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Densification and conversion technologies for bioenergy and advanced biobased material supply chains – a European case study

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Abstract

In the upcoming decades, the European Union intends to shift its main input from fossil energy towards renewable sources and technologies. Today, over 60% of primary renewable energy in the EU28 is based on biomass produced by photosynthesis cultivated in forestry and agricultural systems. The current dominance of biomass within the renewable energy sector can be attributed to its cost-effectiveness and to its simplicity in providing renewable space and process heat and in providing a liquid fuel for transportation compared to other renewable alternatives. With this thesis I seek to explore the continuing substitution of fossil carbon-based economic activities with those based on biogenic carbon. I analyse the possible development of both the bioenergy sector and also of new branches of the bioeconomy, replacing those currently based on considerable amounts of fossil carbon. I discuss densification technologies and the way in which they could help to overcome limitations with regard to resource allocation of feedstock with relatively low carbon density, high water content and high heterogeneity, in comparison to current fossil feedstock. Lastly I examine the commoditisation process of resulting densified biomass products. To tackle these issues and related questions, I (1) construct scenarios for the demand of advanced biobased materials; (2) outline and apply a generic biomass-to-end-use chain tool capable of estimating densified bioenergy carrier deployment costs for a high variety of possible relevant supply chains; and (3) perform an econometric analysis to quantify the integration and efficiency of the European market for the currently most-traded densified bioenergy carrier. I find that, while primary biomass supply for bioenergy and advanced biobased materials could grow from about 7 EJ today to 11-17 EJ in 2050 in the EU28, the share of this supply for biobased chemicals - especially biobased plastics and bitumen - could reach 6-15%. Furthermore, I find that densification technologies such as pelletisation, torrefaction and pyrolysis could already reduce heating costs in Europe, and has the potential to cut the cost of lignocellulosic biomass-based electricity, transport fuel and chemical production in the future. If biomass is torrefied before pelletisation, savings of up to 3 €*GJ^{-1} could be achieved for woodchip-to-FT-synthesis supply chains. Costs saving effects of densification efforts are found to be higher for increased storage times than for increased transportation distances. It can, however, also be demonstrated that European markets for residential heating based on wood pellets are not efficiently integrated today, and that liquidity and competitiveness would have to be altered in order to support the commoditisation process of this product. Therefore, data availability and quality has to be improved to increase transparency and public perception with respect to fungibility of same-quality pellets independent of pellet colour or supply-chain affiliation, e.g. whether regionally or internationally traded.

Keywords: European bioeconomy; biochemicals scenarios; densification technologies; supply chain modelling; commoditisation process; econometric analysis; market introduction; diffusion; bioenergy

Zusammenfassung

In den nächsten Jahrzehnten soll die Deckung des Energiebedarfs der Europäischen Union von fossilen Energieträgern auf erneuerbare Ressourcen verlagert werden. Zurzeit wird über 60% der erneuerbaren Primärenergie in der EU-28 aus Biomasse abgedeckt. Die relative Kosteneffizienz und auch Simplizität der Bioenergie zur Raumwärmeproduktion und zur Produktion von flüssigen Treibstoffen können als mögliche Gründe für die derzeitige Dominanz der Biomasse im Erneuerbarensektor genannt werden. Mit dieser Dissertation möchte ich die aktuellen Substitutionsbemühungen von fossilen- zu biogenen kohlenstoffbasierten ökonomischen Aktivitäten bis 2050 analysieren. Dafür untersuche ich mögliche Entwicklungen im Bioenergiesektor, aber auch von anderen Branchen der Wirtschaft die bis jetzt auf beträchtlichen fossilen Kohlenstoffmengen basieren. Außerdem diskutiere ich Verdichtungstechnologien zur Überwindung der Beschaffungslimitierungen in Bezug auf die relativ geringen Kohlenstoffdichten biogener Rohstoffe. Letzteres erforsche ich den Kommodifizierungsprozess der resultierenden verdichteten Biokohlenstoffträger. Um diese Themen und ihre Fragen zu behandeln (1) erstelle ich Entwicklungszenarien für fortschrittliche Biomaterialien; (2) entwerfe und verwende ich ein generisches Biomasseversorgungskettenmodel und; (3) nutze ich ökonometrische Methoden um die Integration und Effizienz der europäischen Markte für verdichtete biogene Kohlenstoffprodukte zu quantifizieren. Neben einem erwarteten Wachstum der Biomasseversorgung von derzeit 7 EJ auf 11-17 EJ in 2050 weisen die Szenarien zwischen 6-15 % des Biomasseeinsatzes für biobasierte Chemikalien auf. Untersuchte Verdichtungstechnologien können schon jetzt Kosten im Raumwärmesektor und in weiterer Folge auch zur Bereitstellung von Strom sowie flüssigen Biotreibstoffen und auch Chemikalien basierend auf Lignocellulose senken. Ein, der Pelletisierung vorgeschalteter Torrefizierungsprozess könnte Versorgungskettenkosten um bis zu 3 €*GJ^{-1} senken. Einsparungspotentiale sind bezogen auf Speicherkosten höher als für Transportkosten. Allerdings sind selbst die in den letzten Jahren etablierten europäischen Holzpelletsmärkte zur Raumwärmeproduktion noch nicht effizient integriert. Liquidität und Wettbewerbsfähigkeit müssten verstärkt werden um hier den Kommodifizierungsprozess zu unterstützen. Um die besprochenen Sektoren der Bioökonomie zu stärken ist außerdem eine erhöhte Markttransparenz zentral. Diese sollte von allen Marktteilnehmern unterstützt und auch eingefordert werden. Deutlicher Forschungs- und Handlungsbedarf besteht in Bezug auf Marktdatenverfügbarkeit und Marktdatenqualität. Die Markttransparenz sowie die öffentliche Meinung bezüglich der Vertauschbarkeit von Pellets gleicher Qualität soll dadurch verbessert werden.

Stichwörter: Europäische Bioökonomie; Biochemikalienszenarien; Verdichtungstechnologien; Versorgungskettenmodellierung; Kommodifizierungsprozess; Ökonometrische Analyse; Markteinführung; Marktdiffusion; Bioenergie

1. Introduction

1.1 Motivation

The economy is embedded in a constant flow of mass and energy. We generally refer to its inflows, derived from the environment and society, as ‘resources’, and discuss its outflows in terms of ‘wastes and emissions’.

Within the economy, production and consumption of goods and services take place, often using money as a current medium of exchange. While economic development since the industrial revolution has clearly contributed to thriving societies and societal diversity across much of the world, the exploitation of resources that cannot be recovered over a foreseeable timeframe, has resulted in considerable instability in our ecosystem. The planetary boundaries framework of Steffen et al., (2015) discusses the level of influence of human activity on the environment which should be kept to a minimum if we are to decrease the risk of destabilisation of our ecosystem. In the Adoption of the Paris Agreement it was stipulated that the amount of greenhouse gas (GHG-) emissions will have to peak soon, after which rapid reductions will have to be achieved to reach the international target of economy-wide zero net-emissions in the second half of this century (UN/FCCC, 2015).

Prior to the Paris Agreement, the European Council had already decided on its 2030 climate and energy policy framework, which includes a European Union (EU)-wide reduction in domestic GHG-emissions by at least 40% in 2030 compared to 1990 (EUCO, 2014). Considering the leading role of the EU within the Paris framework as a “developed country party”, let alone possible first-mover advantages with regard to the development of technological, societal and institutional innovations and solutions, targets for 2050 can and should be significantly more ambitious. Indeed it will be essential to phase out non-renewable fossil carbon across all sectors of the economy, whilst at the same time enhancing resource efficiency.

To achieve this, those parts of the economy that are currently based on fossil carbon inputs will need to either shift to carbon input of a more recent biological origin, further denoted as biogenic carbon, give up on carbon based energy carriers, or introduce technologies to recycle carbon within the system. Those parts of the economy based on biogenic carbon are defined, in this work, as parts of the bioeconomy. In contrast, technologies enabling the phase-out of fossil-based carbon without making use of biogenic carbon will be referred to as alternative renewable technologies, and may include, for example, renewable electricity not based on biogenic carbon for transportation and for heating, concentrated solar power, photovoltaic, on and off-shore combined with electricity storage options, and hydrogen for transportation as well as CO_2-capture, -reduction and -photo catalysis for the production of carbon based materials and fuels (Tahir and Amin, 2013; Sgobbi et al., 2016; IEA, 2016a).

Even though numerous politically-driven strategies have been developed, the transition of the current markets towards national bioeconomies or even towards more integrated international bioeconomies has not been sketched out so far (Lamers, 2016). While a larger set of literature discusses possible developments in the production and consumption of bioenergy, food and feed, and traditional wood products (e.g. Matzenberger et al., 2015;Capros et al., 2013; Resch et al., 2008; Havlík et al., 2011; Mantau et al., 2010), literature on possible developments in advanced biomaterial production and consumption stands out as relatively scarce (Patel et al., 2006; Europa Innova, 2010; Dammer et al., 2013; Scarlat et al., 2015; Daioglou et al., 2015). There is currently a striking absence of detailed, member state-specific medium to long-term European advanced biobased material scenarios that could provide insights into additional biogenic carbon demand for this developing bioeconomy sector.

On the bioeconomy feedstock supply side, modelling and assessing biomass-to-end-use chains - including sourcing of the feedstock, supply to densification plants, pre-treatment and densification to densified biogenic carbon carriers, distribution to end users and conversion to heat, electricity, transport fuels or chemicals – has attracted the attention of a diverse research community as reviewed in Ba et al., (2016) and Gold and Seuring, (2011). Wood pellets, torrefied pellets and pyrolysis oil based on wood and straw have all been modelled and discussed as possible means of optimising supply chains (Hamelinck et al., 2005;Uslu et al., 2008). However, only Uslu et al. (2008) has so far undertaken a comparison of the different technologies as part of a discussion on possible market entry strategies. In light of recent research and development projects that aimed at increasing the technological readiness level (TRL) of torrefaction and fast pyrolysis (see e.g. the Sector-project (Thrän et al., 2016) and the BioBoost project (KIT, 2014), respectively) an updated assessment is necessary to discuss if and how these technologies could play a role in the cost-efficient deployment of biogenic carbon.

To discuss market introduction and diffusion of densified biogenic carbon carriers after commercialisation of the respective densification technology, the case of wood pellets offers an interesting market for analysis. The expanding international trade in this densified biogenic carbon product has been analysed in several studies (e.g. Goh et al., 2013; Olsson et al., 2011; Sikkema et al., 2011) and in inventories based on projects that included data gathering exercises (e.g. ETA et al., 2007; Cocchi et al., 2011). The focus has almost exclusively been on trade of industrial pellets, and in particular the transatlantic trade flows of pellets from the US and Canada to North Western Europe. However, there is international trade of pellets for the small-scale heating market as well, especially between countries in continental Europe. This latter market has been studied to a significantly lesser extent, but is still highly important as European demand for residential-quality pellets made up more than 30% of total global pellet consumption in 2014 (AEBIOM, 2015). The commoditisation process of wood pellets for residential heating as a densified biocarbon carrier with significant trade streams has been widely discussed (Sikkema et al., 2011); Olsson et al. (2011, 2016); Kristöfel et al., (2014, 2016)). Increased trade data availability (Eurostat, 2017) and continued expansion of wood pellet utilisation opens up the possibility and demands a more in-depth analysis of the development of market related properties of this exemplary biogenic carbon carrier.

1.2 Scope & research questions

With this thesis I seek to explore the development of, and transition towards, a European bioeconomy. The scope of the research lies on the continuing substitution of fossil carbon-based economic activities with those based on biogenic carbon within a timeframe of 2050. The following clustered research questions consider the utilisation of biomass - and more specifically its carbon content - for electricity, heat, transport fuel and material provision, which are currently heavily reliant on the carbon content of fossil fuels. Products based on biogenic carbon will be further denoted as biobased products and bioproducts.

- What are the possible relevant pathways that new and developing branches of the European bioeconomy might take towards phasing out today's fossil based economy? Which advanced biobased materials hold the potential to substitute considerable amounts of fossil-based materials and what plausible magnitudes can be reached in 2030 and 2050? How does additional biomass demand compare to that of established bioenergy scenarios?
- How can the allocation of biomass resources be supported and optimised by currently-available densification technologies including pelletisation, torrefaction, pyrolysis and gasification? What are the market entry strategies for these pre-commercial densification technologies?
- Are there significant correlations between national wood pellet price developments and intra-European wood pellet trade flows? Which policy recommendations can be derived by analysing international wood pellet trade patterns as a leading densified bioenergy product? How can the commoditisation process of resulting densified biomass products be further supported?

It should be noted that the focus of this work is on the parts of the economy in which fossil fuels are a direct and main input, which imposes certain limitations and exclusions. Production and consumption of food and feed, for example, fall out of the scope of this work, despite being indispensable economic activities based on biogenic carbon and therefore indispensable components of the bioeconomy (although they do warrant indirect consideration when it comes to feedstock limitations for non-food purposes). Fertiliser could also not be analysed within this work so far, since although fossil fuels are a main input, this input is only indirect and presents a different level of complexity. Lastly, I have excluded the traditional biomaterials sector, which includes sawn wood utilisation and pulp and paper production, since this sector is not primarily based on fossil carbon for materials production.

It is furthermore worth noting that the scope of this thesis is on techno-economic studies in contrast to socio-economic and environmental research which is only discussed in terms of literature analysis.

1.3 Outline

To answer the research questions outlined above I will discuss the possible expansion of the importance of bioenergy and biomaterials within the EU. Therefore, an overview over the current and possible future role of these economic subsystems will be drawn using established scientific literature and respective scenarios capturing the bioenergy development in **Chapter 2**. Furthermore, I explain the development of European biomaterials scenarios and respective biomass demand and discuss their implications in **Chapter 4**. The existing literature was scanned for advanced biobased materials that exhibited strong growth rates respectively hold the potential for substituting substantial amounts of fossil fuels. Current biobased capacity estimations are collected and the fossil based counterpart calculated. I describe how the fossil based production in the 28 MS are estimated and projected up to 2050. Two substitution storylines are defined and their advanced biobased material production capacities for the upcoming decades are calculated. Based on the calculated capacity scenarios I estimate biomass demand for the comparison with existing bioenergy scenarios.

To study the optimisation potential of biomass resource allocation three important densification technologies are assessed techno-economically in **Chapter 3**. Deployment costs of respective densified biocarbon carriers are modelled for a broad set of potentially relevant generic biomass-to-end-use chains. For the assessment of bioenergy systems the entire biomass-to-end-use chain, from biomass sourcing to biomass conversion has to be considered, including possible pre-treatment steps and densification, its' raw biomass supply and densified biogenic carbon carrier distribution to the conversion sites. Data and specifications on sourcing for two types of biomass, supply and densification in simple pelletisation, torrefaction and pelletisation as well as pyrolysis plants are mainly based on data compilation from several countries and technologies including practical tests from the BioBoost- and the Sector-project (KIT, 2014; Thrän et al., 2016). Based on this assessment conclusions about the market introduction of novel biomass densification technologies are derived.

In order to address the market side of biomass allocation, the commoditisation process of wood pellets for residential heating as an example for a progressed densified biogenic carbon product will be discussed in **Chapter 4**. By making use of modern trade theory, econometric modelling techniques and time series analysis tools including seasonal auto regressive moving averaged models with exogenous variable and co-integration tests, I try to understand and illustrate the current state of the commoditisation process and the efficiency of the European wood pellet for residential heating market. Based on this work and an extensive discussion with experts and stakeholders I derive recommendations to support the market diffusion of this densified biogenic carbon carrier.

The synthesis and discussion **Chapter 6** serves to link the various findings back together and to outline further uncertainties especially with regard to the generalisation of the results and deduced conclusions. Open research questions and research recommendations are stated in the end of the chapter before summarising the main conclusions of this dissertation in **Chapter 7**.

2 Background

2.1 The European energy sector and the role of biomass

About 95 EJ primary energy was used for transformation, consumption and export in the European Union in 2015 (see **Figure 1**). While 35% have been produced within the Union, the rest, about 62 EJ have been imported from third countries. With an overall transformation efficiency of 76% close to 58 EJ have been transformed to refined petroleum products, electricity and heat. After export of about 24 EJ, final energy consumption accounted for about 50 EJ in 2015. Final energy was consumed mainly for "other sectors" (19 EJ) including residential use with 11 EJ, services with 6 EJ, agriculture and forestry, fishing and other non-specified sectors. Transportation consumed about 15 EJ and industry close to 12 EJ with the chemical and petrochemical-, iron & steel-, non-metallic minerals- and paper, pulp and print industry as main contributors with about 59% of final energy consumption in industries. Furthermore, the European energy statistics (Eurostat, 2017a) outline "non-energy consumption" of about 4 EJ which will be later discussed in **Chapter 3**.

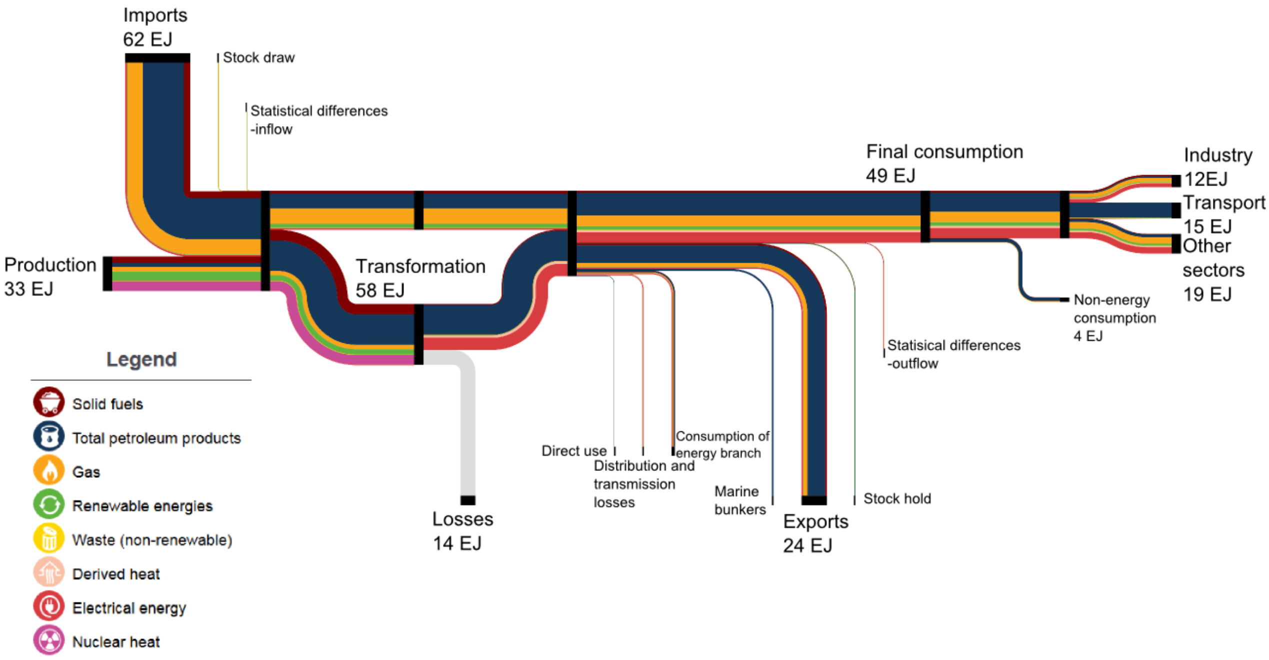

Figure 1: Energy balance flow for Europe (28 Member States) in 2015. Source; (Eurostat, 2017a)

Imported crude oil can be clearly highlighted as the backbone of the economy with about 23 EJ in 2015 which was mainly used for transformation purposes into gas and diesel oil beside about 6 EJ of gas and diesel oil which was already imported ready to be used. Self-efficiency of the EU for crude oil was about 9% while for natural gas 24% can be calculated and for solid fossil fuels about 49%.

Renewable energy, further also denoted as "renewables", was mainly produced within the EU with a self-sufficiency rate of 93%. The 9.1 EJ of renewables in 2015 can be further divided into 5.0 EJ of solid and liquid biofuels and 4.1 EJ other renewables (see **Figure 2**). About 5.2 EJ are transformed into renewable electricity and heat. For accounting reason Eurostat relabels these streams as electricity and derived heat, therefore they are not shown in **Figure 2** but are already integrated in the outflows of the transformation process visualised in **Figure 1**. While 1.2 EJ of solid biofuels have been transformed in thermal power stations and district heating plants, the larger share of solid and liquid biofuels did end up in final consumption (3.6 EJ). Liquid biofuels have been mainly used for transportation, while solid biofuels did end up mainly in the category "other sectors" which was dominated by residential heating with 1.8 EJ. Main bioenergy consuming industries are the paper, pulp and print- and the wood and wood products industries with a cumulated 78% of final consumption.

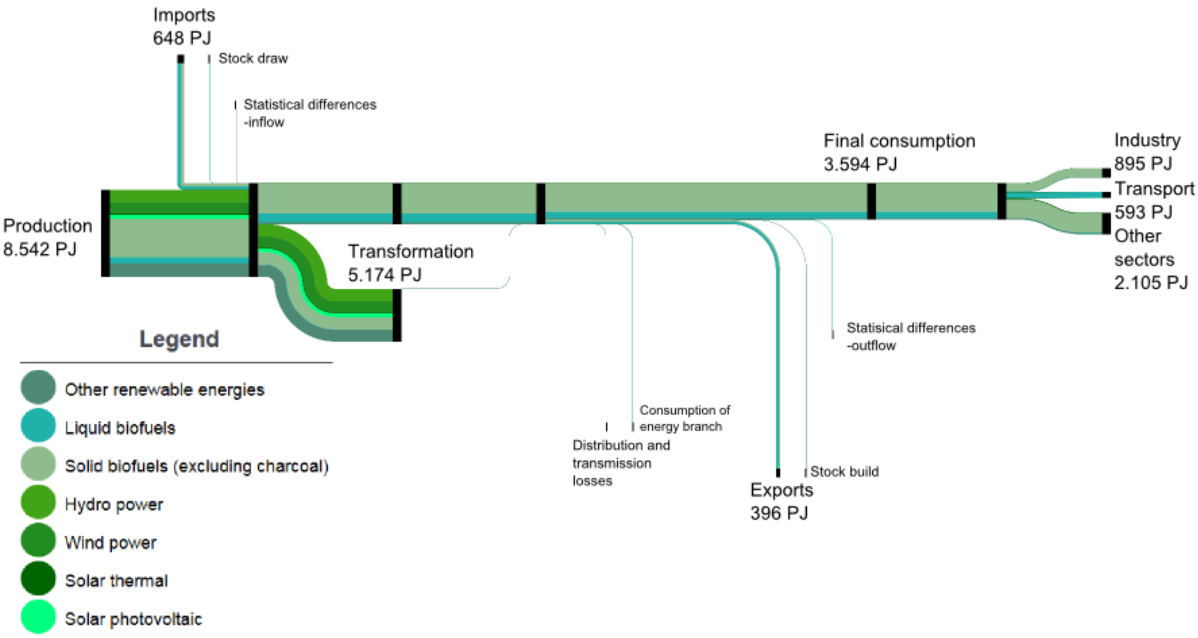

Figure 2: Renewable energy balance flow for Europe (28 Member States) in 2015. Source; (Eurostat, 2017a)

From the 1.3 EJ in the category "other renewable energies" about 46% primary energy production can be denoted as biogas, the rest accounted for tide, wave and ocean, renewable municipal waste, charcoal and geothermal energy. Biogas, a mixture of methane (50-70%) and carbon dioxide, was mainly produced through methanisation in anaerobic digesters processing different types of organic feedstock, liquid and solid waste (EurObservEr, 2014). Biogas is mainly used to produce electricity, followed by heat and a smaller share is used as transport fuel. Main countries for the production and application of biogas are Germany, followed by the United Kingdom and Italy. They mainly make use of the carbon content of slurry, farming waste and domestic waste. Also intermediate crops such as crucifers and grasses or energy crops such as maize are used. Beside these feedstock, which formed the basis (69%) of EU biogas production in 2013, 22% have been derived from landfills and 9% from wastewater treatment facilities (EurObservEr, 2014). Biogas can furthermore be upgraded to biomethane by decreasing the carbon dioxide content which opens up the possibility for injection into existing natural gas grid infrastructure. This practice as well as densification (compressed biogas) and liquefaction are used to a lesser extent within the EU (Thrän et al., 2014). Furthermore, biogas or biomethane is produced through thermal processes like gasification. Feedstock for this process is mainly lignocellulosic biomass such as straw and wood (Billig, 2016).

Liquid biofuels are summarising biogasoline, biodiesels, bio jet kerosene and other liquid biofuels (RAMON, 2017). The European vehicle fleet mainly consumes first generation biodiesel with 80% and first generation bioethanol, a subclassification of biogasoline, with 20% (EurObservEr, 2015). First-generation biofuels are said to include bioethanol from fermentation of sugar and starch food crops and biodiesel from the extraction and/or transesterification of oil containing feedstocks. The breakdown of lignocellulosic feedstock and further fermentation to ethanol or, in case of a breakdown through gasification and further Fischer-Tropsch synthesis is further denoted as second generation biofuels. (Kaltschmitt et al., 2016)

Solid biofuels summarise all "organic, non-fossil material of biological origin which may be used as a fuel for heat production or electricity generation" (RAMON, 2017). Hereunder, fuelwood, wood residues and by-products, bagasse, black liquor, other vegetal materials and residues and animal waste are listed. Solid biofuels represent the single most important renewable energy source with 4.1 EJ primary production and imports in 2015 (see **Figure 2**). Solid biofuels are mainly combusted in boilers for the production of hot water or steam which is further used in industrial processes, district heating networks or in heat collectives or service buildings. Another important application of the steam is the cogeneration of electricity and heat in combined heat and power (CHP-) plants. The electricity output of solid biofuel powered CHP plants dominated over the output of solid biofuel electricity only plants with about 58% of total output in 2015. While the total heat output in 2015 accounted for about 0.4 EJ, electricity output was at about 0.3 EJ based on solid biofuels in the EU. Furthermore, solid biofuels are also used in wood fired heating appliances such as boilers and stoves in households or other end users. (EurObservEr, 2016)

According to the renewable energy supply and consumption database (IEA, 2016b) the feedstock share in the solid biofuels category was dominated by fuelwood, wood residues and by-products with about 77% followed by 15% black liquor, a by-product from the pulp and paper industry, and 9% other vegetal materials and residues in the European OECD countries in 2014. Wood pellets, a densified solid bioenergy carrier accounted for about 4% of the energy content of the fuelwood category in the same year. The solid bioenergy subcategory was thus mainly based on lignocellulosic biomass. Since lignocellulosic biomass can also be used for the production of liquid and gaseous biofuels it can be expected, that solid biofuels can play a role in the supply of feedstock for the solid and gaseous bioenergy categories as well.

2.2 Biomass types and their sustainable potentials

Biomass for energy purposes, thus more specific plant matter and, in case of algae, other organism are cultivated and produced through photosynthesis in agricultural- and forestry- and in aquaculture systems. Through the anabolic conversion of carbon dioxide from the atmosphere based on absorbed (sun)light and subsequent plant internal metabolism carbohydrates including monosaccharides and starch are synthesised. Therefore, also macro- and micro nutrients including phosphor, nitrogen and potassium are absorbed either from the litho-, hydro- or atmosphere. The saccharides are further metabolised and polymerised into lignocellulose and triglycerides. (Campbell et al., 2005)

Based on the main components of considered plants, they will further be denoted as sugar-, starch-, and oil plants as well as lignocellulosic biomass such as wood from forestry, wood from short rotation coppice (SRC), grasses from perennial cultivation (herbaceous lignocellulosic biomass) but also agricultural residues such as straw remaining on the field after harvest of the components which can be processed to food for human consumption. It is estimated, that about two billion tonnes of biomass[1] was used in the EU in 2011 with 21% as food, 44% for feed, 19% for processing and 12% for energy production (Scarlat et al., 2015). The reference indicates a main share of biomass cultivated in agricultural production systems, including sugar-, starch- and oil plants but also fodder crops and crop residues with about 1.5 billion tonnes. Additionally about 300 million tonnes from forestry production systems, 200 million tonnes of meat and animal products and 14 million tonnes of aquatic biomass are included. Biomass use for bioenergy in the EU is furthermore estimated to be distributed with 64% forestry based, 26% agricultural biomass based and with 11% based on the other wastes excluding wood residues and co-products and agricultural by-products and residues already covered by the first two categories. (Scarlat et al., 2015)

Regarding the current utilisation of biomass for materials application in the EU28 Mantau et al., (2010) estimate, that a main share of wood (54%) was furthermore used as roundwood in the sawmill industry, as fibres' feedstock for pulp and paper production or used in the panel industry or for veneer plywood production. Furthermore, Raschka et al, (2012) cited in Carus, (2012) ouline material utilisation of 30 million tonnes of biomass other than wood mainly for polymers,

[1] This does not include various waste generated, such as waste from food industry, food waste or other biogenic waste. Furthermore, the publication does not indicate whether the numbers account for dry or wet biomass. With an indicated 280 Mt for bioenergy in 2012 and a primary energy demand of about 5.2 EJ in the same year according to Eurostat, an average heating value of 20 MJ/kg can be calculated. With dry wood at an average heating value of about 18 MJ/kg I assume that the numbers indicate dry mass.

oleochemicals such as lubricants, paper starch for the textile industry and for the production of pharmaceuticals.

In the publication of de Wit and Faaij, (2010), European biomass resource potentials are estimated following a “food first” paradigm based on excess land and excluding land claimed for current and future food and feed production. They estimate 4.5-9.3 EJ*year^{-1} agricultural- and forestry residues potential for 2030. A dedicated bioenergy crop potential range from arable land of 1.7-12.2 EJ*year^{-1} is furthermore outlined depending on the type of crop cultivation and land considered. An additional 1.6-3.6 EJ*year^{-1} can be considered for (herbaceous) lignocellulose crops produced on pasture land. However, a high share of these potentials is dedicated to the production in the Ukraine (in total 1.5-6.0 EJ year^{-1}).

In a recent paper Kluts et al., (2017) review existing biomass potential studies, including the previously discussed one from de Wit and Faaij, (2010) and highlights sustainability constraints. They find, that while de Wit and Faaij, (2010) mainly consider constraints related to food security and crop and livestock productivity increments, other studies better reflect and consider constraints related to biodiversity and GHG-emissions. For example, Elbersen et al.,(2012,2013) are discussed to include ecologically sustainable potentials of the EU28. They find an overall sustainable potential for 2030 of 15 EJ*year^{-1}. By comparing the constraints included in these studies also with other recent potential analysis Kluts et al., (2017) identifies shortcomings in their constraints accountancy. They suggest that “the identification of sustainable pathways for European bioenergy production requires a more integrative approach combining land demand for food, feed and energy crop production, including different intensification pathways, and the consequent direct and indirect environmental impacts” including a better inclusion of management practices. A more specific assessment of sustainable biomass potentials especially up to 2050 was out of scope of this dissertation.

2.3 A possible development of the European bioenergy sector

In November 2016 the European Commission published a proposal for a directive on the promotion of the use of renewable energies. The proposal aims at “collectively delivering on the commitments made in the 2015 Paris Agreement” by laying down the principles to reach at least 27% renewable energy in the EU final energy consumption by 2030 in a cost-effective manner. Contributions of the individual MS has to be set and outlined in their Integrated National Energy and Climate Plans. (EC, 2016a)

At the same time the Commission proposed to amend the energy efficiency directive to limit the Unions’ 2030 energy consumption to about 41.3 EJ of final energy and about 55.3 EJ of primary energy (EC, 2016b). Thus, a minimum increase from 3.6 EJ to about 14.9 EJ of renewables from 2015 to 2030 is required.

Both proposals have been based on results of ex-post evaluations, stakeholder consultations and impact assessments. Especially modelling tools capable of assessing the impact of various policy options on the development of the bioenergy sector have been used. On the one hand, the partial equilibrium renewable energy model Green-X, combined with an ArcGIS network for the simulation of biomass supply chains (Hoefnagels et al., 2014) and the input-output model MULTIREG was deployed. On the other hand, the PRIMES biomass supply model, "an economic supply model that computes the optimal use of resources and investment in secondary and final transformation, so as to meet a given demand of final biomass energy products under least cost conditions" (Capros, 2010) was used and energy demand data was provided by the larger scale energy system model PRIMES. The following paragraphs are based on the results from the two impact assessments from EC, (2016c).

The two modelling frameworks discuss an increasing share of bioenergy in the gross final energy consumption from about 4% in 2000 to about 10% in 2020 and up to 12% to 14% in 2030 in their reference scenarios. While the share of bioenergy within the renewables category is expected to decline, from about 60% in 2013 to 54% to 43% in 2030 depending on policy options and feedstock restrictions, total biomass supply for energy purposes increases in the respective scenarios. Primary biomass supply is discussed in a range of 6.8 to 8.0 EJ and net-imports from third countries in a range of 0.4 to 1.3 EJ compared to an estimated 2015 value of 0.3 EJ. While the PRIMES-framework does only expect a few shifts in the overall consumption patterns of the MS - with the United Kingdom becoming the third major consumer after Germany and France and displacing Italy - the Green-X scenarios estimate an average intra-EU bioenergy trade of 0.5 EJ.

Regarding the share for different end-use purposes, the reference scenario of the Green-X framework discusses about 16%, 13% and 71% dedication towards electricity, transport and heat respectively. The underlying feedstock is estimated in the reference scenarios of the two modelling frameworks with about 9 and 11% from food crops and the remaining part from lignocellulosic biomass and various waste fractions. This would represent a stagnating share compared to estimated 2015 values of the PRIMES-model, a declining share however can be assumed since the contribution of 1st generation biofuels in the transport sector is proposed to be limited to a maximum of 7% of final consumption and set to be reduced to 3.8% in 2030 (EC, 2016a).

The PRIMES modelling framework furthermore investigates the development up to 2050. Primary domestic production of biomass feedstock for energy purposes of about 8.8 EJ and up to 11.4 EJ and net-imports from third countries of about 1.3 EJ and up to 2.9 EJ are simulated and further applications like bio-kerosene for aviation are considered until 2050 in the PRIMES-scenarios.

3 Advanced biomaterials scenarios for the EU28 up to 2050 and their respective biomass demand

This chapter is adopted from a paper published in the journal Biomass and Bioenergy (Schipfer et al., 2017) together with Lukas Kranzl, David Leclere, Leduc Sylvain, Nicklas Forsell and Hugo Valin.

3.1 Introduction

The consumption of fossil resources largely contributes to destabilise the Earth's climate (Pachauri et al., 2014) and our large dependency on such resources for material and energy supply is a main obstacle to a more sustainable development as defined by the Sustainable Development Goals (United Nations Development Programme, 2015) and the Paris agreement (UN/FCCC, 2015). While the subsidies to fossil fuel resource use currently about four times higher than that of renewable resource use, or than the amount invested in improving energy efficiency (IEA, 2014), a large transformation of our economy is required. Such a transformation needs to be anticipated and efficiently as well as quickly incentivized to meet the Paris agreement. Two broad levels of intervention allowing reducing the fossil carbon intensity of our economy can be investigated: (1) reducing the material and energy intensity of the economy through efficiency increases and; (2) the substitution of fossil resources with alternatives for material and energy supply. The present thesis focuses on the latter.

On the one hand, the utilisation of oil, gas and coal as energy carriers is gradually substituted to reach a more sustainable portfolio including wind, solar, tidal, geothermal and biomass based technologies (IRENA, 2015). In this sector bioenergy leads over other renewable technologies and is expected to keep this position in the upcoming decades (Nakada et al., 2014). In this sector bioenergy leads over other renewable technologies and is expected to keep this position in the upcoming decades (Nakada et al., 2014). On the other hand, in the materials sector, the potential substitution of fossil carbon-based products will be mainly based on biomass, using different conversion technologies such as fermentation, gasification and lignin processing (Gerssen-Gondelach et al., 2014a). A second alternative is the recycling of carbon contained in existing and future materials, without making use of carbon synthesised through photosynthesis. As described in e.g. Tahir and Amin (Tahir and Amin, 2013), recycling technologies are in an early research phase and will not be part of the scope of this thesis.

In several position papers (EC, 2007; European Comission, 2011; European Comission, 2012; European Comission, 2014), the European Commission (EC) and the European Union (EU) Member States (MS) outlined strategies and recommendations to develop a knowledge based bioeconomy (KBBE) in the coming decades. The bioeconomy sectors can be defined as those dealing with "the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy." (European Comission, 2014) Beside traditional biobased products like e.g.

from the pulp and panel industry also more advanced biobased materials like biobased polymers fall in this category (CEN, 2011). Furthermore the 'Cologne Paper' (EC, 2007) defines knowledge based by "transforming life sciences knowledge into new, sustainable, eco-efficient and competitive products."

Despite such a pro-active policy environment in the EU, the literature on potential pathways for the European bioeconomy on a medium or long term (up to 2030 or 2050 respectively) is incomplete. A large literature discussed possible developments of the production and consumption of bioenergy, food and feed, and traditional wood products (e.g. (Matzenberger et al., 2015;Capros et al., 2013; Resch et al., 2008; Havlík et al., 2011; Mantau et al., 2010), etc). On the contrary, the literature on possible developments in advanced biomaterial production and consumption stands out as relatively scarce. (Patel et al., 2006; Europa Innova, 2010; Dammer et al., 2013; Scarlat et al., 2015; Daioglou et al., 2015) While Europa Innova, (2010) discusses several advanced biobased material product groups and outline short term expectations which are updated in Scarlat et al., (2015), Dammer et al., (2013) focuses on biobased polymers and short term expectations only. Patel et al., (2006) and Daioglou et al., (2015) outline long term expectations and scenarios, however in Patel et al., (2006) on a highly aggregated level and in Daioglou et al., (2015) with the focus on the global development. No detailed medium to long term European advanced biobased material scenarios exist so far. In the light of such a gap, I propose an appraisal of the potential for substituting fossil based materials by advanced biomaterials in the EU on a medium (2030) to long (2050) term. I more specifically address the following research questions:

- Which advanced biobased materials hold the potential to substitute substantial amounts of fossil based materials?
- How much of these advanced biobased materials are currently produced and what are plausible magnitudes in 2030 and 2050 respectively?
- At which rate the production of such products should grow to allow the EU phasing out fossil based counterparts?
- What are possible underlying biomass needs and how do they compare to existing biomass for bioenergy scenarios?
- How will the additional biomass demand be distributed within the EU28 and what are possible implications for international biomass trade?

3.2 Methodology

In order to address my research questions I scanned the existing literature for advanced biobased materials that exhibited strong growth rates respectively hold the potential for substituting substantial amounts of fossil fuels. Current biobased capacity estimations are collected and the fossil based counterpart calculated. The following subsection describes how the fossil based production in the 28 MS are estimated and projected up to 2050. I define two substitution storylines and calculate their advanced biobased material production capacities for the upcoming decades. Based on the calculated capacity scenarios I estimate biogenic building block demands for further comparison with existing bioenergy scenarios. The calculation steps and their assumptions are explained and justified in the following subsections.

3.2.1 Fossil based non-energy consumption estimation – now and up to 2050

The first step is to list and assess final products which could be subject to substitution: The world energy statistics and balances database from the IEA and OECD (2015) informs the production of bitumen, lubricants and waxes, further denoted as heavy refinery products. The balance further outlines the non-energy consumption of various types of primary energy carriers (see Appendix A in **Chapter 8.1**) for the production of other materials through steam cracking - referred to as High Value Chemicals (HVC) according to Ren et al., 2006 in Daioglou et al., (2014). Yearly quantities for the non-energy consumption of primary energy carriers for the 28 MS and the years 2008, 2009 and 2010 are further processed to estimate production of various HVCs. According to the EC (Europa Innova, 2010) non-energy use of fossil based HVCs can be further split into polymers, solvents and surfactants with 89.6%, 8.2% and 2.2% respectively. I divide the group of polymers in Polyethylene terephthalate (PET) with 7%, Polyethylene (PE) and Polypropylene (PP) with 48.5% and Polyvinylchloride (PVC), Polyurethane (PUR), Polystyrene (PS) and others with 44.5% (PlasticsEurope, 2015). For the matter of simplification I neglect losses in the mass balance of the conversion process and assume the same non-energy utilisation shares for all MS and the three years as well as for the scenario time span.

The second step is to estimate the evolution of the production of these fossil resource based final products: The EU Energy, Transport and GHG Emissions Trends to 2050 from Capros et al., (2013) contain scenarios for the fossil-, nuclear- and renewable energy consumption of the EU28 up to 2050 on a member state. The resulting secondary products of the corresponding petrochemical industry are also calculated on the member state level and documented as “non-energy uses … such as chemical feed-stocks, lubricants and asphalt …” level (see Appendix B in Chapter 0). The 2013 reference scenario of Capros et al., (2013) is used to project the historic fossil based materials production estimations derived from the database of OECD and IEA (OECD and IEA, 2015) for the 28 MS up to 2050 in five years' time steps.

3.2.2 Advanced biobased materials – status quo

For the European Union four of the five discussed fossil based product groups were identified to hold possible high substitution potentials already in the beginning of this century between the Directory General (DG) Enterprise and the European Renewable Resources & Materials Association (ERRMA) (European Comission, 2002). In the final report of the BIOCHEM project (Europa Innova, 2010) the same products were discussed again as promising product segments and their market shares in 2008 and potentials have been analysed. Estimated production capacities in million tonnes per annum (Mt) and kilo tonnes per annum (kt) are adapted for this thesis.

Surfactants based on biogenic feedstocks represent the highest biobased share of the selected materials today. Surfactants or surface acting agents are blends that lower the surface tension of a medium in which they are dissolved in. This property makes it applicable for example for soaps, herbicides, wetting agents, cosmetics, fabric softeners and "… virtually any other application where two dissimilar types of compounds are brought together". (Salimon et al., 2012)
The biodegradability and lower toxicity can outweigh the higher costs for naturally derived surfactants compared to their mineral oil based complement for certain applications. The EU biobased consumption for this product grew from 1.18 Mt in 1998 to 1.52 Mt in 2008 compared to 1.2 Mt fossil based surfactants ((European Comission, 2002) and (EC, 2010) respectively). It is the only case of the here presented materials where biobased production already overtook fossil based production in the past decade.

Solvents based on renewable raw materials are mainly industrial used ethanol and in small quantities alcohols and acetates (Busch, 2014). Due to the advantage of emitting lower or no quantities of volatile organic compounds (VOCs) than their fossil based counterpart the use of this product for dissolving pigments to produce inks but also paints and varnishes showed a strong growth in the last decades. The EU biobased consumption for this product grew from 60 kt in 1998 to 630 kt in 2008 compared to 4.4 Mt fossil based solvents ((European Comission, 2002) and (EC, 2010) respectively).

Lubricants are used to reduce friction between two surfaces. Because of the lower toxicity and biodegradability compared to the fossil based reference product " … some countries … have banned the use of non-biodegradable lubricants in sensitive areas at least in applications where oils are lost into soil and surface waters." (EC, 2010) The EU biobased consumption for this product grew from 100 kt in 1998 to 150 kt in 2008 compared to 9.3 Mt fossil based ((European Comission, 2002) and (EC, 2010) respectively).

Plastics are used in a wide range of products due to their low costs and good shapeabilities. However the advantage of biodegradability of biobased plastics is not seen as the driving force of its recent development since both, biodegradable fossil based plastics and non-biodegradable biobased (drop-in) plastics exist. Momani, (2009) states comparable properties of polylactic acid (PLA), Polyhydroxybutyrate (PHB) and thermoplastic starch (TPS) with PP, low density PE and high density PE (PE-LD and PE-HD respectively). These resin types are further denoted as biodegradable bio-polymers and are considered to substitute PE-LD, PE-LLD, PE-HD and PP while biobased PET or polyethylene furanoate (PEF) is considered to substitute fossil based PET in my thesis. The EU biobased consumption and production for biobased polymers exhibited a growth from 25 kt in 1998 to 130 kt in 2008 compared to 48 Mt fossil based complements ((European Comission, 2002) and (EC, 2010) respectively). The Institute for Bioplastics and Biocomposites (ifbb, 2016) states a EU biobased production capacity of 261 kt in 2014. A growth rate of about 50% for the six years period between 2008 and 2014 can be outlined. The Nova-Institute (nova-Institut GmbH, 2013) discusses the European focus in 2013 on starch blends and biodegradable plastics with 87.0% before more durable biobased PUR and polyamides (PA) with 13.0% but no capacities for the production of biobased PET.

For **bitumen** based on biomass no data on European wide production quantities could be found so far. With an annual world demand of 200 Mt fossil based bitumen (Bleier, 2012) and a EU annual production of about 20 Mt (OECD and IEA, 2015) it could be another promising substitution candidate. However only results from research and development can be found in literature e.g. in a summarising document (Rosenbloom et al., 2012) on alternative asphalt binders based on different biomass feedstocks and theoretical consideration on the substitution of the Austrian fossil based bitumen consumption with wood based bitumen (Lauk et al., 2012).

Out of the five discussed advanced biobased materials, only data availability for biobased polymers improved after the BIOCHEM-project. However still no official document could be found indicating the spatial distribution of biobased production capacities within the EU. The OECD (Organisation for Econmic Co-operation and Development, 2013) discusses Germany, Italy, France, the Netherlands, the United Kingdom and Sweden to have ongoing legislative activities, public-private partnerships (PPPs) and dedicated funding activities for their national biochemical sectors. In order to derive starting values for the advanced biobased materials scenarios I calculated a weighted 2008 spatial capacity distribution in the listed MS based on their fossil non-energy product quantities. Furthermore I projected the biobased materials capacities to the scenario starting year 2015 using the fossil based growth rates from OECD and IEA, (2015) for the period 2008-2010 and Capros et al., (2013) for 2010 to 2015 for all biobased materials but polymers. For biobased polymers I linearly extended the growth rate from 2008 to 2014 outlined above by one year.

3.2.3 Advanced biobased materials storylines

Based on the non-energy fossil fuel production projections from 2010 to 2050 and based on the advanced biobased materials capacity estimation for 2015 two substitution scenarios are calculated raising the, overall low shares of advanced biobased materials to substantial ones in the time frame of 2015 - 2050. However biobased surfactants have to be noted and treated as an exception since already historic data indicate a higher share than fossil based surfactants on the European market.

The first scenario discusses a 40% substitution of fossil based production quantities with biobased production quantities for lubricants, biodegradable polymers, solvents and PET. Other durable polymers as well as bitumen are not discussed in this scenario which skips down to no significant market introduction for these biobased materials until 2050. With no major breakthrough in the drop-in biopolymers and biobased bitumen research this scenario is further denoted as **reference scenario**. Substitution shares are well below the biochemical target of 30% for 2030 from the public private partnership (PPP) on biobased industries (CEPI, 2015). This scenario illustrates a less optimistic and less technological world but still with significant market developments for lower hanging fruits respectively selected biobased materials.

The second scenario, further denoted as **transition scenario** illustrates a 70% substitution for all products in 2050 including other drop-in polymers and bitumen and therefore outlines an ambitious development of advanced biomaterials production. Biobased surfactants are again considered to reach full substitution in 2050. In the final report of the BREW-project (Patel et al., 2006) a poll including the consortium partners outlines an expected range of 10 - 50% substitution level in 2050 for all biobased chemicals. Scarlat et al., (2015) discuss a potential substitution of 85% of polymers in Europe by 2050. The transition scenario describes a world in which a higher focus is set on substitution of fossil based materials with biomaterials and therefore serves as an upper threshold of the range within the advanced biobased materials are expected to develop heading for a transition to a strong advanced biobased material sector within the current century.

For the case of biobased surfactants no specific substitution targets could be identified in the literature. However a full substitution in 2050 of fossil based surfactants with biobased surfactants is calculated for both scenarios since this product can already exhibit market domination in the historic data. For the moderate and the transition scenario quadratic growth rates to reach the substitution targets in 2050 starting from the 2015 values and the five years’ time steps are calculated.

3.2.4 Biogenic building block demand for bioenergy demand comparison

The production of biobased polymers and solvents is discussed to be mainly based on the conversion of glucose, further denoted as a biogenic building block. (ifbb, 2016; Iffland et al., 2015) Other biogenic building blocks addressed in my thesis are plant or vegetable oils for the production of lubricants and surfactants (Salimon et al., 2012; Lauk et al., 2012; Iffland et al., 2015) and lignin as a binder to substitute fossil based bitumen (Bleier, 2012).

Conversion efficiencies for glucose to biobased polymers and solvents are derived from Iffland et al., (2015). Lower, higher and the stoichiometric or theoretical biomass utilisation efficiencies are adapted for the production of PLA as a representation for the conversion to the biodegradable polymer group. For the substitution of fossil based PET the discussed paper outlines a fivefold conversion efficiency to biobased PEF in contrary to the conversion to biogenic PET. I assume PEF to become the major fossil based PET substitute on a long term and therefore adapt its conversion efficiencies in the present thesis. For the group "other durable polymers" the higher and theoretical conversion efficiencies of glucose based PE are used as representation for deoxygenated (non-biodegradable) bio-polymers. Furthermore the higher and theoretical conversion efficiency for glucose to ethanol is adopted. Ethanol is the main biobased solvent in the EU (Busch, 2014). To derive one tonne of soap via an oleochemical pathway Salimon et al., (2012) state raw material requirements of 2,167 kg. This number is further used to calculate the conversion of plant oil to biobased surfactants. In a newsletter from the European Committee of Organic Surfactants and their Intermediates (CESIO, 2014) a biomass thresholds proposal is discussed differentiating between bio-surfactants and biobased surfactants with biomass content thresholds of 95% and 25% respectively. Based on this proposal the current average biomass content of surfactants in this thesis is defined as 60% with 100% as a theoretical upper limit. The raw material requirements and the range of biomass content are used to estimate a current and a theoretical conversion efficiency. In Lauk et al., (2012) a direct conversion from plant oil to lubricants is assumed with a 100% conversion efficiency. Iffland et al., (2015) however indicate that this conversion rate is only theoretical, conversion rates of 80% from vegetable oil to lubricating and hydraulics oils is currently a more realistic yield. Again the conversion efficiency range is used in the present thesis. For the production of bitumen no conversion factors could be found in the literature. However Bleier, (2012) discusses the binding properties of lignin from a basic research perspective, its actual application for example is stated in a news article (Wageningen, 2015) from March 2015. I assume that lignin can be directly used as a binder replacing fossil based bitumen in the future. All conversion efficiencies used and respective references are outlined in Table **1**.

Table 1: Conversion efficiencies of biobased building blocks to biobased products for the substitution of fossil based products.

Building block	**Product**	**Current efficiency**	**Theoretical efficiency**	**References**
Glucose	Biodegradable polymers	71,85%	80,00%	(Iffland et al., 2015)
Glucose	PEF	53,00%	55,60%	(Iffland et al., 2015)
Glucose	Other durable polymers	28,60%	31,10%	(Iffland et al., 2015)
Glucose	Ethanol	47,20%	51,10%	(Iffland et al., 2015)
Plant oil	Surfactants	76,91%	46,15%	(Salimon et al., 2012), (CESIO, 2014)
Plant oil	Lubricants	80,00%	100,00%	(Lauk et al., 2012), (Iffland et al., 2015)
Lignin	Bio-bitumen	100,00%	100,00%	Own assumption

The used current conversion efficiencies listed in Table **1** are based on either the average of lower and higher biomass utilisation efficiencies or the stated single value in case of the conversion of glucose from Iffland et al., (2015). The current efficiency for lubricants is based on Iffland et al., (2015) while the theoretical efficiency is based on Lauk et al., (2012). For the long term scenarios I estimate biogenic building block demand in 2050 based on current efficiencies and based on theoretical efficiencies assuming favourable technological development in the upcoming decades for the production of lubricants, ethanol and biobased polymers. The negative difference between current and theoretical efficiency for biobased surfactants in contrary should indicate a shift in the biomass content of this biobased product from todays 60% to 100%. On the other hand all other products are defined to contain 100% biomass and are also called advanced biobased materials in this thesis. Furthermore I use the terminologies “biobased” and “bio-“ as tantamount.

The conversion of raw biomass to the biogenic building blocks glucose, plant oil and lignin is out of scope for this thesis. However I want to differentiate between glucose from sugar and starch plant on the one hand and glucose from cellulose and lignocellulose on the other. For example the fermentation of lignocellulose to ethanol is expected to be in a R&D and demonstration phase (Gerssen-Gondelach et al., 2014a) thus makes it useful to discuss its commercialisation after 2030 and 2020. Therefore starting with the year 2035 for the reference scenario and the year 2025 for the transition scenario complete shifts for new glycose based installations towards glycose from cellulose and hemicellulose are calculated. The installed production capacities for sugar and starch based plant utilisation in 2030 and 2020 respectively are held constant until 2050 and only additional advanced biomaterials productions are assumed to be based on wood.

Finally, to enable comparability of biogenic building block demand scenarios and bioenergy scenarios I estimate the heating values of glucose, lignin and vegetable oil. I use a unified correlation for solid, liquid and gaseous fuels from Channiwala and Parikh, (2002).

$$HHV = 0.3941 * C + 1.1783 * H + 0.1005 * S + 0.1034 * O - 0.0151 * N - 0.0211 * A$$

The formula results in the estimated higher heating value (HHV) of the building blocks with mass percentages on dry basis of carbon (C), hydrogen (H), sulphur (S), nitrogen (N), oxygen (O) as well as the ash content (A) of the material is given. For glucose ($C_6H_{12}O_6$), lignin (e.g. $C_{10}H_{12}O_3$) and vegetable oil (e.g. $C_{18}H_{32}O_2$) this results in heating values of 16.4 MJ°kg^{-1}, 28.4 MJ°kg^{-1} and 39.3 MJ°kg^{-1}. The applied correlation offers an average absolute error of 1.45% and bias error of 0.00%. However, I discarded this error due to the higher but not quantifiable insecurities of the other scenario modelling steps.

3.3 Results

3.3.1 Advanced biobased material production scenarios

I identified surfactants, lubricants, solvents, polymers and bitumen as holding a significant potential in terms of substituting fossil based carbon with biogenic carbon. Substitution shares are estimated with about 1.5% around the year 2000, 2.2% in 2008 and 3.1% in 2015 based on (European Comission, 2002; EC, 2010; ifbb, 2016; OECD and IEA, 2015). For 2030 substitution potentials of 30% and 20% are discussed in CEPI, (2015) and Dammer et al., (2013) and for 2050 potentials of 10-50% according to Patel et al., (2006) for all chemicals mainly based on fossil fuels today in the EU28. For polymers in specific Scarlat et al., (2015) discuss a potential substitution of 85% in 2050. While the reference scenario in the presented thesis includes the diffusion of only selected advanced biobased materials (excl. other biobased drop-in polymers and bitumen), the transition scenario sketches market dominance in 2050 for all materials (see Figure **3**). Based on a quadratic growth rate starting with 2015 the reference scenario results in about 7% and 19% substitution shares (of all materials) in 2030 and 2050 respectively. The transition scenario discusses 16% and 72% substitution shares in 2030 and 2050 respectively.

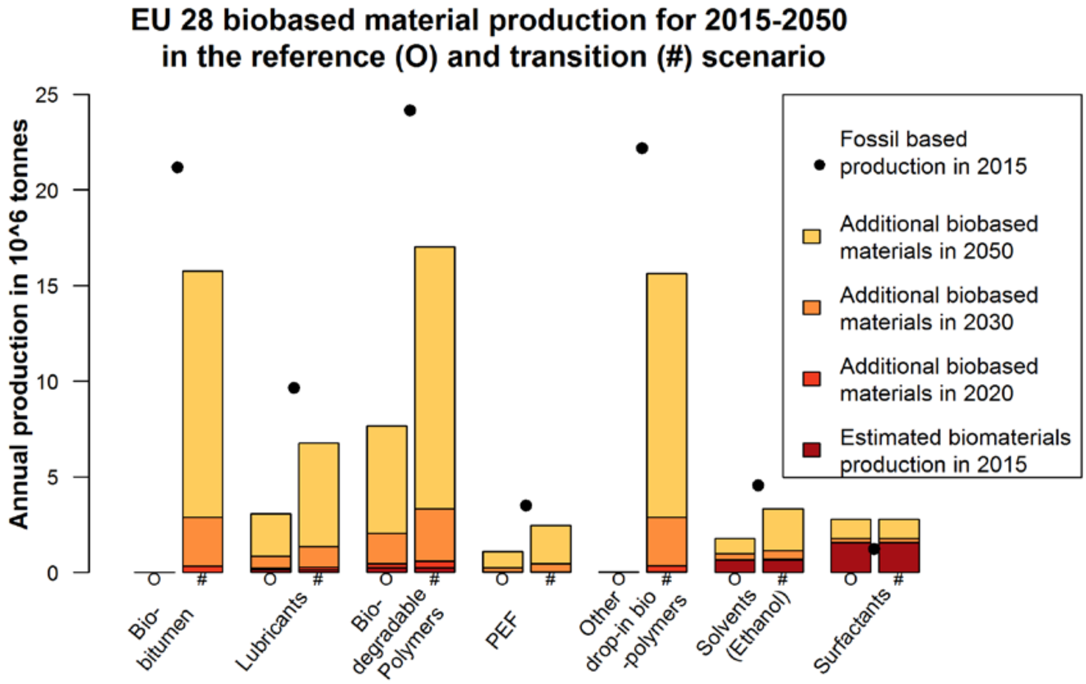

Figure 3: EU28 cumulated production capacities of advanced biobased material scenarios. Source; own illustration

For the investigated product types currently (projection for 2015) bio surfactants hold the highest share. However since surfactants based on biomass have already a higher market penetration than fossil based ones their maximal growth potential (79% between 2015 and 2050) is expected to be the lowest compared to the other investigated biomaterials. For the substitution of fossil based solvents the material utilisation of ethanol is considered. A maximum growth of about 420% from 0.6 Mt in 2015 to 3.4 Mt in 2050 is assumed for the transition scenario. With an estimated fossil based production of about 10 Mt biobased lubricants production is assumed to grow from 0.2 Mt in 2015 to 3.1 Mt and 6.8 Mt for the reference and transition scenario respectively. For this work polymers were split into three types; (1) biodegradable polymers considered to substitute the application of fossil based PE and PP (2) PEF considered to substitute fossil based PET and (3) other drop in biopolymers considered to substitute fossil based PVC, PUR and other resin types. Fossil based PET exhibit a maximum substitution (for the transition scenario) of about 2.5 Mt compared to a total biopolymer production of 35.1 Mt in 2050 for the EU28. For biodegradable polymers a 30 fold and 67 fold increase between 2015 and 2050 is assumed for the reference and transition scenario respectively. The transition scenario furthermore outlines a diffusion of biobased drop-in polymer and biobased bitumen production capacities from nearly vanishing amounts in the EU28 in 2015 to about 16 Mt each.

The simulated substitution scenarios are country specific and simulated based on the expected fossil based biomaterials production in the specific member states. Therefore countries with a considerable share of biobased materials production in 2015 are expected to include Germany, Italy, the Netherlands, the United Kingdom, Sweden and France. However since the fossil based chemical industry in France is stronger than in the UK biobased materials production in France is expected to become more important in all scenario years for the reference and the transition scenario.

3.3.2 Additional demand for biogenic building blocks

Plant oil, glucose and lignin are identified as main biogenic building blocks for the discussed advanced biobased materials production scenarios based on (Salimon et al., 2012; Lauk et al., 2012; Bleier, 2012;Iffland et al., 2015; ifbb, 2016). Based on current conversion rates listed in Table **1** additional conversion capacities are calculated for the scenario years in the 28 MS. While biogenic building block demand for advanced biobased materials are estimated to be about 4.1 Mt in the EU in 2015, the demand for reaching production outlined in Figure **3** would have to increase to 8.9 Mt and 25.0 Mt in 2030 and up to 24.0 Mt and 117.8 Mt in 2050 in the reference and the transition scenario respectively. Oil, for example harvested from oil plants or recovered waste oil is expected to increase from 2.2 Mt to 7.5 Mt and 12.1 Mt in 2050 in the two scenarios respectively for the production of lubricants and surfactants. The utilisation of glucose could increase from 1.8 Mt to 16.6 Mt and 90.0 Mt in the same timeframe and the two scenarios respectively to meet the demand for the production of polymers and solvents. Therefore glucose from sugar plants like sugar beet, starch plants like potato, wheat and corn but also from cellulose and hemicellulose derived from woody biomass are expected to be used. However, based on the relatively early commercialisation phase of lignocellulose fermentation (Gerssen-Gondelach et al., 2014a) market diffusion of woody biomass based glucose to advanced biomaterials is calculated starting with 2035 in the reference and with 2025 in the transition scenario. While I assume that 100% of biobased polymers and solvents are produced based on sugar and starch plants in 2015, the share for woody biomass based capacities in 2050 could reach 67% and 96% respectively. Furthermore the utilisation of lignin as an alternative asphalt binder to bitumen is discussed for the transition scenario only. Lignin demand could reach up to 2.9 Mt in 2030 and 15.8 Mt in 2050 respectively.

Fossil based materials production in the EU28 is estimated to be dominated, in a descending order by Germany, Italy, France, the Netherlands, Belgium, Sweden and the United Kingdom with about 77% cumulated production. This share is expected to decrease slightly to about 74% based on the fossil fuel non-energy use scenario from Capros et al., (2013) in 2050 in contrary to growing shares in Austria, Cyprus, Poland, Hungary and Spain. Based on this development the MS specific scenarios reach up to 7.1 kt and 30.0 kt biogenic building block demand in the reference and transition scenario in Germany in 2050 respectively. The results for Germany are followed by additional biogenic building block demands of 14.8 kt, 14.6 kt, 12.6 kt and 12.4 kt in Italy, France, the Netherlands and Belgium in the transition scenario in 2050 respectively. Values for the reference and the transition scenario as well as the 28 MS are illustrated for 2050 for a comparison in Figure **4**.

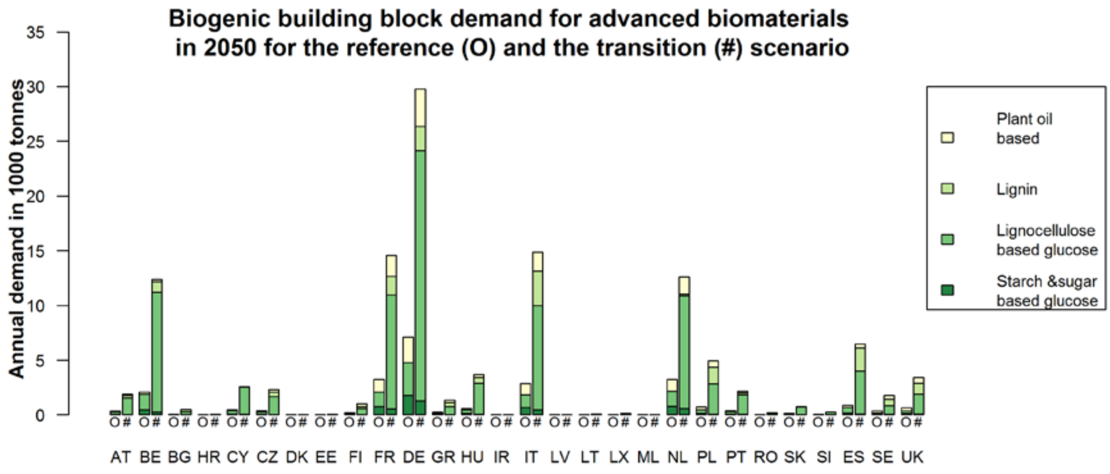

Figure 4: Biogenic building block demand for the production of advanced biomaterials in 2050 scenarios. Source; own illustration

Higher heating values for the discussed biogenic building blocks are calculated and used to convert the quantity based scenarios to energy content based scenarios. I estimate the biomass demand with about 120 PJ in 2015 in the EU28. For 2050 the demand for the discussed advanced biobased materials could reach up to 560 PJ and 2400 PJ in the reference and the transition scenario respectively. Matzenberger et al., (2015) compare moderate and ambitious scenarios of 12 bioenergy models. Average bioenergy demands of 13 EJ and 20 EJ in Western and Central Europe for the moderate and ambitious scenarios are highlighted. Both, biogenic building block- and bioenergy demand will be based on the supply of fresh, pre-treated or waste recovered biomass with the focus on carrying biogenic carbon for either material utilisation or combustion. Putting into contrast the reference and the transition scenarios 4% and 11% of biogenic carbon carriers could be demanded for non-energy utilisation in the strongly growing bioeconomy sector consisting of bioenergy and advanced biomaterials.

Calculating glycose demand based on theoretical instead of estimated current yields result in a reduction of 8% to 9% in the transition and in the reference scenario respectively. Using theoretical yields, the glucose demand reduces more in the reference scenario since biodegradable polymers are the dominant advanced biobased material produced in 2050 and this material type has the highest potential for yield gains. Plant oil demand on the contrary is higher when calculated with theoretical yields instead of current yields. This is because average biomass content in biobased surfactants of 60% is assumed for estimating the current conversion yield, while future conversion yields could be based on the conversion of plant oil into 100% biobased surfactants. The combination of yield and biomass content increases results on the one hand in an increase in biogenic carbon carrier demand from the discussed 560 PJ to 610 PJ in the reference scenario and on the other hand in a decrease from about 2.400 PJ to 2.300 PJ in the transition scenario.

3.4 Discussion

Using available statistical data, I identified the most important advanced biobased materials in terms of volumes as surfactants, solvents, polymers and lubricants. However, data availability on current biobased production capacities in the EU28 is poor, and thus large uncertainty in current substitutions share should be acknowledged. Capacity estimations for biobased surfactants, solvents and lubricants can only be found for the year 1998 in European Comission, (2002) and for the year 2008 in EC, (2010). Since then the 2008 values have been cited as current values (e.g. in Scarlat et al., (2015)). Furthermore in EC, (2010) the capture of the incorporated table indicates EU biobased materials “consumption” values while the column headers read “production” values. Due to the data availability issues production and consumption of biobased materials is put on the same level for this thesis and production at full capacities is assumed. In contrary to the discussed biobased materials, production capacities of biobased polymers are updated more frequently (e.g. ifbb, (2016) and Kaeb et al., (2016)) and the more current data could be used in the present thesis.

My results also rely on estimated trajectories for the final products I consider for substitution. The future fossil based production are derived from non-energy consumption of various fossil fuels and lubricants-, waxes- as well as bitumen production statistics from OECD and IEA, (2015). Daioglou et al., (2014) outline a discrepancy between global production estimations based on this top-down approach and more accurate bottom-up calculations using surveys and information from dedicated institutes. However for the European OSCE countries the results of both approaches mostly coincide, thus making the simpler approach sufficient for the purpose of this thesis. However Daioglou et al., (2014) also discuss ammonia as another product group with considerable growth rates and substitution potentials especially in other world regions. The estimation of European substitution potentials of ammonia produced in the Haber Bosch process with natural gas as main input (Daioglou et al., 2014) was out of scope for this thesis. The development of the non-energy sector is projected based on Capros et al., (2013) who outline a stagnation (5% growth between 2010 and 2050) of fossil based material production in the EU28 up to 2050 with slight shifts in the spatial distribution to countries like Austria, Cyprus, Poland, Hungary and Spain. This development would equal a continuation of the trend that can be observed in the 2000-2010 time frame of the data from OECD and IEA, (2015) and is assumed to be realistic for a Europe without substantial population growth.

There is also considerable uncertainty on the potential substitution rate achievable by 2030 or 2050, and its evolution over time. Substitution scenarios, expectations and targets for the discussed materials are rare: While the PPP on biobased materials aims for 30% substitution of all chemicals in 2030, a rather outdated survey of 2006 expects 10-50% for 2050 (CEPI, 2015; Patel et al., 2006). The most current reference on medium and long term expectations discusses a 85% substitution in 2050, but addresses only biobased polymers (Scarlat et al., 2015). To cover this uncertainty, I designed two different substitution scenarios: they differ by the final substitution share by 2050 (40% and 70% for respectively the reference transition scenarios). The scenarios also differ by final products considered for substitution – the transition scenario covering more ambitious but yet theoretical possibilities. While CEPI, (2015) and Patel et al., (2006) include polymers, lubricants, surfactants and solvents, I further include bitumen due to its high theoretical substitution potential and discuss a 70% substitution of all chemicals in 2050 in the transition scenario. A broader discussion is necessary to estimate the feasibility of the transition scenario as well the realism of a 40% substitution level for the reference scenario is too unambitious for a business as usual development. In the transition scenario, annual growth rates would have to be high, especially for biodegradable and more durable biopolymers, lubricants and solvents and first capacities for PEF and bitumen would have to be installed as soon as possible if considerable shares are expected to be substituted in the upcoming decades.

Finally, I assume that the substitution rate would evolve quadratically over time between their current values and their scenario-specific values by 2050. This would equal the first phase of the generalised S-shaped growth curve often used for simulating low carbon technologies capacities diffusion (Wilson et al., 2013). Due to high substitution targets and comparable low current capacities I assume this approach to be more realistic than a linear growth rates.

Related demand for biogenic building blocks would most likely increase the demand of and competition on fresh biomass and biomass waste streams that carry plant oil, lignin and glucose. Glucose is expected to hold the highest share due to existing conversion pathways to biobased polymers and solvents. In my scenarios I address the market diffusion of lignocellulose fermentation which is assumed to outcompete the utilisation of glucose from sugar and starch plants within the upcoming decades based on the recent market majority estimation of Gerssen-Gondelach et al., (2014a). Therefore all types of woody but also grassy biomass could become the basis of polymers and solvents production. While conversion rates are expected to increase due to technological development, the share of biomass content in biobased materials could also rise in the future. As an example biobased surfactants are discussed to be not fully based on biogenic building blocks today. In general the definition of biobased materials is not yet clear, the discussion and the following standardisation is expected to be based on the results from an ongoing prestandardisation project (nova-Institut, 2014) in the near future.

Biogenic building block demand is converted into biobased energy content demand and compared to a list of bioenergy scenarios analysed in Matzenberger et al., (2015). I avoid the discussion of the underlying demand from different biomass sources by introducing the concept of biogenic carbon carriers. Both, biogenic building block- and bioenergy demand will be based on the supply of fresh, pre-treated or waste recovered biomass with the focus on carrying biogenic carbon for either material utilisation or combustion. I outline in the reference and the transition scenario biogenic carbon carrier demand shares of 4% and 11% in the strongly growing bioeconomy sector consisting of bioenergy and advanced biomaterials. Estimating and including auxiliary energy demand of the conversion processes is out of scope for this thesis.

No data on the spatial distribution of biobased production capacities within the EU28 could be found so far. I assume that advanced biobased materials are currently produced in the MS that have ongoing legislative activities, public-private partnerships and dedicated funding activities for their national biochemical sectors listed in (OECD, 2013). The listed MS are at the same time also the most important fossil chemical production countries. I assume that the combination of existing assets like refineries and transport modes like close ports could be decisive for an early take off of this industry sectors. This assumption is supported by retrofitting activities of old refineries (e.g. Novamont`s Matrica refinery). I do not want to undermine the discussion of structural breaks in the spatial distribution, e.g. of main fossil based chemical importers becoming main biobased chemical exporters, however it is considered out of scope for this thesis. With a comparable share of biobased and fossil based chemical capacities main advanced biobased material producers are assumed to be Germany and France. The main importers for biogenic carbon carriers for material utilisation are expected to be the Netherlands, Italy and Belgium based on my scenarios and todays self-sufficiency rates for bioenergy (Capros et al., 2013). Even if the spatial distribution of production capacities is comparable to the todays fossil based industry, supply structures will have to look fundamentally different. This assumption can be underpinned by a (1) lower carbon density (2) higher water content and higher heterogeneity of the biobased in contrast to the fossil based feedstock. Therefore larger sourcing areas with the inclusion of a higher variety of stakeholders and more transport will be needed while sustainability has to be the ensured in all activities. Pretreatment and densification technologies like e.g. torrefaction, pyrolysis and pelletisation could become important technologies in order to optimise the delivery of biogenic carbon not only for energy but also for material utilisation.

3.5 Conclusion

The European discussion on advanced biobased materials including polymers, surfactants, lubricants and solvents started relatively early, already in the last century. The focus since then was clearly rather on the substitution of fossil energy with bioenergy than on the substitution of fossil materials with biomaterials. This choice could be possibly explained by the comparable simplicity of burning biogenic carbon instead of converting it to biobased materials but also by the several magnitude larger substitution potentials for bioenergy than biomaterials outlined in the present thesis. However if sustainable development, Paris goals and especially the development of a European bioeconomy are targeted, both bioenergy and advanced biobased materials should be considered as a significant contribution to reducing the stress on our planetary boundaries. The higher added values of biochemicals compared to bioenergy in general, novel functionalities like biodegradability for polymers and lower VOCs in solvents as well as carbon capturing options especially for lignin as a bitumen alternative should be seen as complimentary to the emission reduction gains in the bioenergy sector.

However if we want to start to discuss and trigger climate change mitigation effects of this bioeconomy subsector, certain limitations would have to be overcome: A clearer understanding and definition of advanced biobased materials and biomass content is needed as well as official EU wide substitution targets. Data availability has to be improved to a transparent monitoring of biobased production capacities and related biomass demand - at least on a MS level. Therefore the creation of trade codes (e.g. Combined nomenclature –CN-codes) and the extension of national and European statistics should be discussed. The relative late start of the last pillow of the European bioeconomy asks for stronger efforts for scaling up or even initiating market introduction of necessary technologies and industries compared to the bioenergy, traditional materials and the food and feed sector. Lessons learned with regard to necessary commercialisation steps and time frames should be translated, especially from the bioenergy sector. This includes for example the further development and utilisation of pre-treatment and densification technologies like torrefaction, pyrolysis and pelletisation to optimise the supply of biogenic carbon for energy and material application.

With the first detailed medium to long term scenarios for advanced biobased materials, the presented thesis evaluates and reduces the research gap with regard to a European bioeconomy. I quantify potential achievable substitution rates and required biobased capacity evolution over time on a MS level. The results are a better anticipation of a set of sustainable development opportunities and respective efforts. Linking advanced biobased material scenarios to subjacent biomass demand results in a first discussion on (1) which MS could become strong biogenic carbon carriers (i.e. biomass types) for materials importers as well as (2) potential magnitudes of this bioeconomy sector compared to bioenergy scenarios. In a next step, bioeconomy research should implement data on process energy for the conversion to biobased materials and simulate the share of underlying biogenic carbon carriers to estimate emission reductions. Together with a broader stakeholder involvement more concrete substitution pathways on a MS level have to be elaborated and potential impacts of implied biomass needs on international and regional biomass markets explored.

4 Optimisation of biomass-to-end-use chains through densification

This chapter is adopted from a paper which I submitted to the journal Biomass and Bioenergy together with Lukas Kranzl.

4.1 Introduction

Modern bioenergy plays a crucial role in securing the supply of renewable energy and thus in phasing out fossil fuels. In 2015, the energy mix of the EU28 was based on 10% renewables, more than half of which from the category biomass and renewable wastes (EUROSTAT, 2016). Biomass exhibits lower carbon densities, higher moisture contents and higher heterogeneities compared to the feedstock basis of the current fossil based economy. Pre-treatment of biogenic raw materials into homogenous solid, liquid and gaseos densified bioenergy carriers (dBECs) with high energy densities therefore holds the potential to improve overall supply costs and environmental performance of the energy system (Forsberg, 2000;Richard, 2010). While dBECs played a vanishing role just 15 years ago (Junginger et al., 2014), consumption of wood pellets – currently the most important dBEC in terms of energy content- increased up to 4% of the EU28's consumption of fuelwood, wood residues and by-products (AEBIOM, 2015).

The development of a future bioeconomy and the subsequent conversion of biomass resources into bioenergy (European Comission, 2014) but also other bio-based products such as chemicals (Schipfer et al., 2017) will rely on a series of tradable dBECs (Lamers, 2016), such as wood pellets in order to meet demand in countries with resource deficits. In this thesis I focus on pre-treatment and densification of cellulosic biomass by pelletisation, torrefaction and fast-pyrolysis due to their higher technological readiness (TRL 6-7 and TRL 9 in case of simple pelletisation). On the one hand the increased data availability relatively to other thermo-chemical, chemical and biological processes due to recent interdisciplinary research and development projects (KIT, 2014; Thrän et al., 2016) increases the relevance of respective techno-economic discussions. On the other hand beside the advances in technological development compared to e.g. hydrothermal upgrading (HTU) or steam explosion (Bhutto et al., 2017), I also see the starting commoditisation process of torrefied pellets and pyrolysis oil as an advantage supporting my choice. The importance of standardisation as well as of supply chain development and the development of market-related properties of the respective products is discussed for the example of wood pellets in Olsson et al., (2016b).

Modelling and assessing biomass-to-end-use chains - including sourcing of the feedstock, supply to densification plants, pre-treatment and densification to dBECs, distribution to end users and conversion to heat, electricity, transport fuels or chemicals - attracted the attention of a diverse research community as reviewed in Ba et al., (2016) and Gold and Seuring, (2011). Next to wood pellets, torrefied pellets and pyrolysis oil based on wood and straw have been modelled and discussed for optimising supply chains (Hamelinck et al., 2005;Uslu et al., 2008). However, only Uslu et al., (2008) put the different technologies in comparison and discussed possible market entry strategies. Especially in light of the developments since the discussed publication, an updated assessment is necessary to discuss if and how these technologies could play a role in the cost-efficient deployment of renewables.

In this thesis I simulate generic biomass-to-end-use chains to compare economic performances of the currently expected densification technologies. The aim is to highlight combinations of feedstocks, supply chains and end users and their current potentials to reduce costs by deploying respective technologies. I focus on end users situated within the EU and the current, early stage of technology commercialisation and dBEC commoditisation. Thus, I do not address theoretical learning curves nor include feedstock potentials, both important for later technology and dBEC-diffusion stages.

4.2 Methodology

4.2.1 Techno-economic assessment and simulation of biomass-to-end-use chains

For the assessment of bioenergy systems the entire biomass-to-end-use chain, from biomass sourcing to biomass conversion has to be considered, including possible pre-treatment steps and densification, its' raw biomass supply and dBECs distribution to the conversion site (see Figure **5**). Data and specifications on sourcing for two types of biomass, supply and densification in simple pelletisation, torrefaction and pelletisation as well as pyrolysis plants are mainly based on data compilation from several countries and technologies including practical tests from the BioBoost- and the Sector-project (KIT, 2014; Thrän et al., 2016). I calculate costs throughout the entire biomass-to-end-use chains. On the other hand, deriving and analysing prices, thus including profits for the different supply chain stakeholders was out of scope of this study.

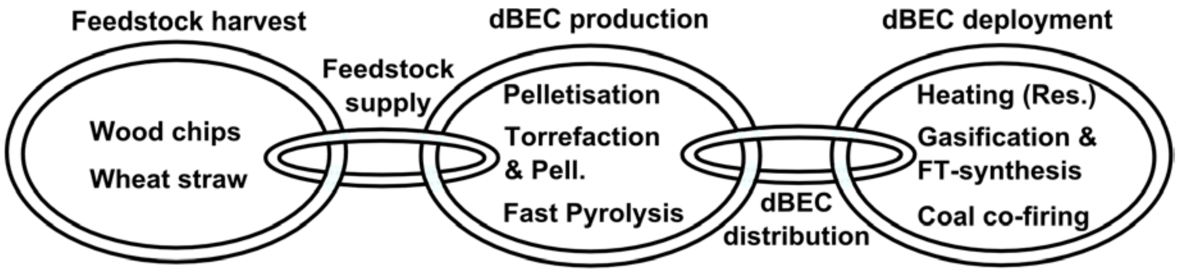

Figure 5: The biomass-to-end-use chain. Different feedstock supply- as well as dBEC distribution distances and modes have been calculated. Source; own illustration

I set up a generic-biomass-to-end-use chain tool. The underlying algorithm calculates dBECs deployment costs by step-wise cumulating the costs of supply chain components. First it optimizes densification plant sizes in a range of up to 500 kt*year^{-1} input and respective feedstock supply distances for various feedstocks, supply modes and feedstock yield, availability and accessibility combinations. Then distribution costs for various, possibly relevant distances and transport mode combinations and also storage are added to the resulting production costs. Finally dBECs deployment for residential heating, gasification and Fischer-Tropsch (FT-) synthesis and coal co-firing are calculated and compared. Ensuring comparability of the different production technologies for each feedstock, supply, dBEC distribution and deployment combination defines the very core of the tool. This results in 72 possibly relevant biomass-to-end-use chains for each technology to be analysed and discussed. To increase readability I use metric tonnes (1 t==1,000 kg) as a mass unit throughout this thesis. Input data was adjusted to the base year 2014 and all results are discussed in $€_{2014}$ per energy content of the respective dBECs. A more detailed representation of the input data and the simulation algorithm can be found in Appendix C (**Chapter 8.4**).

4.2.2 Feedstock supply

In order to simplify the comparative biomass-to-end-use chain assessment I focus on (1) wood chips (beech wood) as wood forest residues, used wood or by-products from forest industries and on (2) wheat straw collected on the roadside next to agricultural land. Similar to the supply chain assessments in Mireles et al., (2015) these feedstock types serve as reference feedstock types that can be considered to be comparable e.g. to miscanthus in the wheat straw case and other types of wood or woody crops in the wood chips case. Supply of feedstock takes place with either a tractor or a truck and an attached trailer. Parameters for the techno-economic evaluation of the feedstock supply step includes handling costs, variable costs per distance including labour and fuel, the maximal cargo capacity in tonnes and the design ratio of the transportation mode in [kg m^{-3}] indicating the minimum density of the transported good. Lower densities lead to derating through not fully using the maximal cargo capacity. All values for feedstock supply are based on or directly taken from Rotter and Rohrhofer, (2014) who documented costs of straw bales and wood chips supply including the discussed derating effects.

4.2.3 Production of densified bioenergy carriers

Straw bales and wood chips are assumed to be processed with various densification technologies. Therefore techno-economic data is adopted from Obernberger and Thek, (2010) for the production of pellets, further denoted also as white or traditional pellets, from BioBoost deliverables (Henrich et al., 2015; Mireles et al., 2015), from Nicoleit et al., (2016) for fast pyrolysis to biosyncrude and from SECTOR project deliverables (Arpiainen et al., 2014a; Koppejan et al., 2015) for torrefaction and pelletisation to torrefied pellets. The more investment cost intensive technologies torrefaction and pyrolysis thermo-chemically decompose the biomass in the absence of oxygen. Depending on the temperatures and residence times the decomposition is either focused on solid fractions in the case of torrefaction or on the liquid fraction in case of fast pyrolysis. Nicoleit et al., (2016) define biosyncrude as "all-in-one-slurry" including a mix of condensates and char from the pyrolysis process, "... reducing the complexity in terms of transport, as only one homogeneous energy carrier is dealt with" with no by-products. This is on the contrary to catalytic pyrolysis, where higher quality bio-oil is produced beside excess electricity, spent catalysts, ash and an unused aqueous phase (Mireles et al., 2015).

In order to calculate possibly relevant dBEC production costs (C_γ), densification plant sizes are optimised depending on feedstock, supply and densification technology parameter and costs. I assume that biomass feedstock is homogenously distributed around the theoretical densification plant and can be collected and supplied using an average supply radius (D_β). The average supply radius, necessary to calculate supply costs (C_β), is based on the discussed feedstock yields (Y_α) as well as the feedstock input size $\left(iSCL_\gamma\right)$ depending on the dBEC output size $\left(oSCL_\gamma\right)$ of the densification plant and its dry mass yield (Y_γ):

$$D_\beta = iSCL_\gamma{}^{0.5} * (Y_\alpha * 100 * \pi)^{-0.5}\ in\ [km]\ and\ with\ iSCL_\gamma = oSCL_\gamma * Y_\gamma{}^{-1} \quad (1)$$

An average scaling factor of $s = 0.7$ is assumed for pyrolysis and torrefaction to scale the annualised capital costs ($CAPEX_\gamma$) based on Svanberg et al., (2013) and Mireles et al., (2015). For pelletisation I assume an average scaling factor of 0.8 to value the higher technological readiness. Therefore, the previously discussed investment costs and capital recovery factors are used to calculate reference annualised capital costs ($refCAPEX_\gamma$) for reference densification plant output sizes ($refSCL_\gamma$).

$$CAPEX_\gamma = refCAPEX_\gamma * oSCL_\gamma{}^{s} * refSCL_\gamma{}^{-s} \quad (2)$$

Bioenergy carrier production costs (C_γ) are now computed based on the objective function including annualised specific capital- and supply costs as well as feedstock- (C_α) and plant specific variable costs ($varC_\gamma$). While increasing densification plant sizes decrease the specific biomass densification costs, supply distances and therefore specific biomass supply costs increase. (Svanberg et al., 2013) An optimisation is implemented to reflect these trades-off and calculate comparable bioenergy carrier production costs for similar biomass availability and supply settings.

$$C_\gamma = min\left\{C_\beta(oSCL_\gamma) + CAPEX_\gamma(oSCL_\gamma)\right\} + varC_\gamma + C_\alpha * Y_\gamma{}^{-1} \quad (3)$$

4.2.4 dBECs-distribution

For transportation of dBECs to end users - further denoted as distribution - I discuss several options including road-,rail- and in case of intercontinental trade ocean shipping as well as bioenergy carrier storage mainly based on Hoefnagels et al., (2013). While real prices payed for payloads depend on supply and demand of transport and handling options and are sensitive for example to economies of distances as well as economies of scale (Kim and Van Wee, 2011), I pursue a more simplified approach to enable a transparent comparison and illustration of possible relevant transport costs that would have to be paid for delivering the discussed densified bioenergy carriers.

Even though this thesis aims for a generalisation of comparative analysis of dBECs it is helpful to discuss exemplary distribution distances and constellations. I further use six representative distribution pathways (RDP1-6), short and long distances for road, rail and sea transport respectively. In Table **2** distances for each transport modi and the compilation of transport nodes are summarised and comparable pathway cases are outlined. While RDP1 could for example represent any regional supply chain RDP2-4 could be used to describe transport to pellet importing countries like Germany, Austria and the Netherlands from e.g. Ukraine and the Finnish Gulf via rail or ocean shipping. For short-sea shipping a delivery to ports like St.Petersburg or Vyborg from the hinterland has to be considered (Proskurina et al., 2015). In the case of long distance road transport, which can be assumed for imports to Italy from Austria for example (Schipfer and Kranzl, 2015), I assume an initial truck transport of 400 km to an intermediary storage from where small-scale end users could be delivered. Wood pellets imports from the west coast of the USA as well as from Canada to Italy and the ARA-ports (Amsterdam, Rotterdam & Antwerp) increased in the recent years (Junginger et al., 2014). RDP6 is based on distances to be considered to represent similar supply chains, but also supply chains from the west coast of Africa would result in comparable distances.

Table 2: Representative distribution pathways (RDPs) and comparable pathway cases.

Abbr.	**1st connection**	**2nd connection**	**3rd connection**	**Comparable pathway cases**
RDP1	50 km Road	no	no	Any regional supply
RDP2	1,300 km Rail	50 km Road	no	Ukraine to Germany or Austria,
RDP3	200 km Rail	2,000 km Sea	50 km Road	Russia to ARA
RDP4	2,000 km Rail	50 km Road	no	Russia to Germany or Austria
RDP5	400 km Road	50 km Road	no	From Austria to Italy
RDP6	200 km Rail	15,000 km Sea	50 km Road	US or CA West Coast, Africa East coast to ARA or Italy

Exemplary storage options for densified bioenergy carrier with 20 days and 100 days storages are considered. Intermediary storage could be situated at the densification plant site, in bioenergy carrier depots (Lamers et al., 2015) at transport hubs or close or directly at the end users site.

4.2.5 dBECs deployment

Bioenergy carriers are considered to substitute fossil energy carriers for (1) small scale heat production for residential consumers (2) large scale power production and (3) Fischer Tropsch (FT-) diesel production for use in the transport sector. Energy conversion processes differentiate in specific conversion costs based on capital and variable costs of the conversion technologies as well as conversion efficiencies. Input data is mainly derived from the ENTRANZE database (ENTRANZE, 2014), from Arpiainen et al., (2015) for co-firing and from Meerman et al., (2012) for gasification and FT-synthesis.

Reference prices for residential heating are calculated based on data from the ENTRANZE-database (ENTRANZE, 2014) and a representative European cross-section (Spain, Germany and Rumania). For co-firing an average 2014 electricity prices without taxes and levies for the largest consumer group from Eurostat, (2016) are used as a reference. The gasification and FT-diesel production path is compared to average EU28 diesel prices without taxes and levies from EC, (2016d).

4.3 Results

4.3.1 Bioenergy carrier production costs and respective optimal densification plant size

I discuss all costs throughout the entire biomass-to-end-use-chains in $€_{2014}$ values. In Figure **6** bioenergy carrier production costs for traditional pellets, torrefied pellets and pyrolysis syncrude oil based on straw and on wood chips as well as their respective cost shares are illustrated. Costs are specified on the net calorific value per energy carrier output. To provide comparability the same input parameters for feedstock harvesting and supply are used for the three technologies, leading to various optimal bioenergy carrier production plant sizes.

I find an optimal annual production plant size of about 90 kt wood pellets while upscaling of a pellets plant based on wheat straw to about 340 kt still leads to higher marginal cost reductions for the installation than supply costs increases. This is on the one hand due to a about five times higher combination of feedstock yield, accessibility and infrastructure surrounding the plant in case of wheat straw than assumed for wood chips. On the other hand a higher moisture content for wood chips leads to higher transportation costs and lower optimal plant sizes.

Comparing the different densification technologies reveals that, with higher investment costs scaling effects become more important over supply cost increments. For the delivery of raw materials I limited the optimisation algorithm to an annual 500 kt straw input; This amount equals to a transport activity of about three trucks per hour approaching the plant, which might raise issues with regard to public perception which is “chiefly related to the impacts of truck movements” (Devine-Wright, 2007).While torrefied straw pellets and straw pyrolysis oil production upscaling are affected by this limit, production of torrefied wood chips pellets and wood chips pyrolysis oil results in optimal plant sizes of about 315 kt and 460 kt input respectively.

For torrefied pellets based on straw and on wood, StT and WtT respectively, production costs of 7.0 and 9.7 $€*GJ_{dBEC}^{-1}$ are derived. For pyrolysis oil (StO and WtO) costs of 13.0 and 14.8$€*GJ_{dBEC}^{-1}$ are calculated. Alakangas et al., (2014) describe production costs of 8.8-11.4 $€*GJ_{dBEC}^{-1}$ for torrefied pellets and 13.9-19.4 $€*GJ_{dBEC}^{-1}$ for pyrolysis oil respectively.

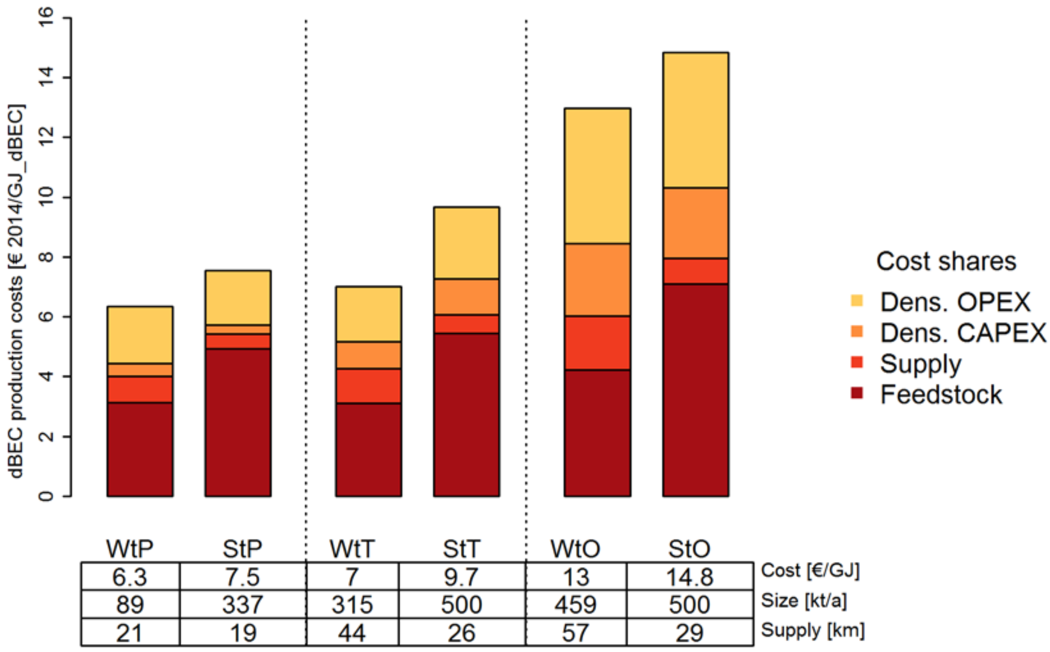

Figure 6: Bioenergy carrier production costs for three densification technologies and two biomass feedstock types [$€_{2014}*GJ_{dBEC}^{-1}$]. Forestry residues are abbreviated with "W" and straw with "S", traditional pelletisation with "P", torrefaction and pelletisation with "T" and fast pyrolysis with "O" resulting e.g. in "StO" as straw to pyrolysis oil.

Based on the net calorific value of the produced dBEC, cost shares for feedstock, supply and densification can be compared. With increasing cost shares for capital and operational expenditures from about 30% for pelletisation to 70% for pyrolysis, shares for feedstock decrease. However, longer supply distances result in increasing supply costs (up to 1.8 $€*GJ_{dBEC}^{-1}$ for WtO) and feedstock costs per energy content dBEC increase to, due to conversion losses in contrast to a 100% conversion efficiency assumed in the case of simple pelletisation. Operational expenditures include the drying process based on natural gas furnaces for all densification technologies. This results in feedstock costs for WtT and WtP at 3.1 $€*GJ_{dBEC}^{-1}$ beneath the original feedstock costs (4.1 $€*GJ_{dBEC}^{-1}$) when specified on the energy content of the resulting densified bioenergy carrier which is higher than the energy content of the original feedstock.

Supply costs vary from 0.5 $€*GJ_{dBEC}^{-1}$ for wheat straw pelletisation to 1.8 $€*GJ_{dBEC}^{-1}$ for pyrolysis oil from wood chips production. Supplying the feedstock with tractors instead of trucks results in 9-12% higher costs for wood chips and 14-59% higher costs for wheat straw supply for the various densification facilities respectively. Increased transportation costs for tractors impact negatively on the plant size optimisation, resulting in shorter supply distances at higher or similar overall supply costs than when supplied via trucks.

Table 3: Calculated supply costs of feedstock to various densification plants [$€_{2014}*GJ_{dBEC}^{-1}$].The values in brackets indicate the supply distances resulting from the pellet plant size optimisation.

Feedstock	Pell. [€/GJ]	Torr. & Pell. [€/GJ]	Pyr. [€/GJ]
Wheat Straw via Truck	0.5 (19km)	0.6 (26km)	0.9 (29km)
Wood Chips via Truck	0.9 (21km)	1.2 (44km)	1.8 (57km)
Wheat Straw via Tractor	0.6 (11km)	1 (26km)	1.4 (29km)
Wood Chips via Tractor	1 (14km)	1.3 (30km)	2 (37km)

Based on dBEC production costs (see Table **4**), less efficient supply transport modes result in strongest effects for the torrefaction of wood pellets (WtT) with about +5.6%, and in general higher for the supply of wood chips for pyrolysis oil (WtO with +5.1%) and simple pelletisation (WtP with +3.0%) than for torrefied straw pellets (StT with +3.8%), pyrolysis oil from straw (StO with +3.7%) and straw pellets (StP with +2.5%). Due to the exponential scaling function and an upper limit of 500kt BEC-output, production costs are more sensitive to lower biomass yields than increased yields. With 80% lower annual yields of 0.62 $t*ha^{-1}$ (instead of 3.10 $t*ha^{-1}$) for straw and 0.13 $t*ha^{-1}$ (instead of 0.65 $t*ha^{-1}$) for residual wood chips, bioenergy carrier production costs increase with about 2.3% to 3.6% and 3.9% to 7.4% while on the contrary maximum cost reductions of 2.0% can be reported for pyrolysis from wood chips with 80% higher yields. Generally, production costs are lower for bioenergy carrier based on chips than based on straw by about 16% for simple pelletisation, 27% for torrefaction and pelletisation and 14% for pyrolysis, mainly due to higher feedstock costs for wheat straw. Also higher investment costs for StT and StP than for WtT and WtP are included in the calculation while no differences for the fast pyrolysis cases are assumed. Variing investment costs furthermore by +-10% leads to a maximum increase of 1.9% pyrolysis oil production costs based on wood chips and effects are comparable low for simple pelletisation with 0.7% and 0.4% for wood and straw pelletisation respectively. Increased investment costs result in increased plant sizes where possible.

Table 4: Calculated sensitivity analysis for different delivery modes (Truck and Tractor), deviating feedstock yields (+-80%) and deviating investment costs (+-10%). Bioenergy carrier production costs in [$€_{2014}*GJ_{dBEC}^{-1}$] and optimized densification plant sizes in kt output annual. The first column (Truck delivery) represents the base case. Asterix indicate exhausted upscaling limit in the densification plant size optimization.

Tech.	Base [€/GJ]	Tractor	Yield-80%	Yield+80%	Inv.Cost+10%	Inv.Cost-10%
StP	7.5 (337kt/a)	+2.5% (-64.0%)	+2.3% (-63.4%)	-0.7% (+44.4%)	+0.4% (+12.7%)	-0.4% (-12.3%)
StT	9.7 (500kt/a)*	+3.8% (+0.0%)*	+3.6% (+0.0%)*	-0.7% (0.0%)*	+1.3% (0.0%)*	-1.3% (+0.0%)*
StO	14.8 (500kt/a)*	+3.7% (+0.0%)*	+3.5% (+0.0%)*	-0.7% (0.0%)*	+1.6% (0.0%)*	-1.6% (0.0%)*
WtP	6.3 (89kt/a)	+3.1% (-52.9%)	+3.9% (-63.4%)	-1.1% (+44.4%)	+0.7% (+12.7%)	-0.7% (-12.3%)
WtT	7 (315kt/a)	+5.6% (-52.9%)	+7.4% (-63.4%)	-2.2% (+44.4%)	+1.3% (+12.7%)	-1.3% (-12.3%)
WtO	13 (459kt/a)	+5.1% (-57.7%)	+6.8% (-68.3%)	-2.0% (+9.0%)*	+1.8% (+9.0%)*	-1.9% (-14.0%)

4.3.2 Representative bioenergy carrier distribution paths and respective costs

Distribution of bioenergy carriers from densification plants to end users has to be considered based on different transport modis as well as transport distances and distribution chain configurations. Figure **7** illustrates total delivery costs, including bioenergy carrier-, transport- and storage costs for a set of representative distribution pathways reaching from regional supply (SDP1) to long distance, intercontinental pathways like production on the Westcoast of Canada or the United States to an end user in close proximity to the ARA ports or an Italian port (SDP6).

All discussed densified bioenergy carriers exceed the design ratios of the different transport modi, thus fully utilising the cargo weight capacities. Cost reduction for transportation can only be achieved through increased energy contents. Based on the discussed energy contents, transportation of torrefied straw pellets and wood pellets are assumed to be 13% and 22% cheaper than their traditional pellets counterparts due to differences in net calorific value of the bioenergy carrier. Transport cost reductions for pyrolysis oil compared to traditional pellets are estimated to be in the same magnitude as for StT (13%). However, no differences in handling and transport of liquid and solid dBEC could be included in the calculation of this thesis since no comparable data set could be found in literature.

Costs for transport ranges from 8.0 €*t^{-1} for RDP1 to 53.4 €*t^{-1} for RDP6 for all densified bioenergy carriers. My simplified assumptions for transportation result in marginal increases of 16.4 €*t^{-1} for 100km for truck and 14.8 and 4.5 €*t^{-1} for 1,000km for rail and sea transport excluding transhipment including empty backhaul. These assumptions result in more expensive long distance truck transport (RDP5), for example representing distribution from Austrian and German producers to Italian consumers, than for medium rail transport and short-sea shipping (RDP2-4).

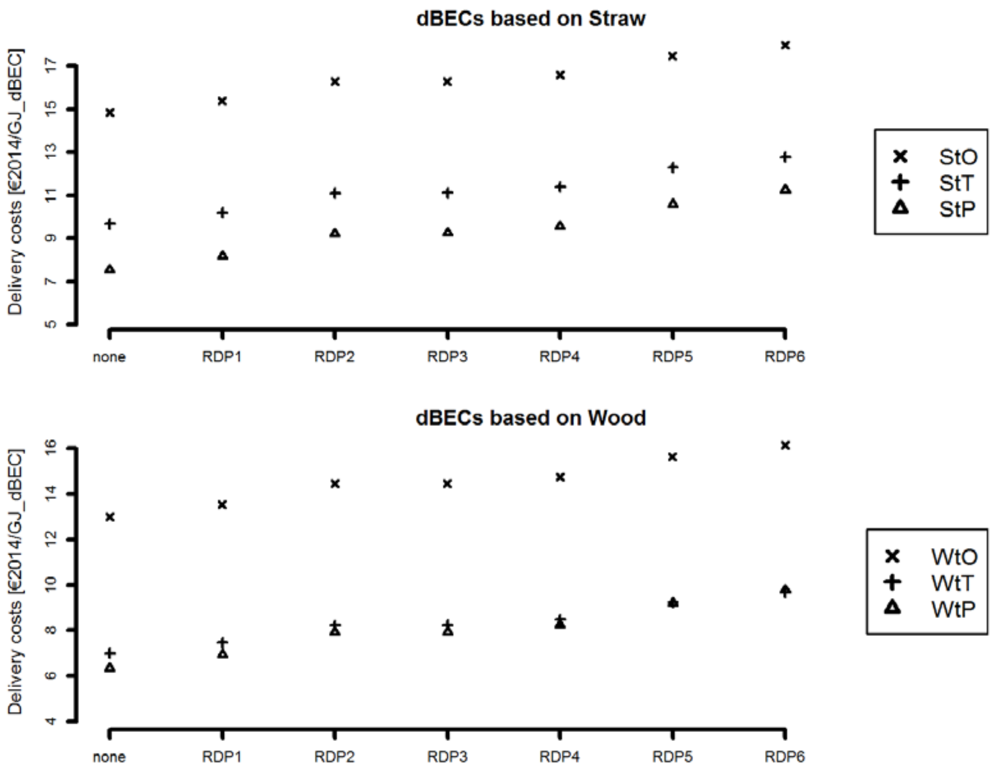

*Figure 7: Calculated bioenergy carrier costs [$€_{2014}$*GJ_{dBEC}^{-1}] without distribution costs ("none") and including distribution costs (further consolidated and denoted as delivery costs) for the six representative distribution pathways (RDPs) in increasing order depending on their transport & storage costs.*

For calculating storage costs however, energy density of the bioenergy carriers become decisive over energy content when storage provider is payed per storage volume. Energy densities of straw and wood pellets are about 3.2 and 2.9 higher than their original feedstocks thus impacting on the storage costs with the same factor. Torrefaction leads to further energy density increases of a factor of 1.4 and 1.4 while pyrolysis oil is 1.7 and 1.4 times denser than torrefied straw and wood pellets respectively. This results in storage costs of about 31 €cent*GJ^{-1} for straw, 10 €cent*GJ^{-1} for StP, 7 €cent*GJ^{-1} for StT while pyrolysis oil can be stored for 9 €cent*GJ^{-1} for 20 days considering also higher costs for liquid than solid storage.

For the sensitivity analysis in Table **5** storing up to 100 days is discussed. Lower bulk densities lead to largest cost increases for wood and straw pellets with +5.0% and +4.7% for the shortest RDP (RDP1) and +3.6% and +3.4% for the long distance RDP6. When comparing the technologies the different cost-increases result in theoretical break-even distances for the considered distribution pathways for torrefied straw pellets in the RDP4 case and for torrefied wood pellets already in the RDP2 case with their conventional pellets counterpart. Varying underlying distance dependent costs for the RDP1 impacts on dBEC delivery costs similarly to if underlying handling costs are varied. At ±50% handling or distance costs dBEC delivery costs increase/decrease by about ±1-2%. With increased distribution chain distance and handling steps the variations can impact up to ±12.6% delivery costs when production costs are low and distribution makes up a considerable share of the delivery costs.

*Table 5: Calculated sensitivity analysis for delivery cost. The two values give the extreme cases (RDP1 | RDP6), for the original values in [$€_{2014}$*GJ_{dBEC}^{-1}] and additional 80 storage days, variations in distance cost (Dist.Cost) and in handling cost (Hand.Cost) the deviations from the original values.*

Tech.	Base [€/GJ]	Store+80d	Dis.Cost ±50%	Hand.Cost ±50%
StP	8.2 | 11.2	+4.8%|+3.5%	±1.6%|±11.9%	±1.6%|±4.1%
StT	10.2 | 12.8	+2.8%|+2.2%	±1.1%|±8.8%	±1.1%|±3.1%
StO	15.4 | 18	+2.4%|+2.1%	±0.8%|±6.2%	±0.7%|±2.2%
WtP	6.9 | 9.8	+5.1%|+3.6%	±1.8%|±12.6%	±1.8%|±4.5%
WtT	7.5 | 9.7	+3.3%|+2.5%	±1.3%|±9.9%	±1.3%|±3.6%
WtO	13.5 | 16.1	+2.9%|+2.4%	±0.9%|±7%	±0.8%|±2.5%

4.3.3 Bioenergy deployment costs

In Figure **8** bioenergy deployment costs are illustrated for three end user types as well as for dBEC-delivery based on the values from the previous chapter to facilitate comparability. Conversion efficiencies inflate the delivered fuel costs while utility costs including capital and operational expenditures increase the levelised costs of useful energy derived depending on the dBEC type used as input.I compare costs between the six dBEC types as well between the bioenergy conversion routes and reference price ranges for EU consumers in 2014.

Simulated energy deployment costs are lowest for gasification and FT-Synthesis followed by residential heating and electricity production in coal co-fired power plants. For large scale combustion (FT and co-firing) torrefied wood pellets are simulated to be about 1.4 €*GJ^{-1} to 2.8 €*GJ^{-1} and 1.0 €*GJ^{-1} to 2.6 €*GJ^{-1} cheaper than their conventional counterparts for the two extreme RDP cases respectively. For residential heating I derive comparable deployment costs for WtP and WtT pathways, however with small variations for various distribution pathways: Small-scale heating based on WtT is about 0.7 €*GJ^{-1} more expensive when based on RDP1 while a 0.1 €*GJ^{-1} cost advantage can be highlighted for RDP6. Similar results are calculated for StP and StT for gasification and FT-synthesis with +0.8 €*GJ^{-1} and -0.4 €*GJ^{-1} respectively. Differences between deployment costs based on torrefied pellets and pyrolysis oil are smallest for straw biomass in the residential heating case. For the RDP1 and small scale combustion a minimum of 0.9 €*GJ^{-1} difference between StO and StT can be outlined. Lower utility costs for small scale oil boilers outweigh lower efficiencies than for small scale pellet boilers only when the differences in bioenergy carrier supply are small enough, which cannot be observed in the discussed cases.

Bioenergy deployment costs are calculated to be more expensive when based on wheat straw than residual wood chips. Due to the relatively low conversation rates, electricity production is affected strongest with 3.1 €*GJ^{-1} and up to 6.8 €*GJ^{-1} cost advantages for the RDP1 and white wood pellets and torrefied wood pellets compared to their straw based counterparts. For the RDP6 pathway the differences increase up to 3.7 €*GJ^{-1} and 7.7 €*GJ^{-1} respectively. WtO is about 4.3 €*GJ^{-1} cheaper than StO in the RDP1.

In comparison to estimated reference energy deployment costs I find, that residential heat production based on wood pellets and torrefied wood pellets can result in average EU28 heating costs for lower RDPs. However, the relatively high range of about 30 to 40 €*GJ^{-1} for estimated EU28 residential heating costs in 2014 cover mostly all calculated cases. This supports the finding of FAO, (2015) and Patel et al., (2016). FT-synthesis based on WtT can be discussed as the most feasible option with respect to large scale bioenergy deployment in my biomass-to-end-use chain selection. In the co-firing case, also combustion of WtT is simulated to be most cost-effective, however within another cost-range than estimated EU28 electricity production costs in 2014. The differences between WtT and WtP co-firing are between 1.5 and 3.0 €*GJ^{-1} for RDP1 and RDP6 respectively. Thrän et al., (2016) describe a difference of about 0.9 €*GJ^{-1}. While the FT-synthesis pathway costs already include a remedy for produced electricity, a thorough assessment of possible differences in CO_2 credits remedies was out of scope for this work.

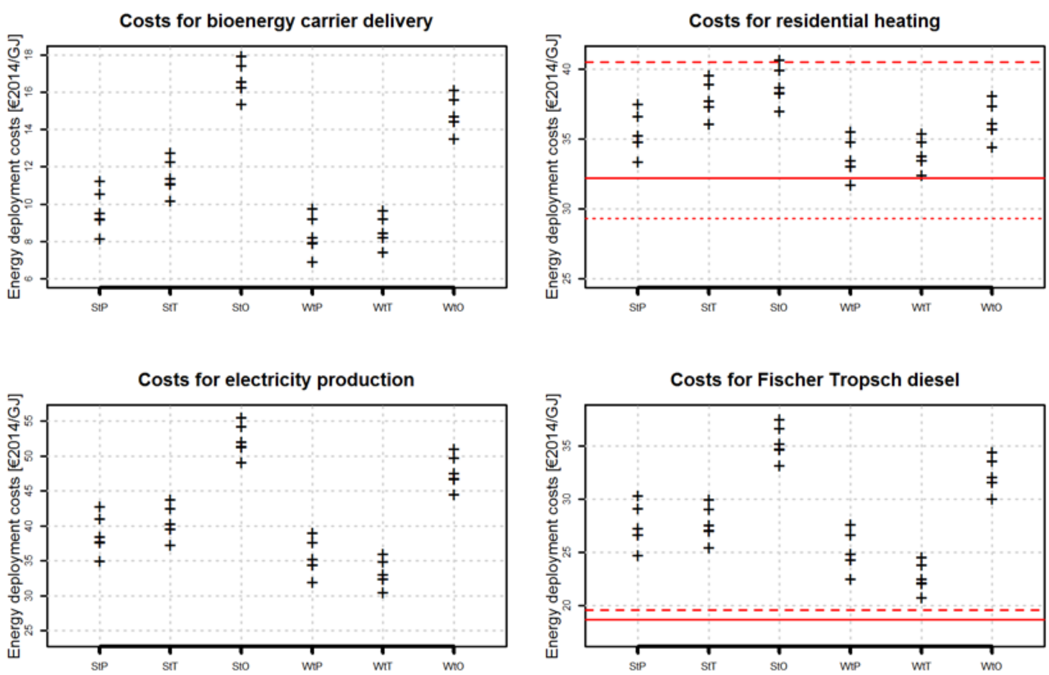

Figure 8: Calculated bioenergy deployment costs for different end users based on the six representative distribution pathways. Red horizontal lines indicate average energy deployment costs based on fossil resources (EU28 in 2014). Solid line indicates median, dotted lines lower and dashed line upper values.

A sensitivity analysis of selected bioenergy deployment pathways as well as selected dBECs comparisons is illustrated by row 1-3 in Table **6**. The discussed base values are illustrated in the first column through a value pair representing the RDP1 and RDP6 values respectively. The most cost-effective bioenergy deployment option, torrefied wood pellets to FT-diesel via gasification exhibits the strongest impacts from 50% reduced biomass costs with up to 5.0% total cost reductions. Reducing feedstock yields by 80% increases bioenergy deployment costs by up to about 2.4%. Storing the torrefied wood pellets 100 days instead of 20 days results in 2.8% increased costs. Increasing distance dependent costs by 50% affects the discussed option by increased total deployment costs up to 8.0% when considering the RDP6 case. For less cost-effective energy deployment cases discussed sensitivities in the production and distribution chain are depressed due lower total deployment cost shares.

I furthermore compare bioenergy deployment based on different bioenergy carriers (in row 4-6 inTable **6**) by discussing deployment cost differences and deviations of these differences due to changing parameters in the biomass-to-end-use chain. Positive differences, like for example for the RDP1 and RDP6 option of WtT against WtP but also for the RDP6 option of StT against their conventional counterpart represent increased cost-efficiency for the more investment intensive densification technologies. Torrefied pelletisation but also pyrolysis oil production benefits from increasing wood and straw yields when compared to less investment-intensive pre-treatment technologies. This is illustrated by slightly increased positive and negative cost differences, however only up to about 0.2 $€*GJ^{-1}$ (for WtT vs. WtP in the FP case) when compared to the base case. Increased distance dependent costs and higher storage time effect the torrefied cases compared to the conventional pelletisation cases positively, while the comparison between straw based pyrolysis oil and torrefied pellets for residential heating is more favorable for the less investment-intensive densification technology. This is mainly due to higher storage costs assumed for liquid versus solid bioenergy carriers.

Table 6: Calculated sensitivity analysis for Bioenergy deployment costs (row 1-3) [$€*GJ^{-1}$] and deployment cost differences (row 4-6) [$€*GJ^{-1}$] for FT-synthesis (FT), electricity production (El.) and residential heating (RH). The value pairs represent the RDP1 and RDP6 values respectively.

Case	**Base [€/GJ]**	**BM.cost-20%**	**Yield+80%**	**Yield-80%**	**dist.cost+50%**	**Store+80d**
WtT FT	22.5|27.7	-5.0%|-4.1%	-0.6%|-0.5%	+2.0%|+1.6%	+1.0%|+8.1%	+2.9%|+2.3%
WtT El.	32|39.1	-4.9%|-4.0%	-0.6%|-0.5%	+1.9%|+1.6%	+1.0%|+7.9%	+2.8%|+2.3%
WtT RH	31.7|35.5	-2.7%|-2.4%	-0.3%|-0.3%	+1.0%|+0.9%	+0.5%|+4.6%	+1.5%|+1.3%
WtT vs WtP FT	1.7|3.1	1.7|3	1.9|3.2	1.3|2.6	1.8|3.6	1.9|3.3
StT vs StP FT	-0.7|0.4	-0.7|0.5	-0.7|0.4	-1|0.1	-0.7|0.9	-0.5|0.6
StO vs StT RH	-0.9|-1.1	-0.4|-0.5	-0.9|-1	-1.2|-1.3	-0.9|-1.1	-1.1|-1.2

4.4 Discussion

A comparative biomass-to-end-use chain assessment tool was applied to simulate and compare bioenergy deployment costs for a set of possible relevant supply chains with dBECs based on pelletisation, torrefaction and pelletisation and fast pyrolysis. The input-data of the tool, adjusted to the base year 2014 is based on the most recent research and development projects and presented techno-economic results can thus be seen as currently relevant for the discussion of possibly market entry strategies for the densification technologies and their dBECs. In order to compare the economic performance of the discussed densification technologies under possible relevant framework conditions, the same chain set-ups are calculated for the three technologies but densification plant size costs are optimised against the respective feedstock supply costs. This results in generally lower overall dBECs deployment costs than discussed and compared in literature (Alakangas et al., 2014; Thrän et al., 2016; Mireles et al., 2015).

Supply chains based on wood exhibit in general cost advantages compared to straw based chains and energy from solid dBECs can be deployed economically more efficiently than liquid ones. Cost differences between torrefied and conventional wood pellets decrease with increasing transport distance and can be partly compensated and reverted for long inter-continental ocean- but also for truck distances between European MS. Due to capacity effect costs in large-scale conversion facilities like coal co-firing and gasification, cost differences can result in reductions of up to about 3 €*GJ^{-1} for torrefied pellets compared to conventional pellets. No capacity effect costs can be expected for small-scale users, still cost advantages for the more investment-intensive technology can be highlighted for longer distance dBEC supply. I find in general that pyrolysis oil, torrefied and traditional pellets based on wood and straw could reduce the costs of the current, average European residential heating systems. Bioenergy already plays an important role in the residential European heating and cooling market with 17% of primary energy input in 2012 for the EU28 (Fleiter et al., 2016). Depending on preferences and existing assets in the different MS, replacement of fossil-based heating devices with pellet-, torrefied pellet- or pyrolysis oil boilers and stoves or the replacement or blending of or with heating oil could be considered.

The production of densified BECs and the subjacent supply of biogenic raw material have to be considered jointly; with increasing investment costs of pre-treatment technologies also optimal densification plant sizes increase, depending on the marginal feedstock supply costs. With higher straw yields - compared to residual forestry wood chips yields, but also due to lower moisture content of straw bales, densification plants based on agricultural residues should be dimensioned up to three times larger than when based on forestry residues. This still results in lower supply distances but higher production costs for straw based dBECs. Varying yields reveal a more stringent sensitivity for decreasing than for increasing yields due to indirect exponential scaling function and possible relevant scaling limitations, i.e. maximum number of truck deliveries to the plants per hour. Energy content differences of dBECs may be the single decisive factor for transport cost reductions since already wood pellets are mostly not affected by the transport mode design factors. However, storage of bioenergy carriers at the production site, during the distribution chain or at the end users site should be considered too, for which energy density differences of the carrier become crucial. I find that, with increased storage periods up to 100 days already short-distance delivery of torrefied wood pellets become cost-effective over traditional wood pellets.

The presented calculations are limited in several ways: Even though the considered technologies have been tested and verified in the recent years, uncertainties about investment costs, scaling effects but also technical performance are relatively high. However, especially for torrefaction and pelletisation I used the information from several technology providers acquired during the FP7 SECTOR project, thus reducing uncertainties compared to previous publications. For the downstream of densified bioenergy carrier comparable data is more limited. Existing data on handling, transport, storage and also conversion costs of wood pellets is already rare, comparative assessments for other dBECs exhibit clear research gaps. Especially with regards to durability, material safety, and biological activity under various framework conditions approximate functions would be necessary to enable a more accurate comparison of distribution and conversion costs. Further logistical improvements like no need for roofing of transport and storage for hydrophobic torrefied pellets as well as pipeline pumping of pyrolysis oil could increase competitiveness of the respective supply chains significantly.

For the extension of biogenic carbon demand of the developing European bioeconomy I can show that, broadening the feedstock and intermediates portfolio is already an economically viable option for small-scale use like residential heating. Especially with regards to the iLUC Directive, FT-Diesel produced in (very) large-scale gasification facilities will also rely on a set of fungible cellulosic based dBECs eventually sourced abroad. With the expansion of intermittent electricity production from solar and wind, co-firing of biomass but also bioenergy storage will gain in importance until electricity storage becomes feasible to bridge the production gaps. For the deployment in large-scale facilities however, a level playing field with fossil energy carriers have to be established - for example through taxing fossil based carbon. This is when larger-scale densification technologies like torrefaction and pyrolysis of forestry and agricultural residues will reduce supply costs for European biogenic carbon deployment significantly.

Further comparative assessments based on empirical data with regards to downstream of dBECs are necessary to improve the findings of this research. Especially comparative data on changes in dBEC quality throughout the supply chains under various weather conditions as well as for different handling, transport and storage options are needed. Future research should also include parallel calculation of emission and socio-economic parameters. The comparative biomass-to-end-use chain calculation tool could further be deployed as an easy applicable open access tool for researchers and market actors to support decision making, further research and to cloud-map interests. Knowledge gaps about social acceptance and participation should also be addressed and the preconditions and development for market-related properties including competitiveness and liquidity analysed.

4.5 Conclusion

I find that increasing energy content and density of dBECs can result in smaller cost ranges for different supply chain set ups, especially for long-distance distribution – e.g., including ocean transport but also longer distance truck transport and also for supply chains based on increased storage periods. Cost reductions can be expected for the deployment of torrefied wood pellets compared to wood pellets for most of the discussed biomass-to-end-use chains. For torrefied straw pellets similar results can only be highlighted for longer-distance distribution for the utilisation in FT-synthesis. The deployment of pyrolysis oil is expected to be more expensive in all cases. Still it could illustrate an economic feasible option for residential heating in selected markets where oil boilers dominate.

However, to reach commoditisation of the bioenergy carriers as well as full commercialisation of the respective technologies, upscaling would have to start now eventually by establishing a residential heating market based on torrefied pellets and pyrolysis oil where framework conditions are most favourable. The Italian wood pellet market for example is based on imports via long-distance shipping but also longer distance truck transport from Germany and Austria, thus torrefied pellets could be delivered with lower costs compared to traditional ones. Furthermore, in this specific market storage is crucial, since prices are low in spring and summer and consumption high in winter. Also, any cost advantages get furthermore inflated by relatively high taxes on bioenergy carrier for residential consumers. Solutions would have to be found for regulatory issues and issues regarding the end-user handling when it comes to using more “coal-like” pellets. Torrefied wood and straw pellets could further broaden bioenergy carrier portfolio and reduce costs for European FT-diesel production as well as co-firing for electricity production mainly due to reduced capacity effect and comparable bioenergy carrier delivery costs in comparison to traditional pellets. Therefore, handling, transport and especially also storage - for electricity production within an energy system with high intermittence shares – has to be empirically and analytically explored and optimised. The commoditisation process of wood pellets in the last decades could further deliver insights in good- and market-related properties of novel densified bioenergy carriers.

5 Modelling the European wood pellets for residential heating market

This chapter is adopted from a paper I submitted to the journal Energy Economics together with Lukas Kranzl, Olle Olsson and Patrick Lamers.

5.1 Introduction

The utilisation of solid and liquid bioenergy carriers has increased significantly in the past decade. As demand has grown, so has international trade in especially ethanol, biodiesel and wood pellets. International bioenergy trade is partly a necessity for countries with strong demand but small resources to make up for absolute shortages of domestic resources, but imports are also used for arbitrage reasons, i.e. to acquire less expensive fuel from international markets than would be available domestically. Therefore, bioenergy trade holds the potential opportunity to secure affordable supply of renewable energy while at the same time supporting economic development of exporting countries.

Wood pellet markets tend generally to be divided into two main segments: the industrial (large-scale) market and a residential market segment serving smaller scale boilers for space heating and hot water preparation, further denoted as "small-scale heating market" (with boilers <100 kW). In industrial markets, wood pellets are used for the production of electricity and/or heat in centralised facilities whereas residential market wood pellets are used for space heating and hot water preparation in residential buildings, but also in e.g. hotels using boilers or stoves. Although there are interactions between the two market segments, the two are generally analysed separately as there are important differences in terms of both physical characteristics and market structures. (Olsson et al., 2016a)

The expanding international trade in wood pellets has been analysed in several studies, e.g., (Goh et al., 2013; Olsson et al., 2011; Sikkema et al., 2011) and inventories based on projects that included data gathering exercise e.g. (ETA et al., 2007; Cocchi et al., 2011) The focus has almost exclusively been on trade of industrial pellets, in particular the transatlantic trade flows of pellets from the US and Canada to North Western Europe. However, there is international trade of pellets for the small-scale heating market as well, especially between countries in continental Europe. This latter market has been studied to a significantly lesser extent, but is still highly important as European demand for residential-quality pellets made up more than 30% of total global pellet consumption in 2014 (AEBIOM, 2015). The most important countries in this market segment with regard to consumption in 2014 were Italy (2.9 Mt), Germany (2.0 Mt), Sweden (1.4 Mt), France (0.9 Mt) and Austria (0.8

Mt)[2]. Within these countries, wood pellets are used mainly for residential and commercial heating rather than for electricity generation. Italy, Austria, France and Germany mainly use pellets for residential heating, whereas Sweden uses a higher share for commercial heating (AEBIOM, 2015).

Improved understanding of how small-scale heating markets function is important for a more complete picture of global pellet markets. There is also growing political awareness in Europe of the importance of heating & cooling to meet climate change mitigation targets, as manifest in the 2016 EU Strategy on Heating and Cooling (European Commission, 2016). EU policy makers are thus well served by a more comprehensive view of European pellet markets for small-scale heating.

In this study, I analyse data on national wood pellet price developments and intra-European wood pellet trade flows with the aim to understand the developments of European market integration as well as to draw conclusions about market functions. The objective is to extract significant characteristics of the time series and to develop a model capable of describing wood pellet trade patterns for residential heating. Therefore, I want to discern key market drivers, especially when it comes to interactions between national markets to derive policy options supporting the wood pellet commoditisation process. Due to limitations in data availability but also due to their leading role in European residential wood pellet heating, I focus my analysis on four national markets: Italy, Germany, France and Austria.

5.2 Background and literature review

European wood pellet markets for small-scale heating have hitherto been analysed only to a limited extent and mostly only beside the markets for industrial applications. Sikkema et al., (2011) conducted the first extensive study on wood pellet trade and wood pellet prices finding “relatively mature industrial pellet markets, compared to non-industrial ones, because of their advanced storage facilities and long-term price setting”. The results of this study were derived from the Pellets@atlas[3] project which collected information on volumes, market prices and quality standards in the 27 EU countries, Norway and Switzerland between 2006-2008. Olsson et al. (2011) analysed interactions between the pellet markets of Sweden, Germany and Austria using price series up until 2008. The conclusion was that Germany and Austria could be considered integrated markets in the sense that price fluctuations in the two countries are interconnected. Sweden however constituted a separate market in the time period 2004-2008. A recent paper from Kristöfel et al. (2016) analyses demand and supply of wood pellets in the heating sector in Austria based on annual and monthly time series including wood pellets prices, prices for saw mill by-products and installed pellet heating

[2] To increase readability of this working paper, we state all wood pellet mass values in mega tonnes (1 Mt = 10^6 kg) and kilo tonnes (1 kt = 10^6 kg). With an average of 16 MJ*kg^{-1} this would equal 16*10^3 TJ and 16 TJ.
[3] Based on data gathered between 2006 and 2008 in the IEE-project Pellets@tlas.

devices as well as the number of Heating Degree Days. The same author also discusses historic price volatility of woody bioenergy carriers (incl. wood pellets) compared to energy and agricultural commodities (Kristöfel et al., 2014). The two papers give a detailed econometric insight and potential impacting factors in and on the wood pellet market of Austria. Kristöfel et al., (2014) find a high exposure of consumers to price changes resulting from supply shocks and that a growing number of pellet boilers will likely result in higher pellet prices in the future. Kristöfel et al., (2014) find no correlations between differences of Austrian prices and prices from Italy and Germany with import and export volumes.

The wood pellet commoditisation process was furthermore discussed by Olsson et al., (2016)**.** They analysed the product- and market related properties of wood pellets. Since wood pellets are used for different purposes, including residential heating, district heating and electricity production in various scales the product can be described as an intermediate good. Furthermore, through homogenisation a higher degree of automatisation can be achieved throughout the supply chain and uncertainties are minimised for the consumers and market transparency is increased. Olsson et al., (2016) find, that the resulting fungibility can be seen as a key property of commodities. Therefore, technical standards like the ISO17225-2 are stepping stones for the commoditisation process; however as long as the quality criteria are not set too tight i.e. consider current technical and economic feasibility. Beside the product related properties Olsson et al., (2016) discussed liquidity, competitiveness and international trade as necessary market related properties of wood pellets with regard to the commoditisation process. They find that off-take contracts and vertical integration are prevailing strategies in the industrial wood pellets market to reduce the risks on both end of the supply chain thus reducing liquidity and competitiveness. Wood pellets are more internationalised than both coal and natural gas markets when comparing international trade with global production. Taking into consideration actual spill overs of market fluctuations from one region to another beside the actually traded volumes, international market integration however is discussed to be rather low.

The literature analysis highlights the need to accompany the established knowledge focusing on single national markets and the industrial wood pellet markets by studying the residential wood pellet market in specific in a more international context. In the upcoming subchapters I therefore want to outline a methodology how to discuss and analyse the market related properties of wood pellets for residential heating, illustrate the main findings and discuss them also by consultation of market parties to get anecdotal evidence and expert opinions to help interpret the results.

5.3 Theory and methodology

5.3.1 Definition of market related properties and trade regimes

To be competitive, markets need many buyers and sellers where no single actor or group of actors can effect on the overall market prices. Price formation should follow standard (theoretical) economical process of supply and demand ensuing adjustments towards a competitive equilibrium (Olsson et al., 2016)**.** A competitive international market furthermore implies adjustments towards competitive spatial equilibrium (CSE) in which excess from one market is transferred to another and prices are equilibrated except for remaining differences that can be assigned to transfer costs.

Market liquidity on the other hand refers to the ease by which an asset can be converted into cash without large price changes. Key factors to ensure or facilitate liquidity is firstly that there is a reasonable amount of market supply and demand, but also that search costs - i.e. “the costs of acquiring adequate information” (Olsson et al., 2016) - are low. In this way market transparency is a precondition to market liquidity. It emerges during the transition from informal to more mature markets with many buyers and sellers, which at some point requires the development of product standards, which in turn facilitate standardised trade procedures typical for established markets.

In a liquid and competitive market, the price of a good or a commodity should - if transfer costs are accounted for - be the same in all locations. Perfectly functioning markets are however arguably a theoretical concept and in reality, prices in different locations will almost always differ slightly for one reason or the other e.g. due to transport costs. Assessing the extent of interconnections between geographical markets is a well-established field of research with applications in many different commodity markets (Bachmeier and Griffin, 2006; Findlay and O’Rourke, 2003; Warell, 2006).

Barrett and Li, (2002) argue that a distinction should be made between market integration and competitive spatial equilibrium, hence market efficiency. In their terminology, if there is trade in a good between two geographically distinct markets, the two markets are by definition integrated. However, physical trade flows do not automatically mean that market fluctuations completely dissipate between the two. In order to clarify this difference, Barrett and Li emphasize the concept of competitive spatial equilibrium as a more distinct description of market interactions.

Barrett and Li present six different regimes that can be used to describe the relationship between different markets in terms of price differentials, transfer costs and trade flows:

1. Perfect integration with trade: Cross-border trade leads to competitive spatial equilibrium, i.e. all arbitrage opportunities are exhausted (arbitrage conditions are binding).

2. Perfect integration without trade: Competitive spatial equilibrium exists but arbitrageurs do not trade since they face zero marginal returns and hence are indifferent about trading or not.

3. Inefficient integration with positive marginal profits to arbitrage: Trade occurs but arbitrage opportunities are not exhausted remaining with price differences larger than transfer costs.

4. Segmented Disequilibrium: Price differences are larger than transfer costs, still no trade between the countries is triggered.

5. Inefficient integration with negative marginal profits to arbitrage: Trade occurs even though price differences are lower than transfer costs.

6. Segmented equilibrium: No trade between countries is triggered because marginal profits to arbitrage would be lower than transfer costs.

While regime 1, 2 and 6 describe a competitive spatial equilibrium, the remaining regimes indicate the presence of long-run profit-maximising strategies or short-run information failures (Padilla-Bernal et al., 2003). I interpret regime 3 and 4 with foregone/or uncleared arbitrage opportunities and that positive marginal profits have not been exhausted due to short-run information failure i.e., traders did not know and could thus not act upon this opportunity. Other explanations for foregone arbitrage opportunities could be barriers like buyers valuing intrinsically the regionality of the products or the trust to established supply sources. I expect regime 5 to be induced by long-run profit maximising strategies such as over the counter (OTC-) forward- or other long term contracts (LTCs). These contracts could explain why trade between two countries occurred even though prices in the sending country would have been more favourable for deals on the domestic market. Other explanations for regime 5 could be short-run information failure about domestic market prices or also "significant unobservable transaction benefits (e.g. first mover advantage)" according to Barrett and Li, (2002).

Therefore, I investigate the time-series characteristics of the residential wood pellet prices and bilateral trade data (1) to illustrate and quantify their characteristics and (2) to check if changing price differences did impact on the trade behaviour between the focus countries. For trade relations without co-moving prices I expect e.g. increasingly favourable price differences to increase trade. Thus, I expect arbitrageurs to partly clear marginal profits efficiently enough to observe an impact in the trade data, however not exhausting these profits which would drive the spatial markets towards equilibrium. I analyse the underlying prices time series and test for best fitting seasonal auto regressive integrated moving average models (ARIMA-models) for the trade data itself before I compare their accuracy with the accuracy of best fitting seasonal ARIMA models with price differences as exogenous variables.

5.3.2 Time series analysis and model comparison

A time series is defined as (weakly) stationary if its mean and auto covariance is time independent. This is when the process can be described as an autoregressive (AR) process with the parameter $|\varphi| < 1$.

$$y_t = \varphi y_{t-1} + \varepsilon_t$$

For $\varphi > 1$, the series will grow exponentially and for $\varphi < -1$ its amplitude grows indefinitely. In the unit root process with $|\varphi| = 1$, the series will not exhibit any clear tendency to return to a long-run average. Especially for prices time series the last case is of specific interest: According to Fama, (1965) prices can be described as a random walk process, if all available information are always fully reflected in the current price. We can transform non-stationary time series into stationary ones by differentiation, if the mean is the reason for non-stationarity. For time series the number d of differentiations necessary in order to yield a stationary series gives its "order of integration" $I(d)$ (see e.g. Johansen, (1997)).

To test for unit roots in time series Phillips and Perron, (1988) proposed to test the null hypothesis that a time series is $I(1)$. Furthermore and in general, two time series which are $I(1)$ will also have linear combinations of $I(1)$. However, if there exists a linear combination which can be described as an $I(0)$ process, the respective two series will not drift apart from each other indefinitely in the long run. These time series will follow a common stochastic trend and are further denoted as cointegrated (Stock and Watson, 1988). Engle and Granger, (1987) suggested to estimate the relationship between two time series with the same order of integration by performing Ordinary Least Square (OLS) regression and to test the regression residuals for stationarity. If the null hypothesis of no-stationarity can be rejected for both sets of regression residuals, one set for each time series as dependent and independent variable, the time series are cointegrated.

Auto regressive moving-average (ARMA) models can be used for stationary time series where values depend linearly on previous values. These models consist of an AR-part with the variable being regressed on its own past values based on different time lags p as well as a MA-part with the error term being a linear combination of past error terms based on different time lags q. For processes which are $I(d)$, time series are differenced until stationarity and estimated using an auto regressive integrated moving average (ARIMA) model. Furthermore, for daily, weekly, quarterly and monthly data additional seasonal differencing is useful to overcome autocorrelation of residuals in the 24th, 7th, 4th or 12th lag respectively. Seasonal differencing can be again performed for the values, indicated by P, the error terms, indicated by Q and the one-step differentials, indicated by D. Seasonal ARIMA models can be written in the following notation:

$$ARIMA(p,d,q)(P,D,Q)_s$$

where (p,d,q) give the non-seasonal part and $(P,D,Q)_s$ the seasonal part with the suffix s as the number of observations for each seasonal cycle. For the general seasonal ARIMA process y_t denotes the solution of the following equation

$$\Phi(B^s)\varphi(B)\nabla_s^D\nabla^d y_t = c + \beta X_t + \theta(B^s)\vartheta(B)\varepsilon_t$$

where ε_t is the white noise process, c the intercept and X_t the exogenous variables multiplied by its regression coefficient β (Papaioannou et al., 2016). The delta operator is defined as $\nabla_s^D = (1 - B^s)^D$ respectively $\nabla^d = (1 - B)^d$ and the backward shift (or lag-) operator used as $B^k y_t = y_{t-k}$. Furthermore the backshift polynomials are defined as

$$\Phi(B^s) = 1 - \Phi B^s - \cdots - \Phi_P B^{Ps}$$

$$\varphi(B) = 1 - \varphi_1 B - \cdots - \varphi_p B^p$$

$$\theta(B^s) = 1 + \theta B^s + \cdots + \theta_Q B^{Qs}$$

$$\vartheta(B) = 1 + \vartheta_1 B + \cdots + \vartheta_q B^q$$

In order to identify the optimal combination of seasonal and non-seasonal model parameters and consequently also to test the added value of exogenous variables, several analytical steps are performed upon the wood pellet trade data. First the data is inspected for any anomalies. Beside the need for differentiation to stabilise the mean of the time series also the application of a logarithmic operator could be necessary to stabilise the variance of the time series. The following steps are performed using the algorithm from Hyndmann and Khandakar, (2008). The number of observations in the seasonal cycle can be mostly fixed based on the context, for the monthly data in this study I choose $s = 12$. Based on the OCSB-test (Osborn et al., 1988) the time series is tested “whether the seasonal pattern changes sufficiently over time to warrant a seasonal unit root, or whether a stable seasonal pattern modelled using fixed dummy variables is more appropriate.” After adjusting to seasonal stationarity (for D>0) or by using the original data (if D=0), the successive Kwiatkowski-Phillips-Schmidt-Shin test (KPSS-test) (Kwiatkowski et al., 1992) is used to determine the number of differences which are necessary to render the remaining series stationary. Thus, the data is tested for a unit root and in case of significance; the differenced data is tested for a unit root and so on. The test is stopped as soon as the first insignificant result is obtained. Next, values of autoregressive order p, and moving averaged q and seasonal counterparts P and Q are identified by minimising the Akaike’s Information Criterion (AIC) for all permutations. The residuals of the respective models are summarised as root mean squared error (RMSE). The RMSE is minimised during the parameter estimation process for each model. By minimising the Akaike’s Information Criterion (AIC), simplicity in terms of number of independently adjusted parameters within the model is traded-off against the maximum likelihood of each model (Akaike, 1974) and the most adequate (p, d, q) and $(P, D, Q)_{12}$ combination is selected. Furthermore, the used algorithm allows for $c \neq 0$ thus includes possible constants, as drifts (for ARIMA-models) and non-zero means (for ARMA-models) where feasible.

By using the Ljung-Box portmanteau test (Ljung and Box, 1978), the white noise behaviour of the residuals of the combination and its respective model in question is tested. More specifically, with the Ljung-Box test I check the null hypothesis of serial correlations of the residuals, which can be rejected at a p-value greater 5%. The test requires the selection of the number of lags h which is recommended with $h = 2s$ for seasonal and $h = 10$ for non-seasonal data in Hyndman and Athanasopoulos, (2013). If the null hypothesis can be rejected, no evidence for serial correlation is given and the model is said to capture the information in the data perfectly.

After finding the optimal seasonal ARIMA-model for the wood pellet trade data, I repeat the process including this time the wood pellet price differences as exogenous variable. Therefore, the algorithm from Hyndmann and Khandakar, (2008) fits a regression with ARIMA errors. After rejecting the null hypothesis of serial correlation of the residuals of the model with exogenous variables, the seasonal ARIMA and the seasonal ARIMAX models are compared using the Bayesian Information Criterion (BIC) as well as the mean absolute scaled error (MASE):

While the AIC can only be used to compare models of one and the same data set I have to consider an augmented criteria to discuss the added value of additional exogenous variables in relation to their simple sARIMA-models. Therefore, I use the BIC, which also penalises the complexity of the model based on the number of observations of the data set. The model with the lower BIC is identified as better model in terms of simplicity and maximum likelihood.

Hyndman et al., (2006) proposed the MASE to measure the relative reduction in error compared to a naïve model. Therefore, the mean absolute error of the ARIMA model is divided by the mean absolute value of the naïve model, or in case of a sARIMA by the mean absolute value of a seasonal naïve model. A MASE close to unity therefore identifies no additional predictive power of the model in question while a lower value refers to more useful models.

5.4 Data

5.4.1 Collection of residential wood pellet prices

Residential wood pellet prices were collected from national pellets associations and national statistics for the MS of interest: Austrian residential wood pellets are based on the "Pelletpreisindex PPI06" from ProPellets, (2017). The Austrian wood pellet association queries prices based on private end user prices, including VAT, not packed and for an ordered amount of 6 t. Furthermore, it reports a feed-in-flat-rate ("Einblaspauschale") for direct delivery of wood pellets by a dedicated truck and pumping/blowing them into the residential pellet storage. The “Einblaspauschale” is estimated with an average of 39 € for each delivery (about 6.5€/t). German wood pellets prices are collected by “Deutsches Pelletsinstitut” (DEPV) for several regions (South Germany, North Germany and Central Germany) for different quantities delivered[4] excluding VAT but including all costs for delivery up to 50 km (Buerger, 2015). The pellet price time series for 6 t delivery was further used for my analysis. Residential wood pellets are mainly sold in 15 kg bags in Italy. The “Associazione Italiana Energie Agroforestali” (AIEL) collects wood pellet prices on “retail level” without transport costs and VAT for bag and bulk purchases[5]. For the focused time range (2012-2016) of this study pellet prices for Italy are only available every two to three months. In France official statistics publish pellet prices for 5 t deliveries up to 50 km and bag purchases (yard sale) including VAT (Beyond20/20, 2017).The former values are used for this study.

To increase comparability of prices between the analysed MS, I discuss only bulk delivery. For Austria the constant feed-in-flat-rate is also added to increase comparability since no time series for such flat rates can be acquired. Taxes are normally paid on pellets as delivered, i.e. total costs including transport. The changes in value added tax for wood pellets in the focus countries are illustrated in **Table 7**.

Table 7: Value added taxes for wood pellets for residential heating purposes. Source; (lko, 2016), (UStG, 2015), (Abibois, 2016), and personal communication with AIEL

Year	**AT**	**DE**	**IT**	**FR**
2012	10%	7%	10%	7%
2013	10%	7%	10%	7%
2014	10%	7%	10%	10%
2015	10%	7%	22%	10%
2016	13%	7%	22%	10%

Wood pellet prices as well as price differences between main trading partners are summarised in **Table 8** and illustrated in **Figure 9**.

[4] Personal communication with Jan Schlaffke/ DEPV 13.12.2016 per e-mail
[5] Personal communication with Laura Bau/ AIEL 02.02.2017 per e-mail

Table 8: Residential wood pellet prices (row 1 to 4) and price differences (row 5 to 9) for the considered time period. Source; ProPellets, (2017), (Buerger, 2015), (Beyond20/20, 2017) and personal communication with AIEL

	Minimum	Maximum	Mean	Standard Deviation
AT	199,81	245,79	219,82	13,23
DE	207	266	230,57	17,2
IT	212	295	252,92	22,91
FR	221,34	260,57	239,68	12,07
AT-DE	0,31	28,82	10,67	6,02
AT-IT	4,36	53,77	30,64	14,5
DE-IT	-15	39	19,92	13,45
DE-FR	-19,9	24,2	8,28	12,51
FR-IT	-14,19	47,81	12,76	15,28

Lowest average wood pellet prices in the period Jan.2012-Sept.2016 can be found for Austria, followed by Germany and France while highest prices are collected for Italian consumers. Prices are in general higher in the winter months for all countries than during the year.

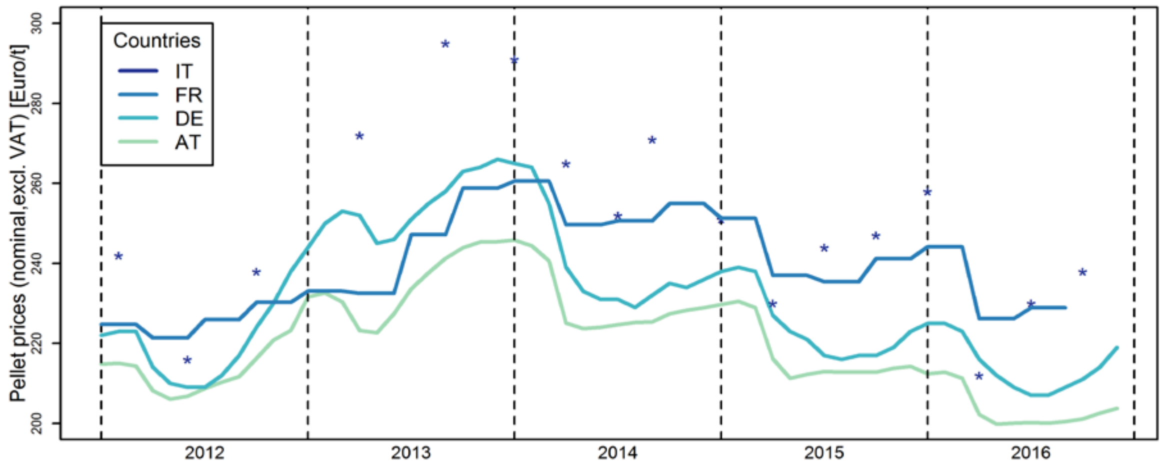

Figure 9: Residential wood pellet prices for the considered time period. Dotted vertical lines indicate December of each year. Source; ProPellets, (2017), (Buerger, 2015), (Beyond20/20, 2017) and personal communication with AIEL

5.4.2 Wood pellet trade and Eurostat

Harmonised statistical approaches on trade of wood pellets to provide information to the market actors have been called upon since the publication of ETA et al., (2007). Until 2009 wood pellet trade was documented in Eurostat under the trade code for “wood waste & scrap” or “sawdust”, both stating “whether or not agglomerated in logs, briquettes, pellets or similar”. Between 2009 and 2012 European statistics used a specific trade code “sawdust and wood waste scraps, agglomerated in pellets”. Sikkema et al., (2011) specified the need for a double-entry bookkeeping system for intra-

European trade and the documentation of extra-European imports and exports in Eurostat. In January 2012 an international pellet code was introduced by the World Customs Organisation in line with the Harmonised System nomenclature (HS 440131). The trade code was adopted by the European Union Combined Nomenclature system (CN), thus listing wood pellet trade explicitly in national statistics of Member States (MS) and in Eurostat.

Trade flow data from Eurostat, (2017),more specific from the International trade in goods statistics (ITGS) is used to perform the analysis in this thesis. European Member States (EU MS) are obligated to report monthly import and export volumes of their goods in quantity and value. Trade streams between the EU MS (intra-EU trade) and between the MS and non-EU countries (extra-EU trade) are published online[6] based on a harmonised approach. National statistical authorities (NSAs), mostly national statistical institutes are in charge with collecting trade data from any businesses (Provider of statistical information – PSIs) and sending them to Eurostat within the legal deadlines.

In practice, intra-EU wood pellet trade data is reported monthly from companies in EU, MS which are exceeding exemption thresholds fixed on national level. For example, any Austrian business with traded monetary values (in any direction) above 750.000 € in the past or current year has to report its imported and exported values and quantities as well as additional information including used transport modes, partner countries and country of origin into the official national INTRASTAT online tool (Schmidt et al., 2015)**.** Exemption thresholds can vary between MS, however MS “have to ensure that at least 97% of their dispatches (intra-EU exports) by value (95% up to 2013) and 93% of their arrivals (intra-EU imports) by value are covered” (Eurostat, 2015). For successfully submitting an INTRASTAT declaration, an existing CN code (Combined Nomenclature) is required.

Since the new code for wood pellets is available, former CN codes used for this commodity are no longer listed (former subheading 440130) and nearly all companies declare their trade electronically and companies were informed well before introduction of new codes[7]. NSAs furthermore check the received data for plausibility, if necessary countercheck it with the declarants, estimate the statistical values to ensure comparability and estimate missing trade flows based on VAT (value-added tax) returns and foresight models including seasonality, working days etcetera[8]. Finally, trade data is compiled by the NSAs for national publication and then forwarded to Eurostat where it is re-compiled in a harmonised approach. The Eurostat publication may differ from the national publication mainly due to better account for the common European border by use of adjusted concepts and definitions.

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[6] http://epp.eurostat.ec.europa.eu/newxtweb/
[7] At least in Austria, personal communication 23.03.2016 Tamara Schmidt, Statistik Austria
[8] To acquire and compare these foresight models for the discussed MS was out of scope of this study

To avoid double counting for EU agglomerates, dispatches and arrivals cover goods which are in free circulation in the receiving MS. Imports and exports on the contrary include goods placed under customs procedure for release into free circulation in the MS of entry or after transfer to another MS. This means that a trade from country A to country B and a subsequent transfer to country C will be declared as imports of country B if put under customs control in country B. Goods in simple transit, entering and leaving a MS, with the exclusive purpose of reaching another MS or country are not recorded at all in the ITGS. However, due to customs simplification ("Single authorisation for simplified procedures" - SASP), customs can be declared in the MS of origin of a company which imports or exports goods in and from another country, which consequently leads to higher reported imports and exports in some countries than actually physically traded.

Exports and dispatches are said to be FOB type values (free on board) while CIF type values (cost, insurance, freight) are used for imports and arrivals. In simplification, this means that transportation costs originating in the sending country are included until the border of the receiving country excluding customs, excise duties or VAT. Depending on the different data collection procedures of the Member States, NSAs also estimate the statistical (at the border-) values by adding or subtracting transport costs. Therefore, NSAs also collect information about transport modes used for the respective trade[9]. In case of any other transport mode than sea or inland waterway traders normally use the incoterms FCA (Free Carrier) and DDP (Delivery, Duty Paid) for exports/dispatches and imports/arrivals respectively[10] . NSAs have to recalculate in order to achieve the harmonised FOB and CIF type values for all transport modes. Quantities as statistical values are collected by the NSAs rounded in full kilogram without packaging. MS are not obliged to collect this so called net mass, but have to estimate it to meet the Eurostat data requirements.

Table 9: Net-trade of trade quantities between reporter and partner between Jan.2012 and Sept.2016. Source; own calculations based on Eurostat, (2017)

Partner	**Reporter**	**Minimum**	**Maximum**	**Mean**	**Standard deviation**
DE	AT	-10619,3	1799,3	-3875,9	2754,1
IT	AT	0	67451,4	37397,3	13127,5
AT	DE	-2372	15730,5	3694,8	3088,3
IT	DE	0	48233,9	11433,3	6963,2
FR	DE	-1115,1	30406,2	9117,8	8136,6
IT	FR	972,1	19166,8	8347,8	4229,7

While the main receiving country of wood pellets for heating in the EU was Italy (with 7.0 Mt over 56 months), Austria and Germany were both important wood pellets trading countries, in terms receiving pellets and sending them to the other focus countries. Imports to Italy are followed by

[9] However only transport modes for imports and exports can be downloaded on Eurostat so far. Transport mode for Intrastat-trade are not online yet.
[10] Personal communication with Michael Wild, Wild / Partner LLC, Principal, 09.09.2016

imports to Germany (2.0 Mt), Austria (1.6 Mt) and France (0.6 Mt). 37% of Italian imports originated from the other focus countries. France imported 45%, Austria 24% and Germany 11% from other focus countries. Italy and Austria also exhibit a seasonal pattern for total wood pellet imports but no such patterns can be found for German and French imports. For Italy and Austria import lows are around January-March while imports increase again starting with May.

Even though the focus countries have been selected to present the most important EU countries where wood pellets are used for heating, I do not observe strong trade links between all of them: Only Germany and Austria indicate a strong bilateral trade i.e., in both directions (739 kt to Austria and 160 kt to Germany). Trade from Austria to Italy accounts for the largest single observed trade (2.076 kt) however this trade is almost entirely uni-directional. Also Germany and France sent a considerable share (654 kt) and (468 kt) of their wood pellets to Italy in the considered time frame. Trade between Germany and France is dominated by pellets sent to France (275 kt).

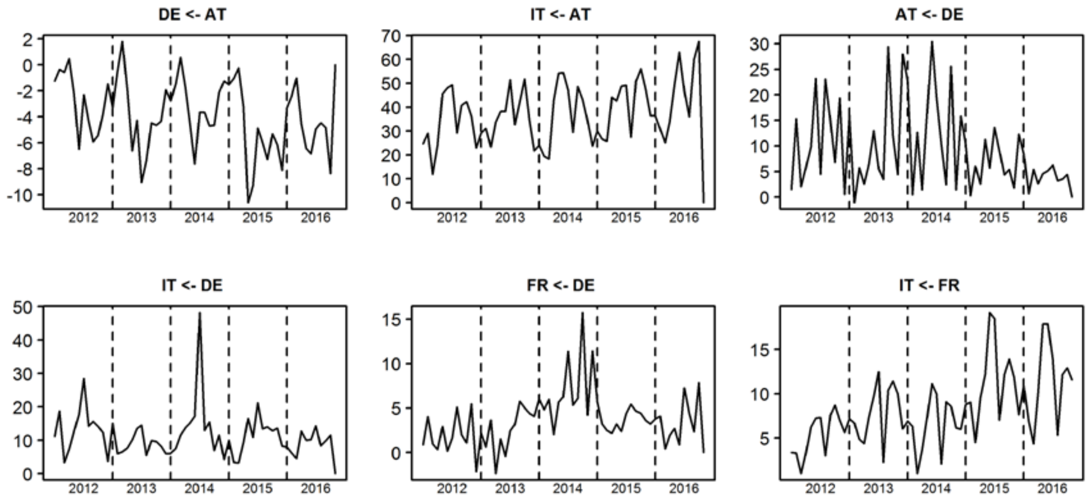

Figure 10: Most important trade streams between the main European wood pellets for residential heating markets. The y-axis indicates monthly net-exports in kilo tonnes. Dotted vertical lines indicate the December of each year. Source; own illustration based on Eurostat, (2017)

5.5 Results

In order to test if markets are integrated in terms of transmission of price fluctuations I test for co-integration. Therefore the Phillips-Perron Test was used to test for Unit Roots in the prices time series. In **Table 10** the test statistics from the tests on the individual variables can be found. The hypothesis of difference stationarity can be rejected only for the differentiated time series. All time series are integrated in the same order. However, the results are only informative for the Austrian and the German time series. (1) The French prices, even though publically available on a monthly basis, contain non-changing values mostly over a period of three months while (2) the Italian prices are only collected and available for a period of two to four months.

Table 10 – Results from stationarity tests of the wood pellet prices. Lag lengths in parenthesis (=10% significance level, **=5% significance level, ***=1% significance level)*

	Levels	**First difference**
Austria	-5.23(3)	-31.952(3)***
Germany	-5.805(3)	-22.294(3)**
France	-3.805(3)	-56.583(3)***
Italy	-6.902(3)	-47.351(3)***

In the next step a pairwise Engle-Granger test is performed for the remaining time series (Germany and Austria) in order to determine if any of the combinations are cointegrated. Therefore, the time series are OLS-regressed and the resulting residuals are tested for Unit Roots. Test results are compared with the critical values for cointegration from Phillips and Ouliaris, (1990) to find, that they are above the 10% confidence interval. Thus, the hypothesis for no-cointegration between Austrian and German prices cannot be rejected for the considered time period.

Table 11: Results from PP-unit root test for residuals of linear combinations of Austrian and German prices. Lag lengths in parenthesis. Time series of dependent variables are given in the first column while independent parameters in the first row. Test results are above the significance level for cointegration.

	Austria	**Germany**
Austria	-11.2157(3)	
Germany		-11.1675(3)

Not tested in this thesis, but mentioned by Carretero, (2014) wood pellet prices are usually highest in the winter months and lowest in the spring months for all countries. For the year 2012 and 2014 it could be argued, that the price lows in the residential heating market were caused by oversupply due to a fire and followed shut-down in a large wood pellet power producer (RWE, Tilbury UK, February 2012) and another power producer based on wood pellets going off the grid in Belgium in March 2014 (Max Green). However, since price lows are also observed in the spring months of other years, I assume that these events had only amplifying impacts on the residential wood pellet prices at best. Furthermore, special offers of pellet traders in Germany and Austria called storage prices (“Einlagerungspreise”) are used to ensure that consumers are sticking to the trader of the past season by filling up their storages between April and June. In Italy, typical storage capacity on the consumer side is smaller and mainly pellets in 15 kg bags are sold, with consumers not having the possibility to store ahead for the entire season like in Germany and Austria.

5.5.1 Modelling of trade flow patterns with and without price differences

In **Table 12 ff** best fitted models for the most important bilateral trade streams and their respective accuracies and test statistics are listed. Only models passing the Ljung-Box portmanteau test of no remaining serial correlations in the residuals are listed.

Most trade relations can be best explained by seasonal ARMA and ARIMA-models, only the trade from Germany to Austria do not show seasonal behaviour in net-trade. A simple mean model is suggested for the net-exports with Germany as reporter and Austria as partner with a non-zero mean of about 10kt*month^{-1}. The symmetrical net-export flow with Austria as reporter and Germany as partner is better described with a seasonal model with a negative drift. The negative drift is a result of declining exports from Austria to Germany in the considered time period. Cumulated net-exports for the entire time frame from Austria to Germany are furthermore at about -225kt while cumulated net-exports with Germany as a reporter point of view are at about 530kt.This indicates a certain asymmetry in the data of the double-book keeping entry system.

Table 12 – Calculated best fitting models for bilateral trade streams (net-trade) without price differences as exogenous variable

Trade	Model type selection	Constant	BIC	MASE
DE<-AT	ARIMA(0,0,0)(1,1,0)[12]with drift	-42	591.43	0.75
IT<-AT	ARIMA(0,0,1)(1,1,0)[12]with drift	190	660.35	0.65
AT<-DE	ARIMA(0,0,0)with non-zero mean	9465	1175.26	0.61
IT<-DE	ARIMA(1,0,0)(1,0,0)[12]with non-zero mean	11641	1156.05	0.65
FR<-DE	ARIMA(0,1,2)(1,1,0)[12]		830.12	0.7
IT<-FR	ARIMA(1,0,0)(1,1,0)[12]with drift	126	596.28	0.48

Best fitting ARIMA models for Austrian and French net-exports to Italy include a drift, indicating increasing exports to Italy. Most optimal models with price differences as exogenous variables are describing the time series slightly better than their sARIMA and ARIMA counterparts. Only German trade to Italy and France indicate higher MASE- and for France also BIC-values in the sARIMAX cases. However, the discussed models include the price differences between partner and reporter with both, negative and positive signs. Price differences which are more favourable for trade result in decreased net-exports in the cases where Austria as a reporter is trading to Germany and Italy. This is also reflected symmetrically with a positive sign in the data where Germany as a reporter is net-exporting to Austria. The optimal model for France to Italy also results in a positive net-export increase when price differences are more favourable.

Table 13 – Calculated best fitting models for bilateral trade streams (net-trade) with price differences as exogenous variable(Ex. Var.)

Trade	Model type selection	Constant	Ex. Var.	BIC	MASE
DE<-AT	ARIMA(0,0,0)(1,1,0)[12]with drift	-43	-241	573.99	0.69
IT<-AT	ARIMA(0,0,1)(1,1,0)[12]with drift	185	-50	643.62	0.62
AT<-DE	ARIMA(0,0,0)with non-zero mean	9608	511	1156.85	0.6
IT<-DE	ARIMA(1,0,0)(1,0,0)[12]with non-zero mean	11746	-100	1138.61	0.65
FR<-DE	ARIMA(2,1,0)		-43	1004.16	0.72
IT<-FR	ARIMA(1,0,0)(1,1,0)[12]with drift	124	7	582.48	0.47

In summary I observe significant and positive net-exports mostly from countries with lower residential wood pellet prices to partners with higher average prices. Only Germany is a net-exporter to Austria even though Austrian price level is below the German one. Residential wood pellet prices between Germany and Austria cannot be said to be cointegrated in the time frame from January 2012 until November 2016 and data availability does not allow testing the other trade relations for cointegration. I allow the model fitting algorithm to select the optimal model in terms of simplicity and maximum likelihood. Still, the optimal models including price differences as exogenous variables (1) are not found to perform significantly better than their ARIMA and sARIMA counterparts and (2) the models with slightly lower BIC- and MASE-values do not unambiguously indicate that arbitrageurs clear profit margins.

5.6 Discussion

5.6.1 Methodology and results

The introduction of a harmonised trade code for wood pellets and the doubly-entry bookkeeping of monthly bilateral wood pellet trade in Eurostat opened up the possibility to analyse the market-related properties of the European wood pellets for small-scale heating market in greater detail than in previous research including Sikkema et al., (2011) and Olsson et al., (2011). By carrying on the discussion of the wood pellet commoditisation process (Olsson et al., 2016) using commodity trade theory, mainly derived from agricultural economics (Barrett and Li, 2002) developing market related properties can be identified more accurately. The identification algorithm of optimal seasonal ARIMA models from Hyndmann and Khandakar, (2008) allows for a generic characterisation of the trade time series as well as the discussion if market clearance from arbitrageurs can be observed.

I find integrated wood pellets for small-scale heating markets in terms of observed trade flows between Italy, Germany, Austria and France. In terms of prices only Germany and Austria could be tested for cointegration. Contrary to previous literature (Olsson et al., 2011; Buerger 2015 and Hruby 2015) which analysed different time frames, these time series cannot be said to be cointegrated for the discussed period. This could be due to the relatively short time period selected for the presented analysis. Thus, the trade relation from Germany to Austria can be discussed as inefficiently integrated with partly remaining positive marginal profits and possibly partly CSE. From the beginning of 2014 also trade from Germany to France and since mid-2013 also from Germany, Austria and France to Italy can be described as inefficient integration with remaining positive marginal profits and expected CSE for some parts of the time series. These trade streams reflect flows towards markets where wood pellets can be sold at a higher price level as in the originating national market. However, no further considerable correlations between price differences and trade can be highlighted, thus the effects of arbitrageurs clearing the markets cannot distinctively be observed. This supports the findings of inefficient integration with partly remaining positive marginal profits for all discussed relations. Furthermore, with about 160 kt exports from Austria to Germany exhibit the lowest cumulated trade volume over the discussed time horizon. This trade stream would have to be described as possibly inefficiently integrated with negative marginal profits since prices are higher in Germany than in Austria. Furthermore, seasonality is identified as an influencing parameter for overall imports, which appear to increase around May for Italy and Austria, when prices are generally lower. According to the discussion with a stakeholder[11], Italian traders' adjusted to the lower storage capacity of the Italian consumers by building intermediary storages and start stocking pellets in May.

The data underlying my results has to be processed critically, because of a relative early stage of the wood pellets commoditisation process. Trade flow data from Eurostat indicate discrepancies between arrivals from country A to B against dispatches from B to A. Eurostat, (2015) gives several possible reasons for these so called asymmetries: (1) Different thresholds in various member states, (2) late or non-response by certain companies, (3) statistical confidentiality, (4) misapplication of the rules and delays, (5) different valuation of transactions and (6) triangular trade. Single authorisations for simplified procedures can be another reason for asymmetries. More specific information from statistical authorities with regard to wood pellets data would be necessary to discuss asymmetries for all focus countries. Specifically for France, I assume misapplication of the rules during 2012 and the first half of 2013 due to an unexplainable overall import expansion after the summer of 2013 and discussions with a trader[10].

The collection of residential wood pellet price data was labour intensive, involving personal communication with experts from statistical agencies and national wood pellet associations. No homogenous methodology is underlying this monthly average price data and, since it reflects the wood pellets prices paid by the small-scale end users, I am left with the question about how representative these prices are in describing cross-border trade mainly executed by traders and retailers. I furthermore discuss possible deviations of regional prices from the national average and

[11] Personal communication with Michael Wild, Wild / Partner LLC, Principal, 09.09.2016

therefore the, in this thesis ignored, importance of regional cross-border trade. However, the presented price time series are the only publically available and comparable reference prices so far.

5.6.2 Recommendations

Price volatilities for consumers are well below the volatility of other energy carriers and wood pellet prices are falling due to relatively mild winters and an oversupply. Still, the development towards a competitive spatial equilibrium should be supported to increase access and affordability of wood pellets on a long run. Therefore, the development of residential wood pellet price benchmarks should be (further) supported and a harmonised approach for the collection of residential wood pellet prices in consumer regions applied. Also stronger efforts in the provision of other wood pellet related data like traded quality types, monthly consumption and production quantities used feedstock as well as higher spatial resolution of trade data would be necessary to reduce risks and to increase transparency, thus increase liquidity of the market.

To increase competitiveness a price benchmark or price indices would be necessary. Valiante et al., (2013) discusses benchmark-based pricing mechanism "... to rely on the liquidity of a reference contract, which is typically a front-month futures contract." The report further discusses that markets tend to be organised with privately negotiated LTCs when a globally recognised price benchmark, dealing with specific regional issues, is too difficult to build. Residential wood pellet futures are available only since October 2015 and LTCs are rarely used (Olsson, 2012). However, stability of trade relations ("established contacts and contracts") are mentioned as rather important in this market[10]. This shows that the wood pellet market for small-scale heating is far from an international recognised price benchmark and related stabilising and (spatially) equilibrating pricing mechanism.

Next to the necessity to increase competitiveness and liquidity of the wood pellet for small-scale heating market, also non-market related properties of the commodities need to be improved: To facilitate trading of wood pellets as an intermediary good, the risk of short- to medium term storage (several weeks up to several months) has to be reduced. This could be done by facilitating the acquisition of risk capital for building and using intermediary storage facilities but also by innovations to avoid losses and accidents in relation to storing solid biofuels. To avoid shortages also a dedicated stock monitoring system could further reduce risks for consumers, and therefore and in a longer run also for other market actors. Furthermore, wood pellets are not perfectly fungible yet, even though technical and sustainable standardisation are developed and used. This is due to intrinsic valuation of non-quality related properties like pellets colour and more regional biomass supply chains. The latter is a characteristic which seems to be grown with the bioenergy market probably caused by the feelings and marketing practices relating to notions like "only regional is sustainable and/or transparent" and "import dependencies have to be avoided in general".

5.6.3 Open questions and broader validity

Beside the uncertainties and open questions with regard to the underlying data, literature and case studies based on comparable methodologies and development stages of similar objects of investigation are missing. Can similar market behaviours be observed for other developing international commodity markets on the way to CSE and higher liquidity? How can inefficient integration, with significant unobservable transaction costs and information barriers, be modelled? What would be the added value of taking into consideration stocking behaviour and balancing supply and demand in comparable econometric analysis? How can we quantify the theoretical advantages of a mature market with global sustainable wood pellet trade? Answering these questions, also by reference to other developing or developed international commodity markets could give valuable insights and support not only the development of wood pellets but also other bioenergy carriers like e.g. ethanol, bio-diesel, bio-methane and torrefied pellets.

Furthermore, I want to highlight the need to observe and analyse how the convergency process of small-scale heating with the large scale wood pellet market is developing. Within the EU, the wood pellet producers for small-scale heating are already competing against each other but will face more and more also pressure from producers initially serving large-scale combustion, intra- and extra-European imports but also due to low prices from conventional fuels. On the one hand, this development will improve market organisation through e.g. higher efficiency, supporting the intermediary character of the commodity and reduce prices for the end users. On the other hand, it will also push smaller producers out of the market unless e.g. they keep managing to convince the users to pay a premium for locally sourced and produced pellets.

5.7 Conclusion

Unfortunately, the current state of market-related properties of the commodity does not allow the composition of a modelling framework based on competitive spatial equilibrium and theoretical rules of functioning markets for the main wood pellet consuming countries for small-scale heating in the EU. Price volatilities for consumers are well below the volatility of other energy carriers and wood pellet prices are low due to relatively mild winters in 2013-2016 and an oversupply. Still, the development towards a competitive spatial equilibrium should be supported to increase access and affordability of wood pellets in the long run. Therefore, the development of price benchmarks should be further supported and a harmonised approach for the collection of residential wood pellet prices in consumer regions introduced. Also, stronger efforts in the provision of other wood pellet related data like traded quality types as well as monthly consumption and production quantities and inventories would be necessary to reduce risks and to increase transparency and thereby increase the liquidity of this market.

With respect to the wood pellet commoditisation process, liquidity and competitiveness of the international markets are the remaining major shortcomings. Discussions with stakeholders revealed less tangible market properties that also have to be considered. Based on market actors, reasons why price differences seem not to influence trade flows in the considered time period could include the following; internationally traded and regionally produced wood pellets are sometimes not perfectly fungible, no matter if certified or not, amongst other things due to consumers assigning an intrinsic higher value to regionally produced wood pellets or for example their colour; another intrinsic valuation is given to established contacts and contracts between consumers, producers and traders. Furthermore, the value of wood pellets as a feedstock intermediate could be improved by reducing physical and financial risks of solid biofuel storage.

Based on the presented results and discussion, future research should focus on how to improve the development of the above mentioned market-related properties of the commoditisation process, competitiveness and liquidity. Modelling trials could be advanced by estimating the share of lower and higher quality wood pellets in the trade flow data by comparing specific costs based on monetary and physical trade flows to current residential pellet prices. Balancing monthly supply and demand as well as including information on inventories is expected to enhance the knowledge of trade flow patterns and price formation. Highlighting different impacts of increased international trade with pellets for small-scale heating through modelling overall cost reductions and effect on the resilience towards (supply chain) exogenous parameter changes (e.g. oil price, heating degree days, windfalls, etc.) could be promising future research objectives. Furthermore the convergency process of pellet markets for small- and large-scale use should be observed and analysed. Future research should also discuss consumer perceptions and address the intrinsic value of locally produced wood pellets as well as of established contacts and contracts in bioenergy trade.

6 Synthesis, discussion and further aspects

6.1 The potential role of biogenic carbon for energy and material deployment

With a primary renewable energy demand of 14.9 EJ in 2030 in the EU28 the share of energy supply based on biomass is expected to increase from 6.9 today to 7.2-9.3 EJ according to various scenario from an previous impact assessment (EC, 2016c). Considering the leading role of the European Union as a party in the Paris Agreement and a hypothetical further increase in energy efficiency from the 30% primary energy reduction in 2030 to a hypothetical 50% reduction in 2050 in comparison to 1990, I want to discuss a theoretical but likely relevant phase out of fossil fuels and thus a renewable energy scenario of 40.0 EJ for 2050. In **Chapter 2.3** I discuss the scenarios from the PRIMES modelling framework which estimate a range of biomass supply for bioenergy from 10.0-14.3 EJ for 2050. This would equal a steady reduction of the role of bioenergy in the renewables sector from about 60% today to 54-43% in 2030 and down to 36-20% in 2050. These estimates are also based on and limited by the current discussions and findings of sustainable biomass potentials and possibly relevant biogenic carbon supply structures (see next sub-chapter) and biogenic carbon trade in terms of net-imports into the EU.

The scenarios in **Chapter 3** discuss a biomass supply for advanced biobased materials of about 0.1 EJ in 2015 and possibly relevant increases to 0.2-0.5 EJ in 2030 and up to 0.6-2.4 EJ in 2050. Combined with the discussed bioenergy scenarios (see **Figure 11**) the resulting sector of the European bioeconomy could be based on 7.4-9.8 EJ biogenic carbon feedstocks in 2030 and 10.6-16.7 EJ in 2050. The share between energy and biochemical could thus be in a range of 3-5% in 2030 and 6-15% in 2050. Uncertainties regarding the development of the biochemical sector mentioned in **Chapter 3** relate to the past and current development of its capacities and production, for which available data is scarce. Substitution potentials and respective biomass demand in the biochemical scenarios are theoretical since overall targets of the industry and politics are not existent at the point of writing this thesis.

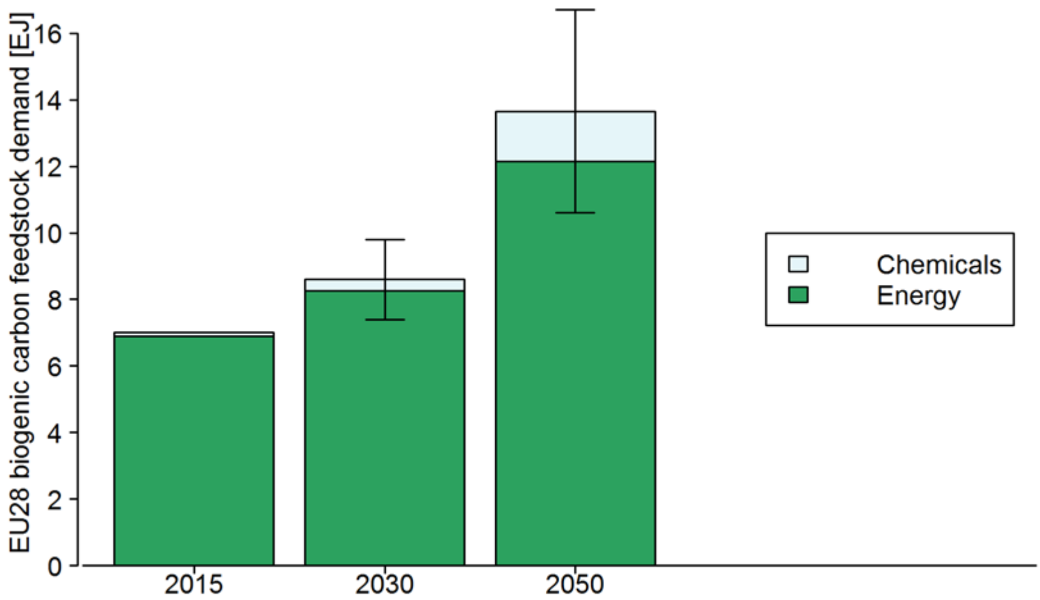

Figure 11: Biogenic carbon feedstock demand for energy and advanced biobased materials (chemicals) in the EU28. Source; own illustration based on own calculations and EC, (2016c)

Uncertainties regarding the underlying bioenergy developments are manifold: First I want to mention, that the phase out of fossil fuels is steered by a political process. 2030-values for Europeans energy efficiency as well as renewable energy share are so far only proposals by the EC, thus yet have to be decided upon by the European Parliament and the European Council. The implementation success of respective decisions clearly depends on the European market, society and other framework conditions with causal links outside the European Union. Further discussed developments up to 2050 are only speculations, however based on a possibly relevant trajectory in light of the ratification of the Paris agreement (EC, 2016e). I further discuss uncertainties related to the portfolio within the renewable energy sector and more specific related to the role of bioenergy including (1) the development of existing renewable energy technologies and respective innovations and; (2) the acceptance and participation of the society with regard to renewable energy technologies and supply chains.

Other renewable energy technologies like wind, solar, hydro-, geothermal- and tidal energy sources on the one hand do not hold the possibility to directly provide the carbon necessary for advanced biomaterials production. Technological development of CO_2-capture, -reduction and -photo catalysis on the other hand could become an interesting alternative to biogenic carbon from the discussed feedstock. However, respective technologies are in an early research and demonstration stage (Tahir and Amin, 2013) and are thus estimated to only play a subsidiary role in the considered time frame up to 2050. Still, it is useful to already propose the possibly resulting products to be included in current legislations, as already done by the EC. The commission took into consideration renewable liquid and gaseous transport fuels of non-biological origin (EC, 2016a). Beside hydrogen as a transport fuel I assume that also carbon carriers not based on photosynthesis could fall under this categorisation. Hydrogen, mainly used in industrial processes and for transportation is estimated to reach between 0.2-1.6 EJ in 2050 in the EU28 however, also mainly based on biomass gasification and carbon capture (Sgobbi et al., 2016). Finally, I want to address the uncertainties regarding the related topic and development of CO_2 capture and sequestration (CCS-) technologies instead of utilisation. On the one hand, CCS-technologies could prolong the relevance of fossil fuels and on the other hand and combined with bioenergy could result in negative net emissions (Daioglou et al., 2015). Due to the pre-commercialisation stage of respective technologies, I do not consider them to be able to alter the notion of this thesis for the discussed time frame. Furthermore, the analysis of the possible role of nuclear fission and fusion as politically accepted (and from the society accepted-) part of the renewable energy mix was out of scope of this thesis.

6.1.1 Biogenic carbon supply structures compared to fossil ones

Under the discussed assumption that considerable large shares of today's fossil based European economy is going to be based on biogenic carbon feedstock in the upcoming decades, feedstock supply structures will look fundamentally different. In **Chapter 3** I underpin this assumption by a (1) lower carbon density; (2) higher water content and; (3) higher heterogeneity of the biobased in contrast to the fossil based feedstock. Therefore larger sourcing areas with the inclusion of a higher variety of stakeholders and more transport will be needed while emission reductions compared to fossil based alternatives have to be the ensured in all activities. The biogenic carbon feedstock portfolio share for European energy consumption in 2030 is discussed for food crops at about 10% or even to decrease due to a proposed phase out of 1st generation biofuels (EC, 2016a). The role of bioenergy based on, for human's indigestible cellulosic biomass is thus expected to increase in the upcoming decades. For the production of advanced biobased materials it is assumed, that today's feedstock basis is mainly sugar- and starch crops, thus food and feed biomass. However, in the scenarios in **Chapter 3** I outline a possibly relevant shift towards cellulosic feedstock since it could decrease final production costs of biomaterials (Gerssen-Gondelach et al., 2014b) when respective technologies are deployed commercially.

6.1.2 About the relevance of biogenic carbon trade

I furthermore introduce in **Chapter 3** the concept of biogenic carbon carriers as any biomass feedstock that is deployed either in energy or advanced biomaterials use. Based on the previous discussions it can be assumed, that biogenic carbon carriers will be sourced and traded to meet the demand especially of Germany and France. While these countries exhibit larger resource potentials (EEA, 2013; Hetemaeki et al., 2014) likely important consumers in terms of volumes which would rely on imports are discussed with the United Kingdom and Italy for bioenergy and Italy, the Netherlands and Belgium for advanced biomaterials production.

Additional to increasing imports of resource deficit MS, international trade of biogenic carbon towards and between the MS is assumed to increase due to market equilibrating effects and to secure supplies in the case of shortages (Junginger et al., 2014). Uncertainties regarding the increasing biogenic carbon trade are mainly related to (1) the distribution of leading MS in the bioeconomy transformation; (2) their underlying biogenic carbon feedstock portfolio and; (3) closely interlinked to the latter, their feedstock potential and production techniques and technologies.

The assumed distribution of leading MS is mainly based on observed current developments and existing capacities of fossil based refineries for chemical production (see exemplary retrofitting activity mentioned in **Chapter 3**). Considering any structural breaks with regard to this development is out of scope of this work. However, it cannot be excluded, that especially downscaling of chemicals production and the related possibility of moving production closer to the sources could become an economic feasible option (Clomburg et al., 2017), rendering trade of biogenic carbon carriers less important.

Still, an increasing role of nationally sourced and internationally traded cellulosic biomass as biogenic carbon feedstock should be discussed. While yields in forestry can be increased through sustainable managing practices such as promoted by the Forest Stewardship Council (FSC) and the Program for the Endorsement of Forest Certification (PEFC) (Goh et al., 2014) also more drastic options for altering productivity have to be mentioned. Here, especially the recent development of CRISPR-Cas9 and related methodologies to anthropologically adapt the genetic basis of cultivated plants could increase the availability of biogenic carbon (Estrela and Cate, 2016). Especially for energy and material purposes respective options can be discussed due to an expected lesser significance of social acceptance in contrast to the utilisation as food. How this development will affect another planetary boundary discussed by Steffen et al., (2015) namely the already highly stressed genetic diversity of our ecosystems will have to be assessed and discussed critically. The cultivation of less traditional biogenic carbon sources with higher productivity and lower environmental impact is another discussed and less contested topic. Exemplary carbon sources that could become more important in the upcoming decades in terms of meeting national biogenic carbon demand of the MS include miscanthus, switch grass, willow, and mixed cultivation systems denoted as agro-forestry systems with short rotation coppice (SRC) cultivation cycles (Mehmood et al., 2017). Also the cultivation of micro- and macro algae are potentially promising options, however with considerable challenges especially with regard to (1) algal farming techniques and (2) efficient (energy- and material-) functionalisation of the harvested carbon and other useful components (Suganya et al., 2016).

6.2 Making biogenic carbon tradable

In order to overcome the lower carbon density, higher water content and higher heterogeneity of biobased in contrast to fossil based feedstock I discuss and compare three biomass pre-treatment and densification technologies in **Chapter 3**. Applying the generic biomass-to-end-use chain assessment tool it can be found, that some combinations of feedstock and supply- and distribution modes- and distance for residential heating, coal co-firing and FT-synthesis could hold cost advantages if biomass is torrefied before pelletisation compared to simple pelletisation. I can furthermore highlight that biomass densification does not only hold the potential to decrease costs of transportation especially for long-distance supply chains and less efficient transport modes like trucks. Due to higher energy contents densification technologies could also contribute to decreasing costs of storage due to their even more positive effects on energy densities.

With higher process temperatures than in torrefaction, fast-pyrolysis can convert high shares of cellulosic biomass into a liquid fraction. Supply chains based on bio-oil are estimated to be more expensive than chains based on pellets and torrefied pellets. Still the deployment of bio-oil is discussed, especially for heating markets which are dominated by oil boilers and the possibly relevant option of blending with conventional heating oil.

Currently most significant cost advantages for torrefied wood pellets compared to conventional wood pellets are found for FT-synthesis due to lower capacity effect costs. However, taking into consideration current production costs for fossil based diesel, market entry strategies for torrefaction based on this end user type appear less promising. Torrefied straw and wood pellets are estimated to be more expensive than their conventional counterparts for the residential heating markets but within the range of estimated average heating costs in 2014 in the EU. Considering longer-distance supply chains and supply chains based on trucks over several hundred kilometres as well as longer storage periods up to 100 days, torrefaction and pelletisation could result in a more cost-efficient wood fuel than simple pelletisation. Solutions would have to be found for regulatory issues and issues regarding the end-user handling when it comes to using more “coal-like” pellets.

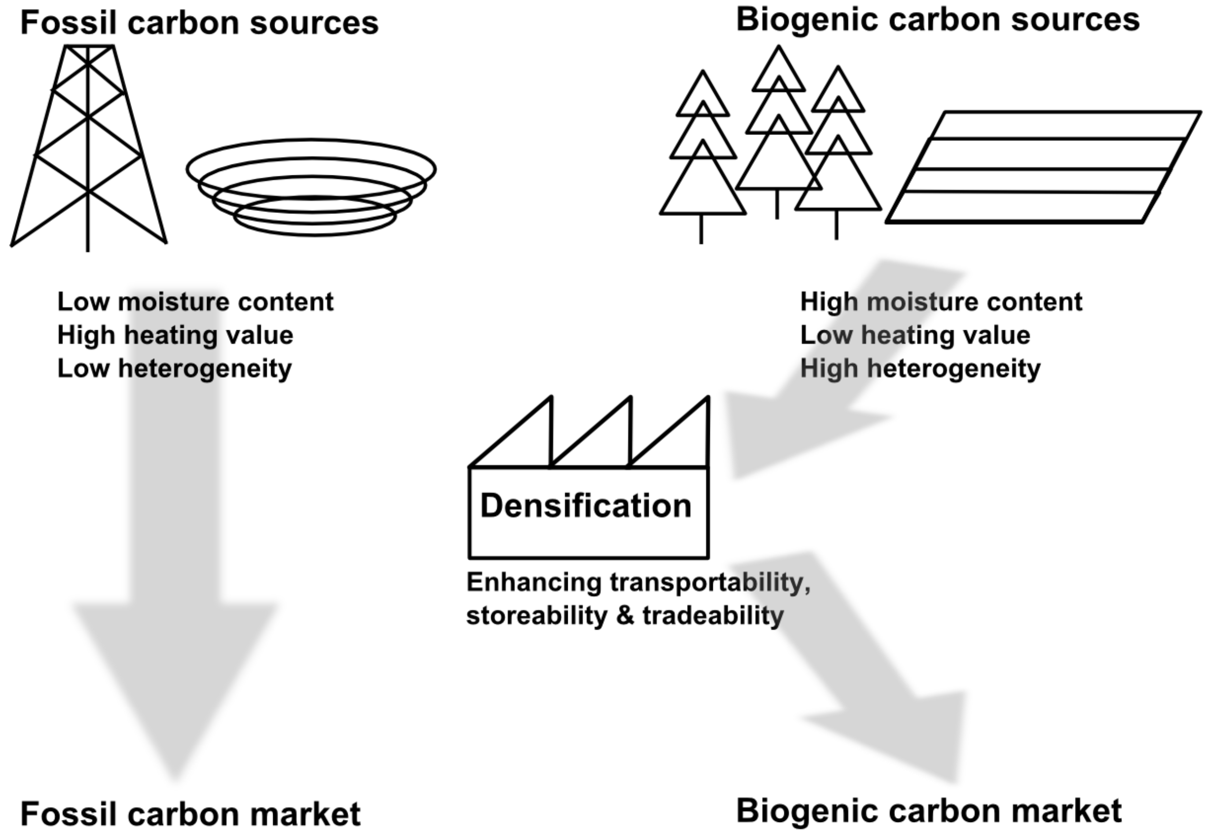

Figure 12: Feedstock allocation for fossil carbon and biogenic carbon based economic activities in the light of establishing carbon markets. Source; own illustration

The main uncertainties with regard to these findings can be found in the input parameters used for calculating costs of production, down streaming and utilisation of torrefied pellets and pyrolysis oil. Beside these uncertainties, discussed in more detail in **Chapter 3** it is unclear how well the presented findings, discussing 2014 values, can be generalised and applied within changing frame conditions and especially for a European bioeconomy up to 2050. If and how fast the currently expected densification technologies will be outperformed by other technologies cannot be said and was out of scope of this work to. Therefore the pace of commercialisation of the technologies and commoditisation of their respective densified products will be decisive. An important obstacle can be seen in off-take agreements for produced densified biocarbon carriers which are necessary in order for densification plant projects to be creditworthy. However, with a limited amount of products on the market for testing over a longer period of time, especially larger scale consumers are not willing to take the risk. Coalitions of product provider based on pilot plants are promising options to tackle this chicken-egg problem.

In future assessments and especially in light of a European bioeconomy, also the production of other chemicals than FT-diesel through the gasification pathway should be discussed. It can be expected, that scaling effect costs could also result in more cost effective deployment of torrefied wood pellets for the production of biochemicals such as polymers than conventional pellets. Also in light of the recent proposal of the commission, in which electricity only plants based on biomass are proposed to be phased out, the production of combined heat and power based on densified biocarbon carriers should be analysed. Therefore, capacity effect costs of CHP-plants would have to be addressed in future research.

6.3 Building up an integrated biogenic carbon market

In **Chapter 4** I discuss the market diffusion process of wood pellets in the European residential heating market- including Italy, Germany, France and Austria- as an exemplary densified carbon carrier commodity. The market related properties of this, most advanced densified bioenergy commodity, are found to not support the composition of a trade modelling framework based on competitive spatial equilibrium and theoretical rules of functioning markets for the main wood pellet consuming countries for small-scale heating in the EU. Most trading parties are found to have inefficiently integrated wood pellets markets with occasional marginal profits for arbitrageurs. It is reasoned, that relatively low liquidity and competitiveness of these markets are hampering the commoditisation process. Therefore, augmenting transparency based on data availability and quality with regards to trade, pellet stocks and prices could boost the process. Further efforts in establishing price benchmarks for wood pellets including futures contracts are also discussed as options to increase liquidity. High financial and technical risks of wood pellet storages are mentioned as another market- but also good related property of this commodity, reduction of these risks could also result in a faster progress of the commoditisation process. Another diffusion inhibiting good related property is discussed to be related to the fact that wood pellets, even though often traded together with a technical certification, are still not perfectly fungible. Still non-regionality or a different colour of wood pellets in contrast to the colour consumers are said to inhibit trade today. Awareness-raising but also solutions like sustainability certifications could help to overcome these limitations.

It is uncertain, how well these findings can be generalised to the commoditisation process of other densified biocarbon carriers including pellets based on other feedstocks, torrefied pellets or even pyrolysis oil. Future research should cover the question how well these findings can also be transferred to other expected commodities like hydrogen energy carriers or biopolymer intermediates for processing in the plastic industries. Still, I am generalising the finding, that both (1) technology optimisation and optimisation of product related properties of biogenic carbon carriers and (2) optimisation of market related properties are indispensable when respective technologies and biogenic carbon products should be introduced and diffused into the market.

6.4 Open questions and future research requirements

With regard to developing the European bioeconomy including the growing branch of bioenergy and the possibly upcoming branch of biomaterials the following questions remained unanswered and the following research requirements can be outlined:

- How can (1) a possible shift to smaller biobased materials production facilities than their fossil based counterparts and (2) a possible re-distribution of main chemicals production MS within the EU be modelled?
- What are drivers and barriers for using densified biogenic carbon carriers for advanced biobased materials production?
- How can empirical data regarding the down streaming of densified biogenic carbon carriers be produced in a harmonised and comparable way? How can this data or even estimate functions be generated with respect to carbon carrier quality and various frame conditions?
- Regarding the early commoditisation stage of wood pellets; what would be the best reference commoditisation process with respect to commodity and market similarity but better data availability?
- How can inefficient integration, with significant unobservable transaction costs and information barriers, be modelled?
- How can we quantify the theoretical advantages of a mature market with global sustainable wood pellet trade?
- What are possible future developments of the convergence process of small-scale heating with the large scale wood pellet market?
- How can social acceptance and participation for bioenergy and biochemical products and production systems be altered? What are current and future limitations and can they be translated and possible avoided in beforehand for other renewable energy production systems and systems that should support the efforts to achieve the Paris goals?
- Can we use relatively new scientific tools including web scraping and HTML-parsing to increase data availability and quality with regard to biogenic carbon commodity market diffusion analysis?

7 Conclusions

This work explores the development of European economic sectors in their possible shift from fossil to biogenic feedstock as a main and direct carbon input. Advanced biobased material scenarios for the 28 EU member states are constructed and incorporated into existing bioenergy scenarios. This helps to yield a better understanding of possibly relevant upcoming biogenic carbon demand within the European Union. To discuss the optimisation potential of feedstock sourcing and supply, the cost-effectiveness of important pre-treatment and densification technologies are assessed by applying a generic biomass-to-end-use chain model for comparing supply chain costs. Modern trade theory, econometric modelling techniques and time series analysis tools are used to quantify the current efficiencies of residential heating markets for European wood pellets.

In this thesis I find that biogenic carbon is and will remain crucial for the European economy up to 2050. While the bioenergy share within the renewable energy sector is, according to most of the official scenarios, expected to decline in the coming decades, this thesis supports the argument that advanced biobased materials have the potential to increase to levels at which they could substantially substitute fossil based materials.

However, the portfolio of products directly based on fossil fuels including materials, heat, electricity and transport fuels, the carbon demand to form the structure of chemicals and materials is limited to about one-tenth of European demand for these applications, and I can also outline a similar maximum and possible relevant share for the direct use of biogenic carbon. The production of biochemicals for plastics and of biogenic bitumen is identified as important upcoming economic activities which could result in additional biogenic carbon demand. The calculated range of biogenic carbon for advanced biobased materials indicates, on the one hand, a minor threat both to biogenic carbon for bioenergy as well as to other bioeconomy sectors not discussed in this thesis, such as the food and feed focused sectors and traditional wood-based sectors. On the other hand, it highlights the limited applicability of cascaded use of biogenic carbon, where bioenergy application is only a secondary process occurring after the initial application.

To optimise efficiency and cost-effectiveness of the allocation of biogenic carbon, currently available densification technologies such as pelletisation, torrefaction and pyrolysis have to be further diffused and introduced into the market. I find that these technologies could already reduce heating costs in Europe when biomass-to-end-use chains based on optimal densification plant sizes are considered. While wood pellets are deployed as cost-effective fuel for heating residential homes today it can be found that some combinations of feedstock and supply-and-distribution modes and distance for residential heating, coal co-firing and FT-synthesis could hold cost advantages if biomass is torrefied prior to pelletisation.

I can furthermore highlight that biomass densification does not only hold the potential to decrease costs of transportation especially for long-distance supply chains and less-efficient transport modes e.g. heavy goods vehicles; due to higher energy contents, densification technologies could also contribute to decreasing costs of storage due to their even greater effects on energy densities. With higher process temperatures than in torrefaction, fast-pyrolysis can convert high shares of cellulosic biomass into a liquid fraction, and supply chains based on bio-oil are estimated to be more expensive than chains based on pellets and torrefied pellets. Nonetheless, the deployment of bio-oil is discussed, especially for heating markets, where oil boilers still play a considerable role and the possibly relevant option of blending with conventional heating oil as a short-term transition option. To harness respective market entrance options, regulatory issues and issues regarding end-user handling when it comes to using more “coal-like” pellets have to be addressed for torrefied products and pyrolysis oil blending possibilities with heating oil should be explored.

Italian, Austrian, French, and German wood pellet markets for residential heating are found to be inefficiently integrated with occasional marginal profits for arbitrageurs. The commoditisation process seems to be limited by the market’s competitiveness and liquidity. To support the development of this energy commodity and the market’s efficiency, data availability and quality has to be improved to increase transparency and public perception with respect to fungibility (inter-changeability) of same-quality pellets independent of pellet colour or supply-chain affiliation, e.g. whether regionally or internationally traded.

Besides the necessity to increase competitiveness and liquidity of the wood pellet for small-scale heating markets, the risk of short to medium-term storage (several weeks to several months) has to be reduced. This could be achieved both by facilitating the acquisition of risk capital for building and using intermediary storage facilities and by encouraging innovation to help avoid losses and accidents in relation to storing solid biofuels. To avoid shortages a dedicated stock monitoring system could further reduce risks for both consumers and – in the long run - other market actors. Finally, financialisation of the residential wood pellet market (by further developing and strengthening futures products and price benchmarks but also by introducing harmonised approaches for the collection of residential wood pellet prices in consumer regions) could foster the development towards a competitive spatial equilibrium. This would increase access and affordability of wood pellets in the long term.

In this thesis I analyse and sketch out an economy-wide phase-out of non-renewable fossil carbon for the European Union up to 2050 and implications for the development and market diffusion of possible relevant biogenic carbon densification technologies and products. A main assumption of this work is that lignocellulosic biomass will play an increasingly important role in the discussed bioeconomy sectors in this time frame. Uncertainties with regard to this development can be discussed as rather low; a scenario without the commercialisation of respective conversion technologies, a clearly limiting factor, is not considered within this thesis.

Since there are so far no overall industry or policy targets to phase out fossil carbon of chemicals and materials, I construct scenarios to be able to quantitatively analyse different pathways for this upcoming bioeconomy sector. Production levels of most of the analysed advanced biomaterials in 2030 and 2050 are significantly higher in the moderate scenario when compared to today's levels, making the uncertainties regarding today's estimates less problematic. To avoid error propagation, biogenic carbon demand is not coupled to the production-level scenarios but is rather calculated separately based on process efficiencies of the different advanced biomaterials.

The techno-economic assessment and comparison of densified biogenic carbon carriers is based on technology performance parameters derived from recent projects and on current values to avoid uncertainties regarding technological learning. The resulting entry strategies for the current market of the pre-commercial densification technologies thus address the question not of *if* commercialisation and diffusion can be achieved, but rather *how*. Uncertainties regarding investment costs, scaling effects, and technical performances as well as those regarding downstreaming, including handling, transport, storage and conversion costs are still relatively high. Best available data and estimations from the R&D projects and related publications is used to minimise these insecurities, substantial data gaps are outlined.

The market diffusion of densified biogenic carbon carriers is analysed by the example of wood pellets – currently the most important densified bioenergy carrier. Market relevant data for this commodity is defined by short time periods and unknown errors, thus the results of the econometric modelling exercise have to be discussed critically. I mitigate the risk of misinterpretation by integrating extensive discussions with researchers and market experts. If and to which extent these lessons learned for European residential wood pellets markets can be generalised for other and upcoming gaseous, liquid and solid densified biogenic carbon products has to be investigated in future research.

8 Appendices

8.1 Abbreviations and nomenclature

AIC	Akaike's Information Criteria
AIEL	Associazione Italiana Energie Agroforestali
ARA	Amsterdam Rotterdam Antwerp
AT	Austria
BIC	Bayesian Information Criteria
CHP	Combined Heat and Power
CIF	cost, insurance, freight
CN	Combined Nomenclature
CO_2	Carbon Dioxide
CSE	Competitive Spatial Equilibrium
dBECs	densified bioenergy carriers
DE	Germany
DEPV	Deutscher Energieholz- und Pellet-Verband e.V.
DG	Directorate-General
EC	European Commission
EU	European Union
EUCO	European Council
FOB	Free on board
FR	France
FT	Fischer-Tropsch
GHG	Green-house-gas
HS	Harmonised System Nomenclature
HTU	Hydrothermal Upgrading
HVC	High Value Chemicals
IEA	International energy agency
IT	Italy
ITGS	International Trade in Goods Statistics
KBBE	Knowledge Based Bioeconomy
LTC	Long-term Contract
MASE	mean absolute scaled error
MS	Member State
NSAs	National statistics agencies
OECD	Organisation for Economic Co-operation and development
OLS	Ordinary Least Squares

OTC	Over the counter

PE	Polyethylene

PEF	Polyethylene furanoate

PHB	Polyhydroxybutyrate

PP	Polypropylene

PPI06	Pellet price index 2006

PS	Polystyrene

PUR	Polyurythane

PVC	Polyvinylchloride

RDP	Representative Distribution Pathway

RMSE	Root Mean Squared Error

SRC	Short rotation coppice

StO	Straw to pyrolysis oil

StP	Straw to pellets

StT	Straw to torrefied pellets

sARIMAx	seasonal Auto-regressive integrated moving average model with exogenous variables

TPS	Thermoplastic starch

TRL	Technological readiness level

VAT	value added tax

VOCs	volatile organic components

WtO	wood to pyrolysis oil

WtP	wood to pellets

WtT	wood to torrefied pellets

8.2 Units

J	Joule

t	tonne

kg	kilogramm

€	Euro

$	Dollar

8.3 References

Abibois, 2016. Le bois de chauffage est taxé à 10% | Se chauffer au bois | S'informer sur le bois en Bretagne [WWW Document]. URL http://abibois.com/se-chauffer-au-bois/le-bois-de-chauffage-est-taxe-a-10.html (accessed 4.13.16).

ACEA, 2013. Differences Between Diesel and Petrol | ACEA - European Automobile Manufacturers' Association [WWW Document]. URL http://www.acea.be/news/article/differences-between-diesel-and-petrol (accessed 10.19.16).

AEBIOM, 2015. AEBIOM Statistical Report 2015 - European Bioenergy Outlook - Key Findings.

Akaike, H., 1974. A new look at the statistical model identification. IEEE Transactions on Automatic Control 19, 716–723. doi:10.1109/TAC.1974.1100705

Alakangas, E., Asikainen, A., Grammelis, P., Hämäläinen, J., Haslinger, W., Janssen, R., Kallner, P., Lehto, J., Mutka, K., Rutz, D., Tullin, C., Wahlund, B., Weissinger, A., Witt, J., 2014. Biomass Technology Roadmap. european Technology Platform on Renewable Heating and Cooling.

Arpiainen, V., Alakangas, E., Kroon, P., Carbo, M., 2015. SECTOR working paper D3.7.

Arpiainen, V., Fagernäs, L., de Wild, P., Carbo, M., Pommer, L., 2014a. SECTOR working paper D3.6.

Arpiainen, V., Wilen, C., Carbo, M., Lemus, J., Pommer, L., Nordin, A., Adell, A., Maaskant, E., 2014b. SECTOR working paper D3.2.

Ba, B.H., Prins, C., Prodhon, C., 2016. Models for optimization and performance evaluation of biomass supply chains: An Operations Research perspective. Renewable Energy 87, 977–989. doi:10.1016/j.renene.2015.07.045

Bachmeier, L.J., Griffin, J.M., 2006. Testing for market integration crude oil, coal, and natural gas. The Energy Journal 55–71.

Barrett, C.B., Li, J.R., 2002. Distinguishing between Equilibrium and Integration in Spatial Price Analysis. Am. J. Agr. Econ. 84, 292–307. doi:10.1111/1467-8276.00298

Batidzirai, B., Mignot, A.P.R., Schakel, W.B., Junginger, H.M., Faaij, A.P.C., 2013. Biomass torrefaction technology: Techno-economic status and future prospects. Energy. doi:10.1016/j.energy.2013.09.035

Beyond20/20, 2017. Beyond 20/20 WDS - Affichage de tableau - Pégase – Granulés de bois, prix moyen pour un ménage, en euros TTC (01/2007-06/2015) [WWW Document]. URL http://developpement-durable.bsocom.fr/Statistiques/ReportFolders/reportFolders.aspx?sCS_referer=&sCS_ChosenLang=fr (accessed 2.7.17).

Bhutto, A.W., Qureshi, K., Harijan, K., Abro, R., Abbas, T., Bazmi, A.A., Karim, S., Yu, G., 2017. Insight into progress in pre-treatment of lignocellulosic biomass. Energy. doi:10.1016/j.energy.2017.01.005

Biermayr, P., 2016. Erneuerbare Energie in Zahlen 2015. Die Entwicklung Erneuerbarer Energie in Österreich Datenbasis 2014.

Billig, E., 2016. Bewertung technischer und wirtschaftlicher Entwicklungspotenziale künftiger und bestehender Biomasse-zu-Methan-Konversionsprozesse.

Bleier, J., 2012. Biobitumen - Bitumen-Ersatzprodukt auf nachwachsender Rohstoffbasis und darauf basierender Asphalt (Berichte aus Energie- und Umweltforschung No. 33/2013), Fabrik der Zukunft. BMVIT, Braunau/Inn.

Buerger, J., 2015. Preisstabilität oder -volatilität von forstlichen und industriellen Biomasse-Sortimenten am Beispiel ausgewählter Märkte. Wien.

Busch, R., 2014. Biobased Products Value Chain.

Campbell, N.A., Reece, J.B., Mitchell, L.G., 2005. Biology. Pearson, Benjamin Cummings.

Capros, P., 2010. THE NEW PRIMES BIOMASS MODEL.

Capros, P., De Vita, A., Tasios, N., Papadopoulos, D., Siskos, P., Apostolaki, E., Zampara, M., Paroussos, L., Fragiadakis, K., Kouvaritakis, N., others, 2013. EU Energy, Transport and GHG Emissions: Trends to 2050, Reference Scenario 2013. EC, Luxembourg.

Carretero Moreno, J., 2014. PELDEX.

Carus, M., 2012. Bio-based economy in the EU-27. Nova-Institute.

CEN, 2011. Final Report of CEN/BT/WG 209 "Bio-based products." EC, Brussels.

CESIO, 2014. European Committee of organic surfactants and their intermediates - newsletter, September 2014 CESIO news.

Channiwala, S.A., Parikh, P.P., 2002. A unified correlation for estimating HHV of solid, liquid and gaseous fuels. Fuel 81, 1051–1063. doi:10.1016/S0016-2361(01)00131-4

Clomburg, J.M., Crumbley, A.M., Gonzalez, R., 2017. Industrial biomanufacturing: The future of chemical production. Science 355, aag0804. doi:10.1126/science.aag0804

Cocchi, M., Nikolaisen, L., Junginger, M., Heinimö, J., Bradley, D., Hess, R., Jacobson, J., Ovard, L.P., Thrän, D., Hennig, C., others, 2011. Global Wood Pellet Industry Market and Trade Study.

Confederation of European Paper Industries, 2015. Biobased for growth. A public-private partnership on biobased industries. CEPI, Brussels.

Czernik, S., Bridgwater, A.V., 2004. Overview of Applications of Biomass Fast Pyrolysis Oil. Energy & Fuels 18, 590–598. doi:10.1021/ef034067u

Daioglou, V., Faaij, A.P.C., Saygin, D., Patel, M.K., Wicke, B., van Vuuren, D.P., 2014. Energy demand and emissions of the non-energy sector. Energy & Environmental Science 7, 482. doi:10.1039/c3ee42667j

Daioglou, V., Wicke, B., Faaij, A.P.C., van Vuuren, D.P., 2015. Competing uses of biomass for energy and chemicals: implications for long-term global CO2 mitigation potential. GCB Bioenergy 7, 1321–1334. doi:10.1111/gcbb.12228

Dammer, L., Carus, M., Raschka, A., Scholz, L., 2013. Market Developments of and Opportunities for biobased products and chemicals. Report written for Agentschap NL, reference.

de Wit, M., Faaij, A., 2010. European biomass resource potential and costs. Biomass and Bioenergy 34, 188–202. doi:10.1016/j.biombioe.2009.07.011

Devine-Wright, P., 2007. Reconsidering public attitudes and public acceptance of renewable energy technologies: a critical review. Manchester: School of Environment and Development, University of Manchester. Available at: http://www. sed. manchester. ac. uk/research/beyond_nimbyism.

EC, 2016a. Proposal for a directive of the european parliament and of the council on the promotion of the use of energy from renewable sources, COM(2016) 767 final.

EC, 2016b. Proposal for a directive of the european parliament and of the council amending Directive 2012/27/EU on energy efficiency, COM(2016) 761 final.

EC, 2016c. Comission Staff Working Document, Impact assessment, Sustainability of bioenergy. Accompanying the document "Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast)". (No. SWD(2016) 418 final Part 4/4).

EC, 2016d. Weekly Oil Bulletin - Energy - European Commission [WWW Document]. Energy. URL https://ec.europa.eu/energy/en/data-analysis/weekly-oil-bulletin (accessed 10.25.16).

EC, 2016e. Paris Agreement to enter into force as EU agrees ratification [WWW Document]. Climate Action - European Commission. URL http://ec.europa.eu/clima/news/articles/news_2016100401_en (accessed 2.6.17).

EC, 2010. BIOCHEM- Bio-based product market potential [WWW Document]. URL http://www.biochem-project.eu/download/toolbox/innovation/06/Bio-based%20product%20market%20potential.pdf (accessed 7.7.14).

EC, 2007. Cologne Paper, in: En Route to the Knowledge-Based Bio-Economy. Presented at the En Route to the Knowledge-Based Bio-Economy, Cologne.

EEA (Ed.), 2013. EU bioenergy potential from a resource efficiency perspective, EEA report. Off. for Off. Publ. of the European Union, Luxembourg.

Elbersen, B., Fritsche, U., Petersen, J.-E., Lesschen, J.P., Böttcher, H., Overmars, K., 2013. Assessing the effect of stricter sustainability criteria on EU biomass crop potential. Biofuels, Bioproducts and Biorefining 7, 173–192.

Elbersen, B., Startisky, I., Hengeveld, G., Schelhaas, M.J., Naeff, H., Böttcher, H., 2012. Atlas of EU biomass potentials. Deliverable 3.3: Spatially dertailed and quantified overview of EU biomass potential taking into account the main criteria determining biomass availability from different sources.

Engle, R.F., Granger, C.W.J., 1987. Co-Integration and Error Correction: Representation, Estimation and Testing. Econometrica Vol. 55, 251–276.

ENTRANZE, 2014. ENTRANZE database [WWW Document]. URL http://www.entranze.eu/ (accessed 5.19.14).

Estrela, R., Cate, J.H.D., 2016. Energy biotechnology in the CRISPR-Cas9 era. Current Opinion in Biotechnology 38, 79–84. doi:10.1016/j.copbio.2016.01.005

ETA, M.P.-B., Dolzan, P., ETA, A.G., LUT, J.H., UU, M.J., LUT, T.R., Walter, A., 2007. Global wood pellets markets and industry: policy drivers, market status and raw material potential.

EUCO, 2014. European Council (23 and 25 October 2014) - Conclusions, EUCO 169/14.

EurObservEr, 2016. Solid-biomass-barometer-2016.

EurObservEr, 2015. Biofuels-Barometer-2015.

EurObservEr, 2014. Biogas-Barometer-2014.

Europa Innova, 2010. BIOCHEM project. D2.3 - Report on the “Assessment of the Bio-based Products Market Potential for Innovation”. Final Report. EC.

European Comission, 2014. Where next for the European bioeconomy? EC, Luxembourg.

European Comission, 2012. Innovating for Sustainable Growth: A Bioeconomy for Europe. EC, Brussels.

European Comission, 2011. Bio-based economy in Europe: state of play and future potential - Part 2. EC, Brussels.

European Comission, 2002. Current situation and future prospects of EU industry using renewable raw materials. EC, ERRMA, Brussels.

European Commission, 2016. Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions: An EU Strategy On Heating And Cooling (No. SWD(2016) 24 final). Brussels, Belgium.

Eurostat, 2017a. International Trade - EU Trade Since 1988 by HS2,4,5 and CN8 [WWW Document]. URL http://epp.eurostat.ec.europa.eu/newxtweb/ (accessed 1.26.17).

Eurostat, 2017b. Eurostat database Energystatistics - Supply, conversion and utilisation (nrg_10) [WWW Document]. URL http://ec.europa.eu/eurostat/data/database (accessed 1.31.17).

EUROSTAT, 2016. Supply, transformation and consumption of renewable energies - annual data [WWW Document]. URL http://ec.europa.eu/eurostat/web/energy/data/database (accessed 6.17.16).

Eurostat, 2016. Database - Eurostat - Energy (nrg) [WWW Document]. URL http://ec.europa.eu/eurostat/web/energy/data/database?p_p_id=NavTreeportletprod_WAR_NavTreeportletprod_INSTANCE_QAMy7Pe6HwI1&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&p_p_col_id=column-2&p_p_col_count=1 (accessed 10.25.16).

Eurostat, 2015. User guide on European statistics on international trade in goods.

Fama, E., 1965. Random Walks in Stock Market Prices. Financial Analysts Journal 55–59.

FAO, 2015. Webinar feat. Douglas Bradley. Markets of pyrolysis oil from wood wastes.

Findlay, R., O'Rourke, K.H., 2003. Commodity market integration, 1500-2000, in: Globalization in Historical Perspective. University of Chicago Press, pp. 13–64.

Fleiter, T., Steinbach, J., Dengler, J., Ragwitz, M., Köhler, B., Reitze, F., Tuille, F., Hartner, M., Kranzl, L., Forthuber, S., Reiter, U., 2016. Mapping and analyses of the current and future (2020-2030) heating/cooling fuel deployment (fossil/renewables). Project for the European Commission.

Forsberg, G., 2000. Biomass energy transport: Analysis of bioenergy transport chains using life cycle inventory method. Biomass and Bioenergy 19, 17–30. doi:10.1016/S0961-9534(00)00020-9

Francescato, V., Antonini, E., Bergomi, L.Z., 2008. Wood fuels handbook. AEBIOM.

Gerssen-Gondelach, S.J., Saygin, D., Wicke, B., Patel, M.K., Faaij, A.P.C., 2014a. Competing uses of biomass: Assessment and comparison of the performance of bio-based heat, power, fuels and materials. Renewable and Sustainable Energy Reviews 40, 964–998. doi:10.1016/j.rser.2014.07.197

Gerssen-Gondelach, S.J., Saygin, D., Wicke, B., Patel, M.K., Faaij, A.P.C., 2014b. Competing uses of biomass: Assessment and comparison of the performance of bio-based heat, power, fuels and materials. Renewable and Sustainable Energy Reviews 40, 964–998. doi:10.1016/j.rser.2014.07.197

Goh, C.S., Junginger, M., Cocchi, M., Marchal, D., Thrän, D., Hennig, C., Heinimö, J., Nikolaisen, L., Schouwenberg, P.-P., Bradley, D., Hess, R., Jacobson, J., Ovard, L., Deutmeyer, M., 2013. Wood pellet market and trade: a global perspective. Biofuels, Bioprod. Bioref. 7, 24–42. doi:10.1002/bbb.1366

Goh, C.S., Junginger, M., Faaij, A., 2014. Monitoring sustainable biomass flows: General methodology development. Biofuels, Bioprod. Bioref. 8, 83–102. doi:10.1002/bbb.1445

Gold, S., Seuring, S., 2011. Supply chain and logistics issues of bio-energy production. Journal of Cleaner Production 19, 32–42. doi:10.1016/j.jclepro.2010.08.009

Hamelinck, C.N., Suurs, R.A.A., Faaij, A.P.C., 2005. International bioenergy transport costs and energy balance. Biomass and Bioenergy 29, 114–134.

Havlík, P., Schneider, U.A., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., Aoki, K., Cara, S.D., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., Obersteiner, M., 2011. Global land-use implications of first and second generation biofuel targets. Energy Policy 39, 5690–5702. doi:10.1016/j.enpol.2010.03.030

Held, A., Ragowitz, M., Sensfuss, F., Pudlik, M., Pfluger, B., Resch, G., Olmos, L., Ramos, A., Rivier, M., Kost, C., Senkpiel, C., Frank, P., Veum, K., Slobbe, J., Joode, J., 2014. Estimating energy system costs of sectoral RES and EE targets in the context of energy and climate targets for 2030.

Henrich, E., Dahmen, N., Niebel, A., 2015. BioBoost Deliverable 5.8. Study on energy carrier use for entrained flow gasification.

Hetemaeki, L., Lindner, M., Mavsar, R., Korhonen, M., 2014. Forest Bioenergy for Europe.

Hoefnagels, E.T.A., Junginger, H.M., Resch, G., Panzer, C., 2011. Long Term Potentials and Costs of RES-Part II: The Role of International Biomass Trade.

Hoefnagels, R., Junginger, M., Resch, G., Matzenberger, J., Panzer, C., Pelkmans, L., 2013. Development of a tool to model European biomass trade IEA Task 40.

Hruby, J., 2015. Pellets Price Analysis by Means of Cointegration. Wien.

http://ifbb.wp.hs-hannover.de/, [Internet], 2016. Institut für Biokunststoffe und Bioverbundwerkstoffe - Biopolymerplattform [WWW Document]. Institut für Biokunststoffe und Bioverbundwerkstoffe - Biopolymerplattform. URL http://ifbb.wp.hs-hannover.de/ (accessed 6.28.16).

Hyndman, R.J., Athanasopoulos, G., 2013. Forecasting: principles and practice. OTexts.

Hyndman, R.J., others, 2006. Another look at forecast-accuracy metrics for intermittent demand. Foresight: The International Journal of Applied Forecasting 4, 43–46.

Hyndmann, R.J., Khandakar, Y., 2008. Automatic Time Series Forecasting: The forecast Package for R.

IEA, 2016a. World Energy Outlook 2016, World Energy Outlook. IEA. doi:10.1787/weo-2016-en

IEA, 2016b. OECD - Renewables supply and consumption. OECD Publishing. doi:10.1787/data-00469-en

IEA, 2014. World Energy Outlook 2014, World Energy Outlook. IEA, Paris.

Iffland, K., Carus, M., de Bie, F., Diels, L., van Haveren, J., Willems, P., Ravenstijn, J., Vink, E., Wagemann, K., 2015. Definition, Calculation and Comparison of the “Biomass Utilization Efficiencies (BUE)” of Various Bio-based Chemicals, Polymers and Fuels.

IRENA, [Internet], 2015. Global Atlas [WWW Document]. Global Atlas For Renewable Energy. URL http://irena.masdar.ac.ae/ (accessed 7.13.15).

Johansen, S., 1997. Mathematical and Statistcal Modelling of Cointegration. European University Institute, Florence.

Junginger, M., Goh, C.S., Faaij, A. (Eds.), 2014. International Bioenergy Trade, Lecture Notes in Energy. Springer Netherlands, Dordrecht.

Kaeb, H., Aeschelmann, F., Dammer, L., Carus, M., 2016. Market study on the consumption of biodegradable and compostable plastic products in Europe 2015 and 2020 - Summary. Nova-Institute.

Kaltschmitt, M., Hartmann, H., Hofbauer, H. (Eds.), 2016. Energie aus Biomasse: Grundlagen, Techniken und Verfahren, 3., aktualisierte und erweiterte Auflage. ed. Springer Vieweg, Berlin Heidelberg.

Kim, N.S., Van Wee, B., 2011. The relative importance of factors that influence the break-even distance of intermodal freight transport systems. Journal of Transport Geography 19, 859–875. doi:10.1016/j.jtrangeo.2010.11.001

KIT, 2014. Biomass based energy intermediates bossting biofuel production - A European Research project on renewable energies.

Kluts, I., Wicke, B., Leemans, R., Faaij, A., 2017. Sustainability constraints in determining European bioenergy potential: A review of existing studies and steps forward. Renewable and Sustainable Energy Reviews 69, 719–734. doi:10.1016/j.rser.2016.11.036

Koppejan, J., Schaubach, K., Witt, J., Thrän, D., 2015. SECTOR working paper D10.2.

Kristöfel, C., Strasser, C., Morawetz, U.B., Schmidt, J., Schmid, E., 2014. Analysis of woody biomass commodity price volatility in Austria. Biomass and Bioenergy 65, 112–124. doi:10.1016/j.biombioe.2014.03.010

Kristöfel, C., Strasser, C., Schmid, E., Morawetz, U.B., 2016. The wood pellet market in Austria: A structural market model analysis. Energy Policy 88, 402–412. doi:10.1016/j.enpol.2015.10.039

Kwiatkowski, D., Phillips, P.C., Schmidt, P., Shin, Y., 1992. Testing the null hypothesis of stationarity against the alternative of a unit root: How sure are we that economic time series have a unit root? Journal of econometrics 54, 159–178.

Lamers, P., 2016. Developing the global bioeconomy: technical, market, and environmental lessons from bioenergy, 1st edition. ed. Elsevier, Cambridge, MA.

Lamers, P., Tan, E.C.D., Searcy, E.M., Scarlata, C.J., Cafferty, K.G., Jacobson, J.J., 2015. Strategic supply system design – a holistic evaluation of operational and production cost for a biorefinery supply chain. Biofuels, Bioprod. Bioref. 9, 648–660. doi:10.1002/bbb.1575

Lauk, C., Schriefl, E., Kalt, G., Kranzl, L., Wind, G., 2012. Studie "Save our Surface", Teilbericht 6: Bedarfs- und Produktionsszenarien von Nahrungsmitteln, Futtermitteln und stofflich sowie energetisch genutzer Biomasse in Österreich bis 2050. Klima- und Energiefond, Wien,Eisenstadt.

Ljung, G.M., Box, G.E., 1978. On a measure of lack of fit in time series models Biometrika, pp.297-303.

lko, 2016. Eckpunkte der Steuerreform 2015/2016 (Teil 2) | Landwirtschaftskammer - Steuer [WWW Document]. URL https://www.lko.at/?+Eckpunkte-der-Steuerreform-2015-2016-Teil-2+&id=2500,2333088 (accessed 4.13.16).

Lüschen, A., Madlener, R., 2013. Economic viability of biomass cofiring in new hard-coal power plants in Germany. Biomass and Bioenergy 57, 33–47.

Mantau, U., Steirer, F., Verkerk, H., Oldenburg, J., Leek, N., Saal, U., Prins, K., 2010. EUwood - Real potential for changes in growth and use of EU forests. Final report. Hamburg/Germany.

Matzenberger, J., Kranzl, L., Tromborg, E., Junginger, M., Daioglou, V., Sheng Goh, C., Keramidas, K., 2015. Future perspectives of international bioenergy trade. Renewable and Sustainable Energy Reviews 43, 926–941. doi:10.1016/j.rser.2014.10.106

Meerman, J.C., Ramírez, A., Turkenburg, W.C., Faaij, A.P.C., 2012. Performance of simulated flexible integrated gasification polygeneration facilities, Part B: Economic evaluation. Renewable and Sustainable Energy Reviews 16, 6083–6102. doi:10.1016/j.rser.2012.06.030

Mehmood, M.A., Ibrahim, M., Rashid, U., Nawaz, M., Ali, S., Hussain, A., Gull, M., 2017. Biomass production for bioenergy using marginal lands. Sustainable Production and Consumption, Sustainable Utilisation of Waste 9, 3–21. doi:10.1016/j.spc.2016.08.003

Mireles, I.H., van Horssen, A., van Harmelen, T., Hagen, E., 2015. BioBoost D6.4 Energy Carrier Chain LCA. Sustainability assessment of energy carriers.

Momani, B., 2009. Assessment of the Impacts of Bioplastics: Energy Usage. Worcester Polytechnic Institute, Worcester.

Nakada, S., Saygin, D., Gielen, D., 2014. Global Bioenergy Supply and Demand Projections: A working paper for REmap 2030. IRENA.

Nicoleit, T., Niebel, A., Funke, A., Lappas, A., Kalogiannis, K., Michaeilof, C., Iliopoulou, E., Iatridis, D., Fougret, C., Jordan, E., Kusche, S., 2016. BioBoost Deliverable 2.6. Final Report of WP2 summarizing the optimization of conversion technology processes: Pyrolysis, catalytic pyrolysis, hydrothermal carbonization.

nova-Institut, [Internet], 2014. BioBasedEconomy [WWW Document]. Project: KBBPPS. Pre-Standardisation Research for Bio-based Products. URL http://www.biobasedeconomy.eu/research/kbbpps/ (accessed 9.26.14).

nova-Institut GmbH, 2013. Production Capacities for Bio-Based polymers in Europe - Status Quo and Trends towards 2020.

OANDA, 2016. Forex-Handel | CFDs & Währungen online handeln | OANDA [WWW Document]. URL http://www.oanda.com/lang/de/ (accessed 12.22.15).

Obernberger, I., Thek, G., 2010. The Pellet Handbook, Earthscan.

OECD, IEA, 2016. OECD iLibrary - IEA Energy Prices and Taxes Statistics [WWW Document]. URL http://www.oecd-ilibrary.org/statistics;jsessionid=1umltcfhogups.x-oecd-live-02 (accessed 10.25.16).

OECD, IEA, 2015. IEA World Energy Statistics and Balances - OECD iLibrary [WWW Document]. URL http://www.oecd-ilibrary.org/energy/data/iea-world-energy-statistics-and-balances_enestats-data-en (accessed 3.23.15).

Olsson, O., 2012. Wood Fuel Markets in Northern Europe. Price Formation and Internationalization. Uppsala.

Olsson, O., Bruce, L., Hektor, B., Roos, A., Guisson, R., Lamers, P., Hartley, D., Ponitka, J., Hildebrand, D., Thrän, D., 2016a. Cascading of woody biomass: definitions, policies and effects on international trade. IEA Bioenergy Task40 Report.

Olsson, O., Hillring, B., Vinterbäck, J., 2011. European wood pellet market integration – A study of the residential sector. Biomass and Bioenergy 35, 153–160. doi:10.1016/j.biombioe.2010.08.020

Olsson, O., Lamers, P., Schipfer, F., Wild, M., 2016b. Developing the Global Bioeconomy, in: Chapter 7: Commoditization of Biomass Markets. Academic Press.

Olsson, O., Lamers, P., Schipfer, F., Wild, M., 2016c. Chapter 7 - Commoditization of Biomass Markets, in: Developing the Global Bioeconomy. Academic Press, pp. 139–163.

Organisation for Econmic Co-operation and Development, 2013. Working Party on Biotechnology. Policies for Bioplastics in the context of a bioeconomy. OECD, Vienna.

Osborn, D.R., Chu, A.P.L., Smith, J.P., Birchenhall, C.R., 1988. Seasonality and the order of integration for consumption Oxford Bulleting of Economics and Statistics.

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., others, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.

Padilla-Bernal, L., Thilmany, D.D., Loureiro, M.L., 2003. An empirical analysis of market integration and efficiency for US fresh tomato markets. Journal of Agricultural and Resource Economics 435–450.

Patel, M., Cramk, M., Dornburg, V., Hermann, B., Roes, L., Hüsing, B., Overbeek, L., Tarragni, F., Recchia, E., 2006. The BREW Project. Medium and Long-term opportunities and Risks of the

Biotechnological Production of Bulk Chemicals from Renewable Resources. Final Report. DG Research, Utrecht.

Patel, M., Zhang, X., Kumar, A., 2016. Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: A review. Renewable and Sustainable Energy Reviews 53, 1486–1499. doi:10.1016/j.rser.2015.09.070

Phillips, P.C.B., Ouliaris, S., 1990. Asymptotic Properties of Residual Based Tests for Cointegration. Econometrica 58, 165. doi:10.2307/2938339

Phillips, P.C.B., Perron, P., 1988. Testing for a Unit Root in Time Series Regression. Biometrika 75, 335–346. doi:10.2307/2336182

PlasticsEurope, [Internet], 2015. Plastics - the Facts 2015. An analysis of European latest plastics production, demand and waste data [WWW Document]. PlasticsEurope. URL http://www.plasticseurope.org/Document/plastics---the-facts-2015.aspx (accessed 7.7.16).

ProPellets, 2017. ProPellets Austria, Holzpellets - Wärme, die nachwächst - ProPellets Austria [WWW Document]. URL http://www.propellets.at/ (accessed 1.26.17).

Proskurina, S., Heinimö, J., Mikkilä, M., Vakkilainen, E., 2015. The wood pellet business in Russia with the role of North-West Russian regions: Present trends and future challenges. Renewable and Sustainable Energy Reviews 51, 730–740. doi:10.1016/j.rser.2015.06.051

Pudelko, R., Borzecka-Walker, M., Kühner, S., Pitzer, E., 2015. BioBoost Deliverable 1.3. Feedstock, potential, supply and logistic.

RAMON, 2017. Europa - RAMON - Classification List [WWW Document]. URL http://ec.europa.eu/eurostat/ramon/nomenclatures/index.cfm?TargetUrl=LST_NOM&StrGroupCode=CONCEPTS&StrLanguageCode=EN (accessed 1.31.17).

Resch, G., Held, A., Faber, T., Panzer, C., Toro, F., Haas, R., 2008. Potentials and prospects for renewable energies at global scale. Energy Policy 36, 4048–4056. doi:10.1016/j.enpol.2008.06.029

Richard, T.L., 2010. Challenges in scaling up biofuels infrastructure. Science 329, 793–796.

Rosenbloom, S., Butler, D.H., Walton, C.M., Skinner, R.E., 2012. Alternative Binders for Sustainable Asphalt Pavements. Transportation research board of the national academies, Washington, D.C.

Rotter, S., Rohrhofer, C., 2014. BioBoost Deliverable 4.1, logistic concept.

Salimon, J., Salih, N., Yousif, E., 2012. Industrial development and applications of plant oils and their biobased oleochemicals. Arabian Journal of Chemistry 5, 135–145. doi:10.1016/j.arabjc.2010.08.007

Scarlat, N., Dallemand, J.-F., Monforti-Ferrario, F., Nita, V., 2015. The role of biomass and bioenergy in a future bioeconomy: Policies and facts. Environmental Development 15, 3–34. doi:10.1016/j.envdev.2015.03.006

Schipfer, F., Kranzl, L., 2015. IEA Bioenergy - Task 40. Country Report for Austria 2014. Vienna University of Technology.

Schipfer, F., Kranzl, L., Leclère, D., Sylvain, L., Forsell, N., Valin, H., 2017. Advanced biomaterials scenarios for the EU28 up to 2050 and their respective biomass demand. Biomass and Bioenergy 96, 19–27. doi:10.1016/j.biombioe.2016.11.002

Schmidt, T., Seiringer, W., Kern, W., 2015. Standard-Dokumentation Metainformation zu den Außenhandelsstatistiken. Statistik Austria.

SECTOR, 2014. SECTOR Consortium Meeting Berlin.

Sgobbi, A., Nijs, W., De Miglio, R., Chiodi, A., Gargiulo, M., Thiel, C., 2016. How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. International Journal of Hydrogen Energy 41, 19–35. doi:10.1016/j.ijhydene.2015.09.004

ShipandBunker, 2015. The Future of Bunker Prices: Relative to Crude, MGO Will Be More Expensive, HFO Will Be Cheaper. Ship & Bunker.

Sikkema, R., Steiner, M., Junginger, M., Hiegl, W., Hansen, M.T., Faaij, A., 2011. The European wood pellet markets: current status and prospects for 2020. Biofuels, Bioproducts and Biorefining 5, 250–278.

statista, 2016. WTI and Brent crude oil: average annual spot prices 2015 | Statistic [WWW Document]. Statista. URL https://www.statista.com/statistics/209641/average-annual-spot-price-of-wti-and-brent-crude-oil/ (accessed 11.24.16).

Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sorlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347, 1259855–1259855. doi:10.1126/science.1259855

Stock, J.H., Watson, M.W., 1988. Testing for Common Trends. Journal of the American Statistical Association 83, 1097–1107. doi:10.1080/01621459.1988.10478707

Suganya, T., Varman, M., Masjuki, H.H., Renganathan, S., 2016. Macroalgae and microalgae as a potential source for commercial applications along with biofuels production: A biorefinery approach. Renewable and Sustainable Energy Reviews 55, 909–941. doi:10.1016/j.rser.2015.11.026

Svanberg, M., Olofsson, I., Flodén, J., Nordin, A., 2013. Analysing biomass torrefaction supply chain costs. Bioresource Technology 142, 287–296. doi:10.1016/j.biortech.2013.05.048

Tahir, M., Amin, N.S., 2013. Recycling of carbon dioxide to renewable fuels by photocatalysis: Prospects and challenges. Renewable and Sustainable Energy Reviews 25, 560–579. doi:10.1016/j.rser.2013.05.027

Tank Storage Magazine, 2012. Petrom opens new storage terminal in Romania. Tank Storage Magazine.

Thrän, D., Billig, E., Daniel-Gromke, J., Ponitka, J., Seiffert, M., Baldwin, J., Kranzl, L., Schipfer, F., Matzenberger, J., Devriendt, N., Dumont, M., Dahl, J., Bochmann, G., 2014. Biomethane. Status and Factors Affecting Market Development and Trade, Joint Study on behalf of IEA Bioenergy Task40 and Task37.

Thrän, D., Witt, J., Schaubach, K., Kiel, J., Carbo, M., Maier, J., Ndibe, C., Koppejan, J., Alakangas, E., Majer, S., Schipfer, F., 2016. Moving torrefaction towards market introduction – Technical improvements and economic-environmental assessment along the overall torrefaction supply chain through the SECTOR project. Biomass and Bioenergy. doi:10.1016/j.biombioe.2016.03.004

Trinh, T.N., Jensen, P.A., Dam-Johansen, K., Knudsen, N.O., Sørensen, H.R., Hvilsted, S., 2013. Comparison of Lignin, Macroalgae, Wood, and Straw Fast Pyrolysis. Energy & Fuels 27, 1399–1409. doi:10.1021/ef301927y

UN/FCCC, 2015. Adoption of the paris agreement.

United Nations Development Programme, 2015. World leaders adopt Sustainable Development Goals. UNDP.

Uslu, A., Faaij, A.P.C., Bergman, P.C.A., 2008. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy 33, 1206–1223. doi:10.1016/j.energy.2008.03.007

UStG, 2015. Umsatzsteuergesetz (UStG).

Valiante, D., Egenhofer, C., Berg, A., Infelise, F., Teusch, J., Centre for European Policy Studies (Brussels, B., European Capital Markets Institute, 2013. Price formation in commodities markets: financialisation and beyond.

Wageningen, [Internet], 2015. Bioasphalt with lignin in Zeeland - Wageningen UR [WWW Document]. URL https://www.wageningenur.nl/en/newsarticle/Bioasphalt-with-lignin-in-Zeeland.htm (accessed 3.24.15).

Warell, L., 2006. Market Integration in the International Coal Industry: A Cointegration Approach. The Energy Journal Volume 27, 99–118.

Wilson, C., Grubler, A., Bauer, N., Krey, V., Riahi, K., 2013. Future capacity growth of energy technologies: are scenarios consistent with historical evidence? Climatic Change 118, 381–395. doi:10.1007/s10584-012-0618-y

8.6 List of figures

8.7 List of tables

8.4 Appendix A

Table 14: Product names with non-vanishing share of non-energy use in the discussed data base. Source: (OECD and IEA, 2015)

Liquid	Solid	Gaseous
Naphtha	Anthracite	NGL
Fuel Oil	Coking coal	LPG
Oil shale oil sands	Other bituminous coal	Refinery gas
Motor gasoline	Lignite	
Gas diesel oil	Coke oven coke	
White spirits	Coal tar	
Other kerosene	BKB	

8.5 Appendix B

Table 15: Non-energy use of fossil fuels according to the 2013 reference scenario. Source: (Capros et al., 2013)

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Austria	1718	1716	1865	1968	2148	2098	2047	2022	2028	2061	2156
Belgium	6739	7516	7593	7520	7896	7879	7884	7965	8001	8074	8238
Bulgaria	1265	1069	443	619	785	799	810	812	811	797	807
Croatia	682	715	596	612	594	599	589	584	578	571	564
Cyprus	84	70	83	84	82	81	85	90	96	102	108
Czech_Republic	2188	3004	2767	2901	2989	2951	2986	3060	3098	3132	3145
Denmark	301	289	265	275	279	283	286	288	292	298	307
Estonia	180	182	37	39	43	45	45	48	49	50	51
Finland	1113	1328	1579	1599	1697	1720	1724	1727	1727	1727	1740
France	16225	14528	11996	11920	12023	12194	12351	12346	12047	11958	11946
Germany	31195	31327	29737	30940	30990	30223	29426	28597	27917	27488	27550
Greece	719	761	1108	1157	1295	1234	1222	1227	1211	1203	1229
Hungary	1579	2162	1977	1982	2176	2480	2746	2815	2803	2773	2726
Ireland	552	308	265	301	332	348	373	395	412	429	450
Italy	8429	8608	9560	9570	9796	9735	9816	9900	9977	10237	10491
Latvia	75	97	73	78	89	95	94	96	95	93	93
Lithuania	662	804	714	626	584	566	558	554	553	548	547
Luxembourg	12	21	17	17	17	17	16	16	16	16	16
Malta	0	20	10	10	10	10	11	11	11	11	11
Netherlands	10491	13013	17579	19188	18818	18033	18000	17912	17395	17309	17282
Poland	4357	4545	4775	5477	6045	6225	6375	6524	6624	6641	6583
Portugal	2334	2505	1741	1665	1724	1676	1625	1610	1586	1608	1686
Romania	1883	2437	1724	1606	1634	1675	1736	1738	1716	1700	1690
Slovak_Republic	1633	1524	1041	1037	1102	1145	1176	1187	1152	1114	1082
Slovenia	238	311	207	209	208	201	200	198	197	195	193
Spain	9407	8361	7041	7191	7537	7878	8014	8063	8067	8054	8133
Sweden	1731	2293	2005	1958	1958	1969	1993	2048	2084	2091	2098
Unitied_Kingdom	11323	11205	8084	8765	9445	9383	9357	9323	9215	9070	9006
EU28	117117	120718	114884	119316	122296	121539	121547	121156	119757	119350	119927

8.4 Appendix C – Input data for the generic biomass-to-end-use chain calculation

8.4.1 Analysing bioenergy sources

For this thesis wood chips and straw bales are assumed to be roadside ready for loading onto a trailer for the supply to a densification plant. I assume straw bales with water contents of 15%wb (moisture on wet basis) and wood chips of 30%wb, bulk densities of 193 kg m^{-3} and 276 kg m^{-3} and energy contents of 17.2 MJ kg^{-1} and 18.4 MJ kg^{-1} gross calorific value respectively (Francescato et al., 2008; Rotter and Rohrhofer, 2014). Yearly feedstock yields and accessibilities vary strongly depending on e.g. field productivity, average field size and agricultural practices for straw bundling. Pudelko et al., (2015) state a range based on a feedstock potential assessment of 0.7 t ha^{-1} to 5.5 t ha^{-1} for wheat straw. We use the average of 3.1 t ha^{-1} for the simulation, which is comparable to about 3.5 t ha^{-1} based on Gerssen-Gondelach et al., (2014b). A yearly wood chip residues yield of about 0.7 t ha^{-1} is adopted from Gerssen-Gondelach et al., (2014b) and a forest residue yield of 0.1 t ha^{-1} from (Svanberg et al., 2013) for the sensitivity analysis. A roadside collected straw bale price of 75€ t_{WM}^{-1} is discussed in Pudelko et al., (2015) when 20% of the potentially harvestable straw is left on the field (based on wet biomass). Due to fertiliser costs that have to be refunded when 100% of the produced straw is harvested, this price can go up to 100€ t_{WM}^{-1} and as low as 48€ t_{WM}^{-1} if 50% of straw is left on the field. In line with the same publication we assume a roadside price of 50€ t_{WM}^{-1} for wood chips.

Table 16: Biomass feedstock specifications based on (Rotter and Rohrhofer, 2014), (Francescato et al., 2008) (Pudelko et al., 2015), (Svanberg et al., 2013), (Gerssen-Gondelach et al., 2014b)

Feedstock	**Characteristic**	**Value**	**Unit**	**Sources**
Wheat straw	Bulk density (fresh)	193	kg/m^3	(Rotter and Rohrhofer, 2014), Table 6
Wood chips	Bulk density	276	kg/m^3	(Francescato et al., 2008), Table 1.6
Wheat straw	Roadside price (if 80% collected)	75,0	€/t	(Pudelko et al., 2015), Fig11
Wood chips	Roadside price	50	€/t	(Pudelko et al., 2015)
Wheat straw	Gross calorific value	17,2	MJ/kg	(Francescato et al., 2008), Table 2.7.1
Wood chips	Gross calorific value	18,4	MJ/kg	(Francescato et al., 2008), Table 2.7.1
Wheat straw	Moisture content	15	%	(Francescato et al., 2008), Table 1.6
Wood chips	Mositure content	30	%	(Francescato et al., 2008), Table 1.6
Wheat straw	Yield & accessability	3,095	t/ha*a	(Pudelko et al., 2015), p.24
Wood chips	Yield & accessability	0,0975	t/ha*a	(Svanberg et al., 2013), Table1
Wheat straw	Yield & accessability	3,488	t/ha*a	(Gerssen-Gondelach et al., 2014b), Table3
Wood chips	Yield & accessability	0,652	t/ha*a	(Gerssen-Gondelach et al., 2014b), Table3

Supply of feedstock takes place with either a tractor or a truck and an attached trailer. Parameters for the techno-economic evaluation of the feedstock supply step includes handling costs, variable costs per distance including labour and fuel, the maximal cargo capacity in tonnes and the design ratio of the transportation mode in [kg m^{-3}] indicating the minimum density of the transported good.

Lower densities lead to derating through not fully using the maximal cargo capacity. All values for feedstock supply are based on or directly taken from Rotter and Rohrhofer, (2014) who documented costs of straw and chips supply including derating effects. In their tables they compare different handling assets including front-end loaders, telescopic handler, forklift trucks and in case of wood chips, container tipping options and handling of roll-off containers.I adopt averages of 1.6 € t_{DM}^{-1} (based on dry biomass) and 3.9 € t_{DM}^{-1} for straw and chips respectively. Costs of different handling assets deviate from this average by 42% and 35% for the two feedstock types respectively. Waiting time costs of 33.1€ h^{-1} and 38.5€ h^{-1} are adopted for waiting trucks and tractors respectively while loading of one dry tonne straw are stated to last 1.3 minutes for straw and 1.9 minutes for chips. Distance variable costs range from about 0.2 € $t_{DM}^{-1}km^{-1}$ to 0.4 € $t_{DM}^{-1}km^{-1}$ depending on transport mode and transported feedstock.

Table 17: Feedstock supply mode specifications based on (Rotter and Rohrhofer, 2014)

Transport-mode	Characteristic	Value	Unit	Source
Tractor_chips	Design ratio	306	kg/m^3	(Rotter and Rohrhofer, 2014), Table11
Tractor_straw	Design ratio	202	kg/m^3	(Rotter and Rohrhofer, 2014), Table11
Truck_chips	Design ratio	217	kg/m^3	(Rotter and Rohrhofer, 2014), Table11
Truck_straw	Design ratio	217	kg/m^3	(Rotter and Rohrhofer, 2014), Table11
Tractor_straw	(Un-) loading cost	1,63	€/tDM	(Rotter and Rohrhofer, 2014), Table28
Tractor_chips	(Un-) loading cost	3,91	€/tDM	(Rotter and Rohrhofer, 2014), Table28
Truck_straw	(Un-) loading cost	1,63	€/tDM	(Rotter and Rohrhofer, 2014), Table28
Truck_chips	(Un-) loading cost	3,91	€/tDM	(Rotter and Rohrhofer, 2014), Table28
Tractor_straw	Variable cost_incl labour.u.fuel	0,34	€/tDMkm	(Rotter and Rohrhofer, 2014), Table24
Tractor_chips	Variable cost_incl labour.u.fuel	0,37	€/tDMkm	(Rotter and Rohrhofer, 2014), Table24
Truck_straw	Variable cost_incl labour.u.fuel	0,15	€/tDMkm	(Rotter and Rohrhofer, 2014), Table24
Truck_chips	Variable cost_incl labour.u.fuel	0,20	€/tDMkm	(Rotter and Rohrhofer, 2014), Table24
Truck_straw		0,66	€/tDM	(Rotter and Rohrhofer, 2014), Table 27
Truck_chips		1,05	€/tDM	(Rotter and Rohrhofer, 2014), Table 27
Tractor_straw		0,77	€/tDM	(Rotter and Rohrhofer, 2014), Table 27
Tractor_chips		1,22	€/tDM	(Rotter and Rohrhofer, 2014), Table 27

8.4.2 Biomass densification technologies

Adjusted for inflation (of yearly 2%) investment costs of about $4.1*10^6$ $€_{2014}$ are assumed for a conventional pellet plant with an output of 40 kt a^{-1} (Obernberger and Thek, 2010). In comparison, a SECTOR meeting concluded in 20 to $25*10^6$ $€_{2014}$ for a 100 kt a^{-1} torrefaction plant based on wood chips and a factor of 1.3 increased investment costs for using straw instead of chips as a lower density feedstock (Arpiainen et al., 2014b). Investment costs for about 150 kt a^{-1} syncrude oil output is estimated with $67*10^6$ $€_{2014}$ (Mireles et al., 2015). Investment costs are annualised using an interest rate of 10% and a depreciation time of 20 years for torrefaction and pelletisation as well as for the pyrolysis pathways. Lower interest rates of 6% are assumed in the discussed reference for traditional pelletisation and are also implemented in the simulation to reflect lower risks for the commercial technology.

Variable costs excluding feedstock costs and energy costs for the evaporation of surplus water content result in 1.7 € GJ^{-1} and 1.5 € GJ^{-1} specified on the energy content of the produced straw- and wood pellets respectively (Obernberger and Thek, 2010). Net calorific values of 15.2 MJ kg^{-1} for straw pellets, based on a reduction of the moisture content to 10%, and an average value of 16.0 MJ kg^{-1} for wood pellets based on Thrän et al., (2016) are assumed. According to Mireles et al., (2015) variable costs excluding feedstock and energy costs are adapted with 2.4 € GJ^{-1} and 1.8 € GJ^{-1} based on the energy content of produced torrefied straw- and wood pellets respectively. Batidzirai et al., (2013) discuss a range of net calorific values for torrefied straw pellets of 17 to 18 GJ t^{-1} while Thrän et al., (2016) summarise a range of 17 to 24 GJ t^{-1} for torrefied pellets based on wood chips. The averages are used for the simulation in this thesis. In Rotter and Rohrhofer, (2014) a detailed table for techno-economic assessment of a fast pyrolysis plant is outlined. Excluding energy- and feedstock about 4.5 € GJ^{-1} can be extracted as variable costs for operating a fast pyrolysis plant. I adopt this value for pyrolysis oil production based on straw and wood chips. Beside the detailed techno-economic summary in the discussed project deliverables, no comparative assessments of costs and product specifications based on the different feedstocks are outlined in the project. I adopt the results from fast pyrolysis experiments from Trinh et al., (2013) who state net calorific values of pyrolysis oil (without char) based on straw and wood of 17.6 GJ t^{-1} and 17.4 GJ t^{-1} respectively.

Table 18: Densified bioenergy carriers specifications based on (Francescato et al., 2008)(Rotter and Rohrhofer, 2014),(Thrän et al., 2016)(Batidzirai et al., 2013),(Trinh et al., 2013)

Energy carrier	**Characteristic**	**Value**	**Unit**	**Source**
Straw pellets	Bulk density	575	kg/m^3	(Batidzirai et al., 2013), p.127
Straw pellets	Energy content	15,2	MJ/kg	(Francescato et al., 2008), Table 2.7.1
Wood pellets	Bulk density	600	kg/m^3	(Thrän et al., 2016), Table 3
Wood pellets	Energy content	16	MJ/kg	(Thrän et al., 2016), Table 3
Torr. Straw pellets	Bulk density	695	kg/m^3	(Batidzirai et al., 2013), p.127
Torr. Straw pellets	Energy density	17,5	GJ/m^3	(Batidzirai et al., 2013), p.127
Torr. Wood pellets	Bulk density	675	kg/m^3	(Thrän et al., 2016), Table 3
Torr. Wood pellets	Energy content	20,50	MJ/kg	(Thrän et al., 2016), Table 3
Wheat straw	Bulk density	193	kg/m^3	(Rotter and Rohrhofer, 2014), p.15
Wood chips	Bulk density	275,5	kg/m^3	(Francescato et al., 2008),Table 1.6
Wheat straw	Energy content	14,2540	MJ/kg	(Francescato et al., 2008), Table 2.7.1
Wood chips	Energy content	12,1480	MJ/kg	(Francescato et al., 2008), Table 2.7.1
Biosyncrude_wheat	Bulk density	1150	kg/m^3	(Trinh et al., 2013), Table 5
Biosyncrude_wheat	Energy content	17,6	MJ/kg	(Trinh et al., 2013), Table 5
Biosyncrude_wood	Bulk density	1120	kg/m^3	(Trinh et al., 2013), Table 5
Biosyncrude_wood	Energy content	17,4	MJ/kg	(Trinh et al., 2013), Table 5

Mass yields on dry biomass basis for torrefaction are discussed in Koppejan et al. (2015). For three different technologies yields of about 79%, 76% and 81% are stated. I adopt the average of 79% for this thesis. Trinh et al., (2013) find mass yields of 60% and 68% for pyrolysis oil based on straw and wood respectively. For traditional pelletisation we assume no dry mass loss since no fractioning of the single components of the feedstock takes place.

Energy costs are calculated based on the differences between feedstock moisture content and a $10\%_{wb}$ dried input into the various processes. To assure comparability between the technologies and produced energy carriers we assume that all drying processes are performed with a natural gas furnace and an OECD average industry natural gas price of 23 € MWh^{-1} in 2014 (OECD, IEA, 2016). The torrefaction and fast pyrolysis process result in energy yields of about 89% for torrefaction and 56% for straw pyrolysis and 74% for wood chips pyrolysis respectively (Henrich et al., 2015; Koppejan et al., 2015). The energy content of the torrefaction gas is discussed to be sufficient to run the process auto thermally (SECTOR, 2014). The combustion energy of the pyrolysis gases also suffice for a self-sustained fast pyrolysis process (Henrich et al., 2015, p. 5).

Table 19: Densification technology characteristics based on SECTOR Meeting, Berlin 2014 and (Obernberger and Thek, 2010)(Arpiainen et al., 2014b)(Mireles et al., 2015),(Trinh et al., 2013)(Koppejan et al., 2015)

Technology	Characteristic	Value	Unit	Sources
StO	Investment costs	67	M€_2014	(Mireles et al., 2015), Annex J
StO	Reference Size	148056	t_out/year	(Mireles et al., 2015), Annex J
StO	Variable&general expenses	4,52	€2012/GJ_out	(Mireles et al., 2015), Annex J
StO	Energy yield	56%	GJ_out/GJ_in	(Trinh et al., 2013)
StP	Investment costs	4,1	M€_2014	(Obernberger and Thek, 2010)
StP	Reference Size	40000	t_out/year	(Obernberger and Thek, 2010)
StP	Variable&general expenses	1,74	€/GJ_out	(Obernberger and Thek, 2010)
StP	Energy yield	100%	GJ_out/GJ_in	(Obernberger and Thek, 2010)
WtP	Investment costs	4,1	M€_2014	(Obernberger and Thek, 2010)
WtP	Reference Size	40000	t_out/year	(Obernberger and Thek, 2010)
WtP	Variable&general expenses	1,54	€/GJ_out	(Obernberger and Thek, 2010)
WtP	Energy yield	100%	GJ_out/GJ_in	(Obernberger and Thek, 2010)
StT	Investment costs	29,25	M€_2014	SECTOR Meeting, Berlin 29.01.2014
StT	Reference Size	100000	t_out/year	SECTOR Meeting, Berlin 29.01.2014
StT	Variable&general expenses	2,39	€/GJ_out	(Arpiainen et al., 2014b), Table 10
StT	Energy yield	89%	GJ_out/GJ_in	(Koppejan et al., 2015), Table3.2
WtT	Investment costs	22,5	M€_2014	SECTOR Meeting, Berlin 29.01.2014
WtT	Reference Size	100000	t_out/year	SECTOR Meeting, Berlin 29.01.2014
WtT	Variable&general expenses	1,83	€/GJ_out	(Arpiainen et al., 2014b), Table 10
WtT	Energy yield	89%	GJ_out/GJ_in	(Koppejan et al., 2015), Table3.2
StO	Mass yield	60,0%	on dry mass basis	(Trinh et al., 2013)
StT	Mass yield	78,7%	on dry mass basis	(Koppejan et al., 2015), Table3.2
WtT	Mass yield	78,7%	on dry mass basis	(Koppejan et al., 2015), Table3.2
StP	Mass yield	100%	on dry mass basis	(Obernberger and Thek, 2010)
WtP	Mass yield	100%	on dry mass basis	(Obernberger and Thek, 2010)
WtO	Investment costs	67	M€_2014	(Mireles et al., 2015), Annex J
WtO	Reference Size	148056	t_out/year	(Mireles et al., 2015), Annex J
WtO	Variable&general expenses	4,52	€/GJ_out	(Mireles et al., 2015), Annex J
WtO	Energy yield	74%	GJ_out/GJ_in	(Trinh et al., 2013)
WtO	Mass yield	68,0%	on dry mass basis	(Trinh et al., 2013)

8.4.3 Distribution of bioenergy carriers

Distance costs for transportation are estimated based on Hoefnagels et al., (2013) and fuel consumption values are adopted from the same reference. I assume labor costs of 20.0 €*h^{-1} and a diesel price of 1.1 €*litre^{-1} which is equivalent to about 27.1 €*GJ^{-1} based on an energy density of 36.9 MJ*litre^{-1} (ACEA, 2013). Diesel prices are average household prices payed in 2014 in OECD countries (OECD, IEA, 2016). Prices for IFO380, used for ocean shipping can be roughly estimated using Brent crude oil prices as indicator: For 2014 and we assume an average Brent Oil price of

12.6 €*GJ^{-1} based on a barrel oil equivalent of 6.1 GJ*barrel^{-1} and an average Euro/US-Dollar exchange rate of 1.1 €*\$$^{-1}$ for the same time frame (statista, 2016; OANDA, 2016). According to ShipandBunker, (2015) IFO380 was priced with an discount at 70-80% to the crude price (in the time frame Nov.2012-Dec.2014). We further use the averaged 75% discount.

Furthermore for empty trips, which could be necessary to return the vehicle to the densification plant, only values for road and ship transport are calculated. An about 38% decreased fuel consumption has a significant impact on the variable costs (-12%) for road transport and a 17% IFO consumption to -7% for shipping, while for rail transport no difference between empty and full load trips is assumed based on the stated fuel and labor prices as well as input parameter from Hoefnagels et al., (2013). Specifying costs on the transported payload results in about 8.2€cent*t_{km}^{-1} for road, 0.7€cent*t_{km}^{-1} for rail and 0.02€cent*t_{km}^{-1} ocean transport respectively including empty backhaul.

No literature is known to the authors comparing loading and unloading options of pellets, torrefied pellets and pyrolysis oil. However, Hoefnagels et al., (2011) state cost ranges of 1.1-2.7 €*t^{-1} for transshipment to truck and ships and 1.9 to 4.5 €*t^{-1} to rails. I adopt the averages of 1.8 €/t and 3.0 €/t respectively for all bioenergy carriers.

Furthermore no costs for dedicated wood pellet silos or pyrolysis oil storage tanks could be acquired. Rotter and Rohrhofer, (2014) state investment costs of 7.8*10^5 €$_{2012}$ for a covered intermediary storage of 7*10^3 m³. Tank Storage Magazine, (2012) states 26*10^6 €$_{2012}$ costs for an 11*10^3 m³ storage for petroleum products. Operation and maintenance costs shares of 7.6% of the investment costs per year are adopted from Rotter and Rohrhofer, (2014). This results in yearly storage costs of about 15.6 €$_{2014}$*m^{-3} for solid bioenergy carriers and 34.5 €$_{2014}$*m^{-3} for pyrolysis oil. Assuming wood pellets to be stored we derive daily costs of 7 €cent*t^{-1} which is comparable to the estimated 8 €cent*t^{-1} stated in Hoefnagels et al., (2011). No comparative assessment for liquid bioenergy carries could be found in literature.

Table 20: Bioenergy carrier distribution characteristics based on (Rotter and Rohrhofer, 2014)(Hoefnagels et al., 2013),(Tank Storage Magazine, 2012)

Transport-mode	Characteristic	Value	Unit	Source
Ocean	Design ratio	600	kg/m^3	(Hoefnagels et al., 2013), Table 5
Rail	Design ratio	400	kg/m^3	(Hoefnagels et al., 2013), Table 5
Rail_oil	Design ratio	684	kg/m^3	(Rotter and Rohrhofer, 2014), Table 36
Truck	Design ratio	225	kg/m^3	(Hoefnagels et al., 2013)
Truck_oil	Design ratio	563	kg/m^3	(Rotter and Rohrhofer, 2014), Table37
Ocean_oil	Design ratio	600	kg/m^3	(Hoefnagels et al., 2013)
Truck	(Un-) loading cost	3,88	€2014/t	(Hoefnagels et al., 2013), Table 3-5
Rail	(Un-) loading cost	6,30	€2014/t	(Hoefnagels et al., 2013), Table 3-5
Ocean	(Un-) loading cost	3,88	€2014/t	(Hoefnagels et al., 2013), Table 3-5
Truck_oil	(Un-) loading cost	3,88	€2014/t	(Hoefnagels et al., 2013), Table 3-5
Rail_oil	(Un-) loading cost	6,30	€2014/t	(Hoefnagels et al., 2013), Table 3-5
Ocean_oil	(Un-) loading cost	3,88	€2014/t	(Hoefnagels et al., 2013), Table 3-5
Truck_oil	Variable cost_incl labour.u.fuel	0,0818	€2014/t*km	(Hoefnagels et al., 2013)
Truck	Variable cost_incl labour.u.fuel	0,0818	€2014/t*km	(Hoefnagels et al., 2013)
Rail	Variable cost_incl labour.u.fuel	0,0074	€2014/t*km	(Hoefnagels et al., 2013)
Ocean	Variable cost_incl labour.u.fuel	0,0022	€2014/t*km	(Hoefnagels et al., 2013)
Rail_oil	Variable cost_incl labour.u.fuel	0,0074	€2014/t*km	(Hoefnagels et al., 2013)
Ocean_oil	Variable cost_incl labour.u.fuel	0,0022	€2014/t*km	(Hoefnagels et al., 2013)
Storage	Covered storage	15,56	€2014/m^3*a	(Rotter and Rohrhofer, 2014), Table30
Storage_oil	Tank farm	34,48	€2014/m^3*a	(Tank Storage Magazine, 2012)

8.4.4 Bioenergy conversion costs

For small scale combustion European averages for heating systems are calculated using weighted averages from three exemplary countries considered as a representative cross-section (Spain, Germany and Rumania) based on data from the ENTRANZE database (ENTRANZE, 2014). With estimated 1,800 heating hours per year operation and maintenance (O&M) as well as annuities are calculated for wood pellets and oil based heating systems. Average utility costs of 22.4 €*GJ^{-1} derived heat (with about 8% O&M) and 15.3 €*GJ^{-1} (with about 9% O&M) are estimated for pellet and oil boilers respectively. Conversion efficiency are derived from the same database for the installation year 2014 for single and central pellets boilers (84%) and for single, central and condensing central oil boilers (80%). An average tax of 13% was payed for wood pellets in the main EU residential wood pellets consuming countries in 2014 (see **Chapter 6**). I adopt this value for all densified bioenergy carriers in the residential heating case.

Arpiainen et al., (2015) estimate economics of co-firing coal with traditional and torrefied wood pellets. By using harmonised cost-figures of a 400 MW$_{el}$ (MW electricity production) power plant co-fired with 10% wood pellets, extra yearly utility costs are estimated at 2.65*10^6 €$_{2013}$ and 0.79*10^6 €$_{2013}$ for the two densification technologies excluding the fuel costs respectively. These numbers are based on 2.16 PJ yearly biomass input and 40% efficiency for coal, torrefied pellets and

39.7% efficiency for white pellets. Lüschen and Madlener, (2013) estimates cost composition for electricity production from coal fired power plants. With 100% coal firing costs are estimated at 71 $€_{2009}$*MWh_{el} with 49% share in utility costs based on a 600 MW_{el} sized power plant with an efficiency of 40% and 6,000 full-load hours. Co-firing of 10% pyrolysis oil is possible in coal-fired power plants with minor adjustments (Czernik and Bridgwater, 2004), I assume no extra costs. I derive utility costs of about 14.6 €*GJ_{el}^{-1}, 11.9 €*GJ_{el}^{-1} and 10.7 €*GJ_{el}^{-1} for wood pellets, torrefied wood pellets and pyrolysis oil co-firing respectively.

For gasification and FT-synthesis efficiencies of 49%,43% and 47% based on a comparative study from Meerman et al., (2012) for coal, pellets and torrefied pellets are adopted respectively. Utility costs of 10.3 $€_{2014}$*GJ_{FT}^{-1}, 13.8 $€_{2014}$*GJ_{FT}^{-1} and 11.5 $€_{2014}$*GJ_{FT}^{-1} are derived for a 2.0 GW_{th} (thermal) coal equivalent input gasification and FT-synthesis plant. Furthermore electricity is co-produced with 10%, 12% and 11% efficiencies for the three solid energy carriers which is assumed to be sold to the European electricity market price. For pyrolysis oil to Fischer Tropsch diesel I adopt the coal fired key figures, assuming that no derating of the capacity takes place.

8.4.5 Energy reference prices

Reference prices for residential heating are calculated based on data from the ENTRANZE database (ENTRANZE, 2014) and the discussed representative European cross-section. Average utility costs are estimated with 12.8 €*GJ^{-1} and a share of 6% coal, 9% electricity, 20% oil and 54% gas boilers as well as 11% district heating connected residents. An average OECD-EU household bitumeus coal price of 6.3 $€_{2014}$*GJ^{-1} (OECD, IEA, 2016), EU28 average household prices for 19.5 $€_{2014}$*GJ^{-1} payed for electricity, 19.2 $€_{2014}$*GJ^{-1} payed for natural gas (Eurostat, 2016) and 24.1 $€_{2014}$*GJ^{-1} for domestic fuel oil (EC, 2016d) are further used. This results in average heating costs of 32.2 $€_{2014}$*GJ^{-1}. With minimum and maximum fuel values a range between 29.3 and 40.5 $€_{2014}$*GJ^{-1} can be estimated.

For co-firing an average 2014 electricity prices without taxes and levies for the largest consumer group from Eurostat, (2016) of 15.6 €cent*kWh^{-1} are used as a reference. The gasification and FT-diesel production path is compared to average EU28 diesel prices without taxes and levies from EC, (2016d) with 18.7 $€_{2014}$*GJ^{-1} assuming a net calorific value of 10.1 kWh*$liter^{-1}$ (Biermayr, 2016). Average diesel prices ranged between 15.5 and 19.6 €*GJ^{-1} in 2014.

Table 21: Bioenergy conversion characteristics based on (OECD, IEA, 2016)(ENTRANZE, 2014)(Arpiainen et al., 2015)(Lüschen and Madlener, 2013)(Meerman et al., 2012)(EC, 2016d),(Held et al., 2014)

Technology	Characteristic	Value	Unit	Sources
Res_pell	without fuel	22,4	€/GJ_out	(ENTRANZE, 2014)
Res_torrpell	without fuel	22,4	€/GJ_out	(ENTRANZE, 2014)
Res_syn	without fuel	15,3	€/GJ_out	(ENTRANZE, 2014)
Co_pell	without fuel	14,6	€2014/GJ_out	(Lüschen and Madlener, 2013), Fig.5
Co_torrpell	without fuel	11,9	€2014/GJ_out	(Lüschen and Madlener, 2013), Fig.5
FT_pell	without fuel	13,8	€2014/GJ_out	(Meerman et al., 2012), Fig.13
FT_torrpell	without fuel	11,5	€2014/GJ_out	(Meerman et al., 2012), Fig.13
FT_syn	without fuel	10,3	€2014/GJ_out	(Meerman et al., 2012), Fig.13
Co_syn	without fuel	10,7	€2014/GJ_out	(Lüschen and Madlener, 2013), Fig.5
Ind_pell		33,3	€2014/GJ_out	(Held et al., 2014)
Ind_torrpell		33,3	€2014/GJ_out	(Held et al., 2014)
Ind_syn		33,3	€2014/GJ_out	(Held et al., 2014)
Co_torrpell	Yield cofired power plant	40%		(Arpiainen et al., 2015)
Co_pell	Yield cofired power plant	40%		(Arpiainen et al., 2015)
FT_pell	FT Efficiency HHV	55%		(Meerman et al., 2012), Table.1
FT_torrpell	FT Efficiency HHV	58%		(Meerman et al., 2012), Table.1
FT_syn	Energy Yield	59%		(Meerman et al., 2012), Table.1
Co_syn	Energy Yield	40%		(Arpiainen et al., 2015)
Ind_pell		89%		(Held et al., 2014)
Ind_torrpell		89%		(Held et al., 2014)
Ind_syn		89%		(Held et al., 2014)
Res_pell	Efficiency	84%		(ENTRANZE, 2014)
Res_torrpell	Efficiency	84%		(ENTRANZE, 2014)
Res_syn	Efficiency	80%		(ENTRANZE, 2014)
FT_pell	FT Efficiency HHV	12%		(Meerman et al., 2012), Table.1
FT_torrpell	FT Efficiency HHV	11%		(Meerman et al., 2012), Table.1
FT_syn	Energy Yield	10%		(Meerman et al., 2012), Table.1
Ind_pell		25%		(Held et al., 2014)
Ind_torrpell		25%		(Held et al., 2014)
Ind_syn		25%		(Held et al., 2014)
Diesel	EU28 2014 average w/o taxes and levies	18,7	€2014/GJ	(EC, 2016d)
Electricity	EU28 average electricity price for largest consumers w/o taxes and levies	13,6	€2014/GJ	(Eurostat, 2016)
Residential	EU28 average heating costs for residential	32,2	€2014/GJ	(Held et al., 2014) (EC, 2016d) (Eurostat, 2016) (OECD, IEA, 2016)