283.41	-287.63	-297.07	-126.67	-130.88	-140.34
			CCS	-250.81	-250.5	-231.48	-290	-289.68	-270.66	-133.26	-132.94	-113.93
Natural gas	gas		BASE**	-56.39	-61.21	-77.84	-70.53	-75.34	-91.97	-13.99	-18.81	-35.44
		PSA	H_2+off gas	-30.15	-31.79	-60.21	-44.02	-45.66	-74.08	11.47	9.82	-18.6
Steam coal	gas		BASE**	-42.79	-47.17	-74.08	-56.93	-61.31	-88.21	-0.39	-4.78	-31.68
		PSA	H_2+off gas	-16.8	-18.01	-56.52	-30.67	-31.89	-70.39	24.81	23.6	-14.91
Feedstock	gas		BASE**	-4.29	-7.35	-2.52	-28.11	-31.17	-26.34	67.19	64.12	68.95
		PSA	H_2+off gas	20.99	21.07	14.03	-2.39	-2.3	-9.35	**91.14**	**91.22**	**84.18**
Product carbonisate	gas		BASE**	-338.89	-347.26	-404.71	-407.68	-416.05	-473.5	-132.52	-140.89	-198.34
		PSA	H_2+off gas	-295.39	-294.81	-382.77	-358.57	-357.98	-445.95	-105.86	-105.28	-193.23
Natural gas	gas/oil		BASE**	-56.39	-61.21	-77.84	-70.53	-75.34	-91.97	-13.99	-18.81	-35.44
		CHP	only gas (no consumers for heat)	-96.07	-100.34	-110.11	-111.43	-115.69	-125.46	-50.01	-54.29	-64.05
			only gas (40 €/MWh for heat)	-86.01	-90.28	-100.04	-101.37	-105.63	-115.4	-39.96	-44.22	-53.98
			gas+oil (no consumers for heat)	-108.89	-111.6	-118.5	-124.42	-127.14	-134.03	-62.29	-65	-71.9
			gas+oil (40 €/MWh for heat)	-96.87	-99.57	-106.48	-112.39	-115.11	-122	-50.26	-52.97	-59.87
Steam coal	gas/oil		BASE**	-42.79	-47.17	-74.08	-56.93	-61.31	-88.21	-0.39	-4.78	-31.68
		CHP	only gas (no consumers for heat)	-81.3	-85.1	-106.02	-96.66	-100.46	-121.37	-35.25	-39.04	-59.97
			only gas (40 €/MWh for heat)	-71.24	-75.04	-95.96	-86.6	-90.39	-111.32	-25.18	-28.98	-49.9
			gas+oil (no consumers for heat)	-93.94	-96.18	-114.37	-109.48	-111.71	-129.9	-47.34	-49.57	-67.77
			gas+oil (40 €/MWh for heat)	-81.92	-84.15	-102.34	-97.45	-99.68	-117.87	-35.31	-37.54	-55.74
Feedstock	gas/oil		BASE**	-4.29	-7.35	-2.52	-28.11	-31.17	-26.34	67.19	64.12	68.95
		CHP	only gas (no consumers for heat)	-39.47	-41.83	-28.08	-65.35	-67.71	-53.96	38.17	35.8	49.56
			only gas (40 €/MWh for heat)	-29.41	-31.77	-18.02	-55.29	-57.65	-43.9	48.23	45.87	59.63
			gas+oil (no consumers for heat)	-51.62	-52.4	-35.87	-77.81	-78.58	-62.06	26.94	26.17	42.69
			gas+oil (40 €/MWh for heat)	-39.59	-40.36	-23.84	-65.77	-66.55	-50.03	38.98	38.19	54.72
Product carbonisate	gas/oil		BASE**	-338.89	-347.26	-404.71	-407.68	-416.05	-473.5	-132.52	-140.89	-198.34
		CHP	only gas (no consumers for heat)	-553.51	-561.27	-609.16	-644.74	-652.51	-700.39	-279.82	-287.57	-335.46
			only gas (40 €/MWh for heat)	-439.52	-447.29	-495.18	-530.76	-538.52	-586.41	-165.82	-173.59	-221.47
			gas+oil (no consumers for heat)	-659.02	-658.98	-694.32	-755.13	-755.1	-790.44	-370.67	-370.63	-405.97
			gas+oil (40 €/MWh for heat)	-527.47	-527.43	-562.77	-623.58	-623.55	-658.89	-239.12	-239.09	-274.43
Natural gas	gas/oil		BASE**	-56.39	-61.21	-77.84	-70.53	-75.34	-91.97	-13.99	-18.81	-35.44
		CHP/PSA	only gas (no consumers for heat)	-64.19	-65.2	-92.72	-80.39	-81.4	-108.92	-15.59	-16.61	-44.13
			only gas (40 €/MWh for heat)	-58.83	-59.85	-87.37	-75.03	-76.05	-103.57	-10.24	-11.25	-38.77
			gas+oil (no consumers for heat)	-77.92	-77.37	-101.4	-94.25	-93.69	-117.73	-28.94	-28.38	-52.42
			gas+oil (40 €/MWh for heat)	-70.55	-69.99	-94.03	-86.88	-86.32	-110.36	-21.57	-21.01	-45.04
Steam coal	gas/oil		BASE**	-42.79	-47.17	-74.08	-56.93	-61.31	-88.21	-0.39	-4.78	-31.68
		CHP/PSA	only gas (no consumers for heat)	-48.61	-49.12	-88.42	-64.81	-65.32	-104.62	-0.01	-0.53	-39.82
			only gas (40 €/MWh for heat)	-43.25	-43.77	-83.06	-59.45	-59.97	-99.26	5.34	4.83	-34.46
			gas+oil (no consumers for heat)	-62.21	-61.16	-97.06	-78.54	-77.49	-113.38	-13.22	-12.16	-48.07
			gas+oil (40 €/MWh for heat)	-54.84	-53.78	-89.68	-71.17	-70.11	-106.01	-5.85	-4.8	-40.7
Feedstock	gas/oil		BASE**	-4.29	-7.35	-2.52	-28.11	-31.17	-26.34	67.19	64.12	68.95
		CHP/PSA	only gas (no consumers for heat)	-4.46	-3.47	-4.69	-31.77	-30.78	-32	**77.46**	**78.46**	**77.24**
			only gas (40 €/MWh for heat)	0.89	1.89	0.67	-26.42	-25.42	-26.64	**82.81**	**83.81**	**82.59**
			gas+oil (no consumers for heat)	-17.72	-15.14	-13.35	-45.24	-42.66	-40.88	64.86	67.45	69.23
			gas+oil (40 €/MWh for heat)	-10.34	-7.76	-5.98	-37.87	-35.29	-33.51	72.23	74.82	76.59
Product carbonisate	gas/oil		BASE**	-338.89	-347.26	-404.71	-407.68	-416.05	-473.5	-132.52	-140.89	-198.34
		CHP/PSA	only gas (no consumers for heat)	-691.69	-685.65	-838.79	-822.63	-816.59	-969.73	-298.87	-292.84	-445.97
			only gas (40 €/MWh for heat)	-561.96	-555.92	-709.05	-692.89	-686.86	-840	-169.13	-163.1	-316.23
			gas+oil (no consumers for heat)	-825.85	-809.61	-931.29	-957.01	-940.77	-1062.45	-432.36	-416.12	-537.81
			gas+oil (40 €/MWh for heat)	-677.21	-660.97	-782.65	-808.38	-792.14	-913.82	-283.72	-267.48	-389.16

Table 68: Matrix of the considered utilization pathways of Peat; Comparison of mLR and LC (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

Peat			Gate fee	mid						low						high					
			WEO (2016)	Current Policies		New Policies		450		Current Policies		New Policies		450		Current Policies		New Policies		450	
Heating	TCR product | Downstream processes		Utilization	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR
Natural gas	carbonisate		BASE*	354.2	327.1	357.2	321.6	364.4	300.2	299.3	298.9	302.3	293.4	309.6	272	445.6	374	448.7	368.5	455.9	347.1
Feedstock	carbonisate		BASE*	341.8	320.7	346.9	316.3	387.6	312.1	271.3	284.6	276.5	280.2	317.1	275.9	459.3	381	464.4	376.6	505.1	372.3
Product carbonisate	carbonisate		BASE*	402.6	315.5	407.2	310.3	443.7	297.1	331.2	288.3	335.8	283	372.3	269.9	521.6	360.9	526.2	355.6	562.7	342.5
Product syngas	carbonisate		BASE*	496.8	394.5	501	386.7	534.5	376.6	406.3	348.6	410.5	340.8	444	330.6	647.6	471.1	651.8	463.3	685.3	453.2
Natural gas	gas		BASE**	354.2	327.1	357.2	321.6	364.4	300.2	299.3	298.9	302.3	293.4	309.6	272	445.6	374	448.7	368.5	455.9	347.1
		PSA	H_2+off gas	407.5	412.3	410.5	411.1	417.8	373.1	352.6	382.9	355.6	381.7	362.9	343.6	498.9	461.3	502	460.1	509.2	422.1
Feedstock	gas		BASE**	341.8	320.7	346.9	316.3	387.6	312.1	271.3	284.6	276.5	280.2	317.1	275.9	459.3	381	464.4	376.6	505.1	372.3
		PSA	H_2+off gas	395.1	405.6	400.3	405.6	441	385.5	324.6	367.9	329.8	367.8	370.5	347.7	512.6	468.6	517.7	468.6	558.4	448.4
Product carbonisate	gas		BASE**	402.6	315.5	407.2	310.3	443.7	297.1	331.2	288.3	335.8	283	372.3	269.9	521.6	360.9	526.2	355.6	562.7	342.5
		PSA	H_2+off gas	472	416.2	476.6	416.6	513.1	383.1	400.6	386.2	405.2	386.7	441.7	353.1	591	466.2	595.6	466.6	632.1	433
Natural gas	gas/oil		BASE**	354.2	327.1	357.2	321.6	364.4	300.2	299.3	298.9	302.3	293.4	309.6	272	445.6	374	448.7	368.5	455.9	347.1
		CHP	only gas (no consumers for heat)	408.2	310.3	415.7	307.8	456.5	313.5	348.4	279.4	355.9	277	396.7	282.6	507.9	361.7	515.4	359.3	556.2	364.9
			only gas (40 €/MWh for heat)	348.9	283.5	356.4	281	397.2	286.7	289.1	252.6	296.6	250.2	337.4	255.8	448.6	334.9	456.1	332.5	496.9	338.1
			gas+oil (no consumers for heat)	451.9	296.1	456.5	295.3	495	303.8	393.1	268.4	397.7	267.5	436.2	276	549.9	342.4	554.6	341.6	593	350.1
			gas+oil (40 €/MWh for heat)	383.6	268.5	388.3	267.6	426.8	276.2	324.8	240.7	329.5	239.9	368	248.4	481.7	314.7	486.3	313.9	524.8	322.4
Feedstock	gas/oil		BASE**	341.8	320.7	346.9	316.3	387.6	312.1	271.3	284.6	276.5	280.2	317.1	275.9	459.3	381	464.4	376.6	505.1	372.3
		CHP	only gas (no consumers for heat)	394.8	303.3	404.5	302.1	481.8	326.5	318	263.7	327.7	262.4	405	286.9	522.8	369.4	532.5	368.1	609.8	392.6
			only gas (40 €/MWh for heat)	335.4	276.5	345.2	275.3	422.5	299.7	258.6	236.9	268.4	235.6	345.7	260.1	463.5	342.6	473.2	341.3	550.5	365.8
			gas+oil (no consumers for heat)	438.6	289.9	445.6	290.1	519.9	315.5	363.1	254.2	370	254.4	444.3	279.9	564.5	349.3	571.5	349.5	645.8	375
			gas+oil (40 €/MWh for heat)	370.4	262.2	377.3	262.5	451.6	287.9	294.8	226.6	301.8	226.8	376.1	252.2	496.3	321.6	503.2	321.9	577.5	347.3
Product carbonisate	gas/oil		BASE**	402.6	315.5	407.2	310.3	443.7	297.1	331.2	288.3	335.8	283	372.3	269.9	521.6	360.9	526.2	355.6	562.7	342.5
		CHP	only gas (no consumers for heat)	480.7	285.9	491.5	283.8	576.3	299.7	400.8	255.2	411.5	253	496.4	269	614.1	337.1	624.8	335	709.6	350.9
			only gas (40 €/MWh for heat)	401.4	264.7	412.2	262.6	497	278.5	321.4	234	332.2	231.9	417	247.8	534.7	316	545.5	313.8	630.3	329.7
			gas+oil (no consumers for heat)	537.2	243.7	544.1	244.2	624.9	261.2	459	219.5	465.9	219.9	546.7	236.9	667.5	284.2	674.5	284.6	755.3	301.6
			gas+oil (40 €/MWh for heat)	446.4	224.8	453.4	225.2	534.2	242.2	368.2	200.5	375.2	201	455.9	218	576.8	265.2	583.8	265.7	664.5	282.7
Natural gas	gas/oil		BASE**	354.2	327.1	357.2	321.6	364.4	300.2	299.3	298.9	302.3	293.4	309.6	272	445.6	374	448.7	368.5	455.9	347.1
		CHP/PSA	only gas (no consumers for heat)	529.1	479.6	538	482.7	586.6	470.2	457.9	439.3	466.8	442.4	515.4	429.9	647.8	546.8	656.7	549.9	705.3	537.4
			only gas (40 €/MWh for heat)	468	445.1	476.9	448.2	525.5	435.7	396.7	404.8	405.6	407.9	454.2	395.4	586.7	512.3	595.6	515.4	644.2	502.9
			gas+oil (no consumers for heat)	555.1	439.8	560.6	444.2	605.4	434.7	486.5	404.5	492	408.9	536.8	399.4	669.4	498.7	674.9	503.1	719.8	493.6
			gas+oil (40 €/MWh for heat)	483.1	404	488.6	408.4	533.5	398.9	414.5	368.7	420	373.1	464.9	363.6	597.5	462.8	602.9	467.2	647.8	457.7
Feedstock	gas/oil		BASE**	341.8	320.7	346.9	316.3	387.6	312.1	271.3	284.6	276.5	280.2	317.1	275.9	459.3	381	464.4	376.6	505.1	372.3
		CHP/PSA	only gas (no consumers for heat)	513.1	470.5	524.7	475.2	616.7	487.3	421.6	418.7	433.2	423.4	525.2	435.5	665.5	556.8	677.2	561.4	769.2	573.5
			only gas (40 €/MWh for heat)	451.9	436	463.6	440.6	555.6	452.7	360.4	384.2	372.1	388.9	464.1	401	604.4	522.3	616	526.9	708.1	539
			gas+oil (no consumers for heat)	539.6	431.9	547.8	437.6	634.4	449.6	451.5	386.5	459.6	392.3	546.3	404.3	686.5	507.4	694.6	513.2	781.3	525.2
			gas+oil (40 €/MWh for heat)	467.7	396	475.8	401.8	562.5	413.8	379.6	350.7	387.7	356.5	474.3	368.5	614.5	471.6	622.6	477.4	709.3	489.4
Product carbonisate	gas/oil		BASE**	402.6	315.5	407.2	310.3	443.7	297.1	331.2	288.3	335.8	283	372.3	269.9	521.6	360.9	526.2	355.6	562.7	342.5
		CHP/PSA	only gas (no consumers for heat)	673.4	514.2	687	520.2	795.1	516	571.5	468	585.2	474	693.2	469.8	843.1	591.2	856.8	597.3	964.8	593
			only gas (40 €/MWh for heat)	586	481.2	599.6	487.3	707.7	483	484.1	435	497.8	441	605.8	436.8	755.7	558.2	769.4	564.3	877.4	560
			gas+oil (no consumers for heat)	702.4	427.4	711	435.7	810.7	431.3	605.9	391.7	614.5	399.9	714.2	395.6	863.3	486.9	871.9	495.2	971.6	490.8
			gas+oil (40 €/MWh for heat)	601.2	397.7	609.8	405.9	709.4	401.5	504.6	362	513.2	370.2	612.9	365.8	762.1	457.2	770.7	465.4	870.3	461

Table 69: Matrix of the considered utilization pathways of Peat; Difference mLR-LC as an indicator of profitability (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

Peat			Gate fee	mid			low			high		
			WEO (2016)	Current Policies	New Policies	450	Current Policies	New Policies	450	Current Policies	New Policies	450
Heating	TCR product | Downstream processes		Utilization	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC
Natural gas	carbonisate		BASE*	-27.07	-35.6	-64.27	-0.35	-8.89	-37.55	-71.6	-80.14	-108.81
Feedstock	carbonisate		BASE*	-21.04	-30.61	-75.57	**13.28**	3.71	-41.24	-78.24	-87.81	-132.75
Product carbonisate	carbonisate		BASE*	-87.11	-96.97	-146.59	-42.91	-52.77	-102.4	-160.76	-170.62	-220.25
Product syngas	carbonisate		BASE*	-102.25	-114.29	-157.91	-57.7	-69.74	-113.36	-176.51	-188.56	-232.17
Natural gas	gas		BASE**	-27.07	-35.6	-64.27	-0.35	-8.89	-37.55	-71.6	-80.14	-108.81
		PSA	H_2+off gas	4.79	0.58	-44.71	**30.25**	**26.03**	-19.25	-37.65	-41.87	-87.15
Feedstock	gas		BASE**	-21.04	-30.61	-75.57	**13.28**	3.71	-41.24	-78.24	-87.81	-132.75
		PSA	H_2+off gas	10.53	5.33	-55.47	**43.23**	**38.03**	-22.77	-43.97	-49.17	-109.97
Product carbonisate	gas		BASE**	-87.11	-96.97	-146.59	-42.91	-52.77	-102.4	-160.76	-170.62	-220.25
		PSA	H_2+off gas	-55.82	-59.96	-130.02	-14.4	-18.54	-88.59	-124.86	-128.99	-199.05
Natural gas	gas/oil		BASE**	-27.07	-35.6	-64.27	-0.35	-8.89	-37.55	-71.6	-80.14	-108.81
		CHP	only gas (no consumers for heat)	-97.96	-107.87	-143.05	-69.03	-78.93	-114.12	-146.19	-156.09	-191.27
			only gas (40 €/MWh for heat)	-65.45	-75.36	-110.54	-36.52	-46.42	-81.6	-113.68	-123.58	-158.76
			gas+oil (no consumers for heat)	-155.75	-161.26	-191.21	-124.7	-130.22	-160.16	-207.5	-213.01	-242.96
			gas+oil (40 €/MWh for heat)	-115.17	-120.68	-150.63	-84.11	-89.63	-119.58	-166.92	-172.43	-202.38
Feedstock	gas/oil		BASE**	-21.04	-30.61	-75.57	**13.28**	3.71	-41.24	-78.24	-87.81	-132.75
		CHP	only gas (no consumers for heat)	-91.43	-102.46	-155.28	-54.27	-65.31	-118.12	-153.37	-164.4	-217.21
			only gas (40 €/MWh for heat)	-58.92	-69.95	-122.76	-21.76	-32.79	-85.61	-120.86	-131.89	-184.7
			gas+oil (no consumers for heat)	-148.75	-155.46	-204.34	-108.87	-115.59	-164.45	-215.21	-221.93	-270.8
			gas+oil (40 €/MWh for heat)	-108.16	-114.88	-163.75	-68.29	-75	-123.88	-174.63	-181.34	-230.21
Product carbonisate	gas/oil		BASE**	-87.11	-96.97	-146.59	-42.91	-52.77	-102.4	-160.76	-170.62	-220.25
		CHP	only gas (no consumers for heat)	-194.84	-207.72	-276.63	-145.59	-158.47	-227.38	-276.93	-289.8	-358.72
			only gas (40 €/MWh for heat)	-136.69	-149.57	-218.47	-87.44	-100.32	-169.22	-218.77	-231.65	-300.56
			gas+oil (no consumers for heat)	-293.44	-299.96	-363.72	-239.49	-246	-309.77	-383.37	-389.89	-453.65
			gas+oil (40 €/MWh for heat)	-221.65	-228.16	-291.93	-167.7	-174.21	-237.97	-311.58	-318.1	-381.86
Natural gas	gas/oil		BASE**	-27.07	-35.6	-64.27	-0.35	-8.89	-37.55	-71.6	-80.14	-108.81
		CHP/PSA	only gas (no consumers for heat)	-49.52	-55.31	-116.39	-18.59	-24.39	-85.45	-101.07	-106.87	-167.94
			only gas (40 €/MWh for heat)	-22.9	-28.7	-89.76	8.04	2.24	-58.84	-74.45	-80.24	-141.31
			gas+oil (no consumers for heat)	-115.27	-116.33	-170.7	-81.98	-83.03	-137.4	-170.76	-171.82	-226.2
			gas+oil (40 €/MWh for heat)	-79.14	-80.2	-134.58	-45.84	-46.9	-101.28	-134.64	-135.69	-190.07
Feedstock	gas/oil		BASE**	-21.04	-30.61	-75.57	**13.28**	3.71	-41.24	-78.24	-87.81	-132.75
		CHP/PSA	only gas (no consumers for heat)	-42.54	-49.54	-129.46	-2.82	-9.81	-89.73	-108.75	-115.74	-195.66
			only gas (40 €/MWh for heat)	-15.92	-22.92	-102.83	**23.8**	**16.81**	-63.11	-82.13	-89.13	-169.04
			gas+oil (no consumers for heat)	-107.76	-110.11	-184.78	-65	-67.34	-142.02	-179.04	-181.38	-256.06
			gas+oil (40 €/MWh for heat)	-71.63	-73.97	-148.65	-28.87	-31.21	-105.88	-142.91	-145.25	-219.92
Product carbonisate	gas/oil		BASE**	-87.11	-96.97	-146.59	-42.91	-52.77	-102.4	-160.76	-170.62	-220.25
		CHP/PSA	only gas (no consumers for heat)	-159.16	-166.8	-279.12	-103.52	-111.17	-223.48	-251.89	-259.53	-371.84
			only gas (40 €/MWh for heat)	-104.75	-112.39	-224.7	-49.12	-56.76	-169.07	-197.47	-205.12	-317.43
			gas+oil (no consumers for heat)	-275.03	-275.38	-379.45	-214.2	-214.55	-318.61	-376.42	-376.77	-480.84
			gas+oil (40 €/MWh for heat)	-203.47	-203.83	-307.9	-142.64	-142.99	-247.06	-304.86	-305.21	-409.29

Table 70: Matrix of the considered utilization pathways of Lignite; Comparison of mLR and LC (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

Lignite			Gate fee	mid						low						high					
			WEO (2016)	Current Policies		New Policies		450		Current Policies		New Policies		450		Current Policies		New Policies		450	
Heating	TCR product | Downstream processes		Utilization	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR	LC	mLR
Natural gas	carbonisate		BASE*	304.3	298.9	307.5	292.9	315	272.6	294.8	293.8	298	287.8	305.5	267.5	323.3	309.1	326.4	303.2	334	282.9
			BBQ briquetts	304.3	294.6	307.5	292.4	315	281.8	294.8	289.5	298	287.3	305.5	276.7	323.3	304.8	326.4	302.6	334	292
			Active carbon	304.3	564.6	307.5	562.4	315	551.7	294.8	559.4	298	557.2	305.5	546.6	323.3	574.8	326.4	572.6	334	562
			animal feed additive	304.3	564.6	307.5	562.4	315	551.7	294.8	559.4	298	557.2	305.5	546.6	323.3	574.8	326.4	572.6	334	562
Feedstock	carbonisate		BASE*	272.6	281.8	277.9	277	320.2	275.4	260.7	275.4	266	270.6	308.3	269	296.3	294.6	301.7	289.8	343.9	288.2
			BBQ briquetts	272.6	277.5	277.9	276.5	320.2	284.6	260.7	271.1	266	270.1	308.3	278.2	296.3	290.3	301.7	289.3	343.9	297.4
			Active carbon	272.6	547.4	277.9	546.4	320.2	554.5	260.7	541	266	540	308.3	548.1	296.3	560.2	301.7	559.2	343.9	567.3
			animal feed additive	272.6	547.4	277.9	546.4	320.2	554.5	260.7	541	266	540	308.3	548.1	296.3	560.2	301.7	559.2	343.9	567.3
Product carbonisate	carbonisate		BASE*	340.6	328.7	345.9	323.7	387.5	319.7	328.2	322.1	333.4	317.2	375	313.1	365.6	341.9	370.8	336.9	412.4	332.9
			BBQ briquetts	340.6	325.7	345.9	323.4	387.5	326.1	328.2	319.1	333.4	316.8	375	319.5	365.6	338.9	370.8	336.5	412.4	339.3
			Active carbon	340.6	515.3	345.9	513	387.5	515.7	328.2	508.7	333.4	506.4	375	509.2	365.6	528.5	370.8	526.2	412.4	528.9
			animal feed additive	340.6	515.3	345.9	513	387.5	515.7	328.2	508.7	333.4	506.4	375	509.2	365.6	528.5	370.8	526.2	412.4	528.9
Product syngas	carbonisate		BASE*	427.8	219.1	432.2	208.8	467.5	190.1	411.5	215.6	415.9	205.2	451.2	186.5	460.4	226.2	464.8	215.8	500.1	197.1
			BBQ briquetts	427.8	211.7	432.2	207.8	467.5	205.8	411.5	208.2	415.9	204.3	451.2	202.2	460.4	218.8	464.8	214.9	500.1	212.8
			Active carbon	427.8	675.5	432.2	671.6	467.5	669.5	411.5	671.9	415.9	668	451.2	666	460.4	682.5	464.8	678.6	500.1	676.6
			animal feed additive	427.8	675.5	432.2	671.6	467.5	669.5	411.5	671.9	415.9	668	451.2	666	460.4	682.5	464.8	678.6	500.1	676.6
Natural gas	gas		BASE**	304.3	298.9	307.5	292.9	315	281.8	294.8	293.8	298	287.8	305.5	276.7	323.3	309.1	326.4	303.2	334	292
		PSA	H_2+off gas	344.7	361.4	347.8	359	355.3	335.5	335.2	356.1	338.3	353.8	345.9	330.3	363.7	371.9	366.8	369.5	374.3	346
Feedstock	gas		BASE**	272.6	281.8	277.9	277	320.2	284.6	260.7	275.4	266	270.6	308.3	278.2	296.3	294.6	301.7	289.8	343.9	297.4
		PSA	H_2+off gas	312.9	343.8	318.3	342.7	360.5	338.4	301.1	337.2	306.4	336.1	348.6	331.8	336.7	356.9	342	355.8	384.3	351.5
Product carbonisate	gas		BASE**	340.6	328.7	345.9	323.7	387.5	326.1	328.2	322.1	333.4	317.2	375	319.5	365.6	341.9	370.8	336.9	412.4	339.3
		PSA	H_2+off gas	393.6	406.4	398.9	406.2	440.5	393.3	381.1	399.5	386.4	399.3	428	386.4	418.5	420.2	423.8	420	465.4	407
Natural gas	gas/oil		BASE**	304.3	298.9	307.5	292.9	315	281.8	294.8	293.8	298	287.8	305.5	276.7	323.3	309.1	326.4	303.2	334	292
		CHP	only gas (no consumers for heat)	350.4	294.8	356.8	291.3	388.9	304.2	340	289.1	346.4	285.7	378.5	298.5	371.2	306.1	377.6	302.7	409.7	315.5
			only gas (40 €/MWh for heat)	306.2	267.8	312.7	264.4	344.8	277.3	295.8	262.2	302.3	258.8	334.4	271.6	327	279.2	333.5	275.7	365.6	288.6
			gas+oil (no consumers for heat)	393.6	286.8	396.7	284.3	426.3	299.7	383.3	281.7	386.4	279.2	416	294.6	414.1	297.2	417.3	294.7	446.9	310.1
			gas+oil (40 €/MWh for heat)	338.1	256.1	341.2	253.6	370.8	269	327.8	250.9	331	248.4	360.6	263.8	358.6	266.4	361.8	263.9	391.4	279.3
Feedstock	gas/oil		BASE**	272.6	281.8	277.9	277	320.2	284.6	260.7	275.4	266	270.6	308.3	278.2	296.3	294.6	301.7	289.8	343.9	297.4
		CHP	only gas (no consumers for heat)	315.6	275.9	324.5	273.7	394.6	307.3	302.6	268.8	311.5	266.7	381.6	300.2	341.6	290	350.5	287.9	420.6	321.4
			only gas (40 €/MWh for heat)	271.5	248.9	280.3	246.8	350.4	280.3	258.4	241.9	267.3	239.7	337.4	273.3	297.5	263.1	306.4	261	376.5	294.5
			gas+oil (no consumers for heat)	359.3	269.6	364.8	268.3	431.9	302.6	346.4	263.1	351.9	261.8	419.1	296.1	384.9	282.5	390.4	281.2	457.6	315.5
			gas+oil (40 €/MWh for heat)	303.8	238.8	309.3	237.5	376.4	271.8	290.9	232.3	296.4	231	363.6	265.3	329.4	251.7	335	250.4	402.1	284.7
Product carbonisate	gas/oil		BASE**	340.6	328.7	345.9	323.7	387.5	326.1	328.2	322.1	333.4	317.2	375	319.5	365.6	341.9	370.8	336.9	412.4	339.3
		CHP	only gas (no consumers for heat)	407.7	324.2	417.7	322.2	497	354.6	393.6	316.6	403.6	314.7	482.9	347	435.8	339.2	445.9	337.2	525.1	369.6
			only gas (40 €/MWh for heat)	347.9	295.9	358	294	437.2	326.3	333.8	288.4	343.9	286.4	423.1	318.8	376.1	311	386.1	309	465.4	341.4
			gas+oil (no consumers for heat)	464.9	294.2	470.4	293.9	545.5	326.5	451.1	287.8	456.5	287.4	531.6	320.1	492.6	307.1	498	306.7	573.1	339.3
			gas+oil (40 €/MWh for heat)	390.1	264.3	395.6	264	470.7	296.6	376.3	257.9	381.8	257.6	456.9	290.2	417.8	277.2	423.3	276.8	498.4	309.5
Natural gas	gas/oil		BASE**	304.3	298.9	307.5	292.9	315	281.8	294.8	293.8	298	287.8	305.5	276.7	323.3	309.1	326.4	303.2	334	292
		CHP/PSA	only gas (no consumers for heat)	443	437.3	450.7	438.2	489.3	438.6	430.5	429.9	438.3	430.8	476.8	431.2	468	452.2	475.7	453.2	514.3	453.5
			only gas (40 €/MWh for heat)	404.1	408	411.9	408.9	450.4	409.3	391.6	400.5	399.4	401.4	437.9	401.8	429.1	422.9	436.9	423.8	475.4	424.2
			gas+oil (no consumers for heat)	481.9	412.9	485.5	414.2	519.4	416.1	470.2	406.5	473.7	407.8	507.7	409.7	505.5	425.6	509	426.9	543	428.8
			gas+oil (40 €/MWh for heat)	431.7	379.9	435.2	381.2	469.1	383.1	419.9	373.5	423.5	374.8	457.4	376.8	455.2	392.6	458.8	393.9	492.7	395.8
Feedstock	gas/oil		BASE**	272.6	281.8	277.9	277	320.2	284.6	260.7	275.4	266	270.6	308.3	278.2	296.3	294.6	301.7	289.8	343.9	297.4
		CHP/PSA	only gas (no consumers for heat)	401.2	412.4	411.9	415.1	496.1	442.7	385.6	403.1	396.2	405.7	480.5	433.4	432.5	431	443.1	433.7	527.3	461.3
			only gas (40 €/MWh for heat)	362.3	383.1	373	385.7	457.2	413.3	346.7	373.7	357.3	376.4	441.6	404	393.6	401.7	404.2	404.4	488.5	432
			gas+oil (no consumers for heat)	442.6	391.6	448.9	394.4	525.8	419.5	427.9	383.7	434.2	386.5	511.1	411.6	472	407.5	478.3	410.3	555.3	435.4
			gas+oil (40 €/MWh for heat)	392.3	358.7	398.6	361.4	475.5	386.6	377.6	350.7	383.9	353.5	460.8	378.6	421.7	374.5	428	377.3	505	402.5
Product carbonisate	gas/oil		BASE**	340.6	328.7	345.9	323.7	387.5	326.1	328.2	322.1	333.4	317.2	375	319.5	365.6	341.9	370.8	336.9	412.4	339.3
		CHP/PSA	only gas (no consumers for heat)	559.4	547.5	572.4	552.8	674.9	578	541.2	536.3	554.2	541.6	656.7	566.8	595.8	570	608.8	575.2	711.3	600.4
			only gas (40 €/MWh for heat)	502.8	511.1	515.7	516.4	618.2	541.6	484.5	499.9	497.5	505.1	600	530.3	539.2	533.6	552.1	538.8	654.6	564
			gas+oil (no consumers for heat)	605	475.1	611.6	480.8	702.3	500.8	588.3	466.5	594.9	472.1	685.6	492.1	638.4	492.5	645	498.2	735.7	518.2
			gas+oil (40 €/MWh for heat)	533.7	438.7	540.3	444.3	630.9	464.3	517	430	523.6	435.6	614.2	455.6	567.1	456	573.7	461.7	664.3	481.7

Table 71: Matrix of the considered utilization pathways of Lignite; Difference mLR-LC as an indicator of profitability (*: Gas and carbonisate for energetic utilization, oil for refinery process, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin; **: Gas for energetic utilization, oil for refinery process, carbonisate optimal utilization pathway, prices discounted by HHV, assumption oil: high O, S, and N content is compensated due to the biogenic origin)

Lignite			Gate fee	mid			low			high		
			WEO (2016)	Current Policies	New Policies	450	Current Policies	New Policies	450	Current Policies	New Policies	450
Heating	TCR product | Downstream processes		Utilization	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC	Δ mLR-LC
Natural gas	carbonisate		BASE*	-5.44	-14.54	-42.35	-1.05	-10.15	-37.97	-14.18	-23.29	-51.1
			BBQ briquetts	-9.73	-15.07	-33.2	-5.34	-10.69	-28.82	-18.47	-23.82	-41.95
			Active carbon	260.23	254.89	236.76	**264.62**	259.27	241.14	251.49	246.14	228.01
			animal feed additive	260.23	254.89	236.76	**264.62**	259.27	241.14	251.49	246.14	228.01
Feedstock	carbonisate		BASE*	9.2	-0.91	-44.73	14.69	4.56	-39.26	-1.75	-11.86	-55.68
			BBQ briquetts	4.91	-1.44	-35.58	10.39	4.03	-30.11	-6.04	-12.4	-46.53
			Active carbon	**274.87**	**268.52**	234.38	**280.35**	**273.99**	239.85	263.92	257.56	223.43
			animal feed additive	**274.87**	**268.52**	234.38	**280.35**	**273.99**	239.85	263.92	257.56	223.43
Product carbonisate	carbonisate		BASE*	-11.91	-22.14	-67.81	-6.03	-16.27	-61.94	-23.66	-33.9	-79.57
			BBQ briquetts	-14.92	-22.52	-61.39	-9.04	-16.65	-55.52	-26.68	-34.27	-73.14
			Active carbon	174.71	167.12	128.25	180.59	172.99	134.12	162.96	155.36	116.5
			animal feed additive	174.71	167.12	128.25	180.59	172.99	134.12	162.96	155.36	116.5
Product syngas	carbonisate		BASE*	-208.65	-223.46	-277.4	-195.88	-210.69	-264.63	-234.2	-249.01	-302.94
			BBQ briquetts	-216.02	-224.38	-261.69	-203.25	-211.6	-248.91	-241.57	-249.92	-287.23
			Active carbon	247.7	239.35	202.04	260.48	252.12	214.81	222.15	213.8	176.5
			animal feed additive	247.7	239.35	202.04	260.48	252.12	214.81	222.15	213.8	176.5
Natural gas	gas		BASE**	-5.44	-14.54	-33.2	-1.05	-10.15	-28.82	-14.18	-23.29	-41.95
		PSA	H_2+off gas	16.68	11.2	-19.8	20.92	15.44	-15.56	8.19	2.71	-28.29
Feedstock	gas		BASE**	9.2	-0.91	-35.58	14.69	4.56	-30.11	-1.75	-11.86	-46.53
		PSA	H_2+off gas	30.88	24.4	-22.11	36.18	29.71	-16.8	20.26	13.78	-32.73
Product carbonisate	gas		BASE**	-11.91	-22.14	-61.39	-6.03	-16.27	-55.52	-23.66	-33.9	-73.14
		PSA	H_2+off gas	12.77	7.35	-47.22	18.34	12.92	-41.63	1.62	-3.8	-58.37
Natural gas	gas/oil		BASE**	-5.44	-14.54	-33.2	-1.05	-10.15	-28.82	-14.18	-23.29	-41.95
		CHP	only gas (no consumers for heat)	-55.6	-65.5	-84.72	-50.85	-60.74	-79.98	-65.09	-74.99	-94.23
			only gas (40 €/MWh for heat)	-38.4	-48.3	-67.53	-33.64	-43.54	-62.78	-47.89	-57.79	-77.02
			gas+oil (no consumers for heat)	-106.75	-112.38	-126.57	-101.64	-107.27	-121.46	-116.96	-122.59	-136.78
			gas+oil (40 €/MWh for heat)	-82.02	-87.65	-101.85	-76.93	-82.56	-96.74	-92.24	-97.87	-112.05
Feedstock	gas/oil		BASE**	9.2	-0.91	-35.58	14.69	4.56	-30.11	-1.75	-11.86	-46.53
		CHP	only gas (no consumers for heat)	-39.72	-50.72	-87.32	-33.78	-44.78	-81.38	-51.6	-62.6	-99.19
			only gas (40 €/MWh for heat)	-22.52	-33.51	-70.12	-16.58	-27.58	-64.18	-34.4	-45.4	-81.99
			gas+oil (no consumers for heat)	-89.68	-96.5	-129.34	-83.3	-90.11	-122.96	-102.45	-109.26	-142.12
			gas+oil (40 €/MWh for heat)	-64.96	-71.77	-104.63	-58.57	-65.39	-98.23	-77.72	-84.55	-117.39
Product carbonisate	gas/oil		BASE**	-11.91	-22.14	-61.39	-6.03	-16.27	-55.52	-23.66	-33.9	-73.14
		CHP	only gas (no consumers for heat)	-83.52	-95.52	-142.41	-76.97	-88.97	-135.86	-96.62	-108.62	-155.51
			only gas (40 €/MWh for heat)	-52	-64	-110.89	-45.45	-57.45	-104.34	-65.1	-77.11	-124
			gas+oil (no consumers for heat)	-170.67	-176.5	-218.99	-163.26	-169.09	-211.59	-185.48	-191.31	-233.8
			gas+oil (40 €/MWh for heat)	-125.79	-131.62	-174.11	-118.38	-124.21	-166.7	-140.6	-146.43	-188.92
Natural gas	gas/oil		BASE**	-5.44	-14.54	-33.2	-1.05	-10.15	-28.82	-14.18	-23.29	-41.95
		CHP/PSA	only gas (no consumers for heat)	-5.66	-12.5	-50.66	-0.62	-7.46	-45.62	-15.74	-22.58	-60.75
			only gas (40 €/MWh for heat)	3.87	-2.95	-41.13	8.92	2.08	-36.08	-6.21	-13.05	-51.21
			gas+oil (no consumers for heat)	-69.07	-71.35	-103.34	-63.65	-65.94	-97.92	-79.9	-82.18	-114.17
			gas+oil (40 €/MWh for heat)	-51.76	-54.04	-86.03	-46.34	-48.63	-80.61	-62.59	-64.87	-96.86
Feedstock	gas/oil		BASE**	9.2	-0.91	-35.58	14.69	4.56	-30.11	-1.75	-11.86	-46.53
		CHP/PSA	only gas (no consumers for heat)	11.2	3.19	-53.41	17.5	9.5	-47.1	-1.41	-9.42	-66.02
			only gas (40 €/MWh for heat)	20.74	12.73	-43.87	27.05	19.04	-37.56	8.12	0.12	-56.48
			gas+oil (no consumers for heat)	-50.95	-54.5	-106.29	-44.18	-47.72	-99.52	-64.5	-68.05	-119.83
			gas+oil (40 €/MWh for heat)	-33.64	-37.19	-88.97	-26.87	-30.41	-82.2	-47.19	-50.74	-102.53
Product carbonisate	gas/oil		BASE**	-11.91	-22.14	-61.39	-6.03	-16.27	-55.52	-23.66	-33.9	-73.14
		CHP/PSA	only gas (no consumers for heat)	-11.88	-19.6	-96.9	-4.9	-12.63	-89.92	-25.85	-33.57	-110.86
			only gas (40 €/MWh for heat)	8.37	0.65	-76.64	15.35	7.63	-69.66	-5.59	-13.3	-90.61
			gas+oil (no consumers for heat)	-129.9	-130.84	-201.47	-121.89	-122.83	-193.46	-145.91	-146.85	-217.49
			gas+oil (40 €/MWh for heat)	-95.02	-95.96	-166.6	-87.01	-87.96	-158.59	-111.03	-111.98	-182.62

PUBLICATIONS RESULTING FROM RESEARCH

Jäger, Nils; Conti, Roberto; Neumann, Johannes; Apfelbacher, Andreas; Daschner, Robert; Binder, Samir; Hornung, Andreas (2016): Thermo-Catalytic Reforming of Woody Biomass. in: Energy Fuels 30 (10), pp. 7923–7929. DOI: 10.1021/acs.energyfuels.6b00911.

Neumann, Johannes; Jäger, Nils; Apfelbacher, Andreas; Daschner, Robert; Binder, Samir; Hornung, Andreas (2016): Upgraded biofuel from residue biomass by Thermo-Catalytic Reforming and hydrodeoxygenation. in: Biomass and Bioenergy 89, pp. 91–97. DOI: 10.1016/j.biombioe.2016.03.002.

Conti, Roberto; Jäger, Nils; Neumann, Johannes; Apfelbacher, Andreas; Daschner, Robert; Hornung, Andreas (2017): Thermocatalytic Reforming of Biomass Waste Streams. In: Energy Technol. 5 (1), pp. 104–110. DOI: 10.1002/ente.201600168.

Ahmad, Ejaz; Jäger, Nils; Apfelbacher, A.; Daschner, Robert; Hornung, Andreas; Pant; K.K. (2018): Integrated thermo-catalytic reforming of residual sugarcane bagasse in a laboratory scale reactor. in: Fuel Processing Technology (171), pp. 277–286. DOI: 10.1016/j.fuproc.2017.11.020.

Hornung, Andreas, Jäger, Nils (Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e. V.) WO002018036839A1, 2017.