Master's Thesis

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Location specific factors that shape the future rollout of advanced biofuel production in the European Union

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Abstract

The EU aims to become climate neutral by 2050. Based and on the importance of the transport sector for decarbonization strategies, European policies and regulations foster the development and establishment of advanced biofuels. Considering the current slack in development of advanced biofuels, acceleration of development, and a pan-European rollout of such fuels, are urgently needed. The importance of locational conditions and location specific factors for sustainable energy production, as well as their relevance for a potential large-scale deployment has been pointed out. Yet the predominant lack of information about which location specific factors will shape this required deployment in the EU is ubiquitous and constitutes the research question's objective. To approach this blind spot, the industrial location theory serves as an analytical framework in this thesis and supports realizing the research purpose. Based on the theory's assumptions of transport cost, agglomeration, infrastructure, and policy conditions being vital for industrial location decisions, dynamics, interrelationships, and interdependencies in the field were investigated. Three different approaches were utilized to answer the research question, starting with a location analysis of plants currently producing intermediates or final fuels using lignocellulosic feedstock. Moreover, a review of supply chain modelling studies allowed for deductions relating to optimization viewpoints. Simultaneously, semi-structured interviews with 17 experts from relevant industries contributed to necessary in-field insights and perspectives. The study identified distinct location specific factors. Those factors center around case specific opportunities for transport- and production cost reduction and point at feedstock availability and feedstock proximity as fundamental prerequisites. Subsequently, making use of existing (transportation-) infrastructure and industrial areas was found to be vital. Strategies including Retrofitting, Co-location, Co-processing were identified to be elementary for reducing advanced biofuel production cost. Centralized- and distributed supply chains designs emerged as most likely options for the future rollout. Centralized and simple supply chains for smaller scale production plants and distributed supply chains for larger plant capacities and more complex supply chains. The thesis concludes that using existing infrastructure, suitable industries and feedstock abundant areas constitute important and foundational location specific factors. Facilitating the rollout requires for scenario and case specific policy instruments. Yet, the results indicate that the rollout will not take place in the needed time.

Keywords: Advanced Biofuels, Industrial location, Agglomeration, Location specific factors, EU

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Abbreviation List

Abbreviation	Definition
CAPEX	Capital Expenditures
CtL	Carbon to Liquid
EU	European Union
FAME	Fatty Acid Methyl Ester
FQD	Fuel Quality Directive
GHG	Greenhouse Gas
HEFA	Hydroprocessed esters and fatty acids
IEA	International Energy Agency
ILUC	Indirect Land Use Change
JRC	Joint Research Center
LR	Literature Review
OPEX	Operational Expenditure
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non-biological Origin
RCF	Renewable Carbon Fuels
SAF	Sustainable Aviation Fuel
TRL	Technological Readiness Level
UCO	Used Cooking Oil

1. Introduction

To limit global warming to maximum 2 ^{0}C, and preferably below to 1.5 ^{0}C, compared to pre-industrial levels, as agreed upon in the Paris Agreement (UNFCC, 2015), requires a large and rapid reduction in greenhouse gas (GHG) emissions towards climate neutrality around 2050 (IPCC, 2022). To reach those targets in the European Union (EU), the EU Green Deal (2019), a large set of policy initiatives, was approved in 2020. The Green Deal and its intended changes on policy, governance, social and economic level, focus on making Europe climate neutral by 2050 (European Commission, 2019). Disruptive thinking and disruptive technologies are inevitable to create the change, which is needed, since the current policy framework would only reduce GHG emissions around 60% by 2050 (European Commission, 2019). Those disruptive actions and their final goal of climate neutrality require all-encompassing action on every level, including a circular economy and bioeconomy. According to the European Commission, bioenergy use could increase up to 20% of overall energy use by 2050 (Tsiropoulos et al., 2020). To reach these all-encompassing transitions, around 25 years will be needed to achieve the full mobilization and transformation of industry, including value- and supply chains (European Commission, 2019).
Within the realms of supranational climate targets, such as the Green Deal, the transport sector was identified to be pivotal for contributing to pan European decarbonization strategies (Chiaramonti et al., 2021). The sector, that encompasses road, rail, and aviation, contributes to over a quarter of GHG emissions in the EU. Among measures to reduce GHG emissions in transport, that include efficiency improvement and electrification, biofuels are essential for sectors with few decarbonization alternatives such as aviation and shipping. Biofuels, that represent a part of the so-called bioeconomy, are facilitated by multiple promotion policies, that are adapted over the years.
In 2009 the first RED (2009/28/EC) defined targets, such as increasing the share of energy from renewable sources to 20% in overall community energy consumption. Furthermore, the mandatory minimum target for the share of biofuels in transport petrol and diesel consumption for member states was lifted to 10%, to be reached by 2020 (European Commission, 2009). In the 2015 ILUC amendment – (Directive (EU) 2015/1513), biofuels and bioliquids, produced from food and feed crops, were capped at 7% leaving the focus, among other sources of renewable energy, on advanced biofuels (or second-generation biofuels) produced from non-food feedstocks (European Commission, 2015).

The RED_II, which is the recast of the RED, provides the outline for renewable energy targets to 2030. According to the goals set in the RED_II, by 2030, EU member states must achieve a target of 14 % share of renewable transport fuels. There is also a dedicated sub-target for advanced biofuels, starting at a minimum share of final consumption of energy in the transport sector, starting at 0,2 % in 2022, at least 1 % in 2025 and at least 3,5 % in 2030 (European Commission, 2018). Biofuels and bioliquids, produced from food and feed crops remain capped at 7 %. Furthermore, biofuels produced from non-food feedstocks without advanced processing technology, that are included in Annex IX-B of the RED_II, are capped at 1,7 %. Advanced biofuels produced from Annex IX-A-feedstocks and especially lignocellulosic advanced biofuels will gain in importance in the future (European Commission, 2021c).

A provisional agreement for a third version of the RED (RED_III) was reached in March 2023 and advances the RED_II ambitions. RED_III will reinforce regulations for renewable energy use in the transport sector (European Commission, 2023b). According to this most up-to-date revision of the RED, GHG reduction of 14.5% are targeted, next to a 29% share of renewable energy consumption and the increase a combined sub-target for advanced biofuels of 5.5%. (European Commission, 2023b). All these goals are set for feedstock of biological origin, whereas RFNBOs are targeted to at least contribute 1% (European Commission, 2023b).

Looking at the impact of renewable energy policies in the EU, it can be observed that these have already been effective in increasing the share of renewable energy in transport to 10.2% by 2020, thereby in fact meeting the target set in Directive 2009/28/EC on the promotion of the use of energy from renewable sources (Eurostat, 2022). It can also be observed that implementing measures to reduce GHG emissions has a significant impact, especially in the transport sector. Nevertheless, additional measures will be needed to align the transport sector to the EU climate targets. Decarbonization of the transport sector can be significantly facilitated by the promotion of renewable fuel technologies, thereby ensuring security of energy supply and energy diversification (European Commission, 2022). Advanced biofuels represent the most feasible option to do that. Installed production capacity today is still very small (0.43 Mt/y), increasing to 1.85 Mt/y if planned capacity is considered (European Commission, 2022). A lack of investment in the respective advanced fuel industry, together with aligned policies is pointed out by literature. Ramping up the production capacity of advanced biofuels with significant investments and mitigation of regulatory uncertainty is therefore urgently needed (Chiaramonti et al., 2021; IEA, 2020; IRENA, 2019).

1.1 Problem description and research gap

Model projections on the future development of biofuels exist but lack in common attributes, with some focusing on the global scale, biomass availability or conversion capacity. Availability of detailed future projections, both on supply and especially demand, are marginal. Due to the complexities accompanying medium to long-term scenario modellings in fuels and especially alternative fuels, models must harness different angles of available information, such as detailed analysis of feedstock availability, Technological Readiness Level (TRL) and industrial potential. Framed by state-of-the-art policy conditions or sometimes even based on arbitrary assumptions on agriculture-, industry-, energy- and climate policies presumably apparent in the future, such future modellings are shaped by best estimates.

A recent meta-analysis review of published advanced biofuels scenarios in the EU depicts these system immanent uncertainties. The ranges of projections that Chiaramonti et al. (2021) portray are vast, ranging from 1.2 - 4.8 Mtoe in 2030, up to 31.0 – 133.7 Mtoe by 2050. Adding to the immanent uncertainties, it stands out that none of the mentioned projections and considerations provide insight in the geographical locations of feedstock supply, conversion, and end-use markets. This creates a significant blind spot. Van Der Hilst (2018, p. 164) emphasizes, that "the sustainability of biomass production for energy depends on site-specific biophysical and socio-economic conditions". Likewise, Thrän et al. (2020, p. 1) stress that „bioenergy provision is embedded in national and regional energy systems, industrial infrastructure, land uses and value chains, but also energy system transformation strategies", thereby implicitly emphasizing the importance of locational conditions and location specific factors also for (lignocellulosic) advanced biofuel production facilities.

Location specific choices have been investigated for existing first-generation ethanol (Haddad, Taylor, & Owusu, 2010), and biodiesel plants (Fortenbery, Deller, & Amiel, 2013) located in the US. Among other factors, ethanol plants were found to locate close to biomass and biodiesel plants do tend to spatially cluster together in certain geographic locations (Fortenbery et al., 2013, p. 131). The research at hand ought to investigate, if similar findings and location factors can be concluded for European advanced biofuel plants, as well. Several existing studies have investigated the market development of biofuels within Europe but provide limited insights in the underlying locational factors (IEA, 2021, 2022a; IRENA, 2014). There are approaches to get hold of energy systems of predefined scopes in the EU, however those keeping the focus of intersectoral observations (Del Granado et al., 2020). The main reason is that the energy system models used to make these scenario projections, lack geographic details. Results are often limited to the EU as a single region. Detailed integrated supply chain management models on the other hand, do provide such details but are often limited to individual supply chains (Awudu & Zhang, 2012; Mafakheri & Nasiri, 2014; Sokhansanj, Kumar, & Turhollow, 2006) or individual regions, such as Sweden (De Jong et al., 2017) or Serbia (Bojic at al., 2017) and do not consider the EU climate policy ambitions beyond 2030. To overcome the shortcomings of individual models, Mandley et al., (2022) increased the geographic and market details for bioenergy deployment in Europe using a combined modeling approach. Nevertheless, they find that locational factors, including infrastructure, are not properly addressed in their approach and that more details are needed about what shapes these kinds of developments. Therefore, more insights are needed in the potential geographic deployment of advanced biofuels and the underlying locational factors that shape the future rollout of advanced biofuel production in the European Union.

1.2 Aim and research questions

Based on the foregoing exemplifications, the lack of knowledge about reasonable and efficient locations of advanced biofuels biorefineries, stands out. For this reason, the objective of this research is to determine location specific factors that will be crucial for the future roll-out of lignocellulosic advanced biorefineries. Hence, the main research question is as follows:

RQ1: **What are the most important location specific factors, relevant for the European future rollout of biorefineries focused on producing lignocellulosic advanced biofuels?**

To approximate the objective systematically the following sub research questions will be addressed to accommodate for the complexity of this blind spot within advanced biofuel research and provide inputs for answering the main RQ. The sub-questions aim at providing more clarity in the opaque field of lignocellulosic advanced biofuels. By also addressing topics that are not directly related to the main research question at first sight, such as RQ1.1, relevant context for the RQ is established. The sub-questions accompanying the main RQ are as follows:

RQ1.1: *How much advanced biofuel is currently deployed and what are the projected future developments regarding advanced biofuel deployment for 2030, respectively 2050 in the EU?*

RQ1.2: *Where are current plants located and what are observable circumstances surrounding their current location?*

RQ1.3: *What are key determining factors for locating biorefineries identified in modelling studies and how do they relate to the factors for location decisions?*

RQ1.4: *How do experts perceive this upcoming market and what factors do they consider crucial for the future rollout?*

The results of this thesis will be used as an input to supply chain modelling of advanced biofuels in the EU. Furthermore, insights in locational factors are valuable and can be used for a variety of objectives, such as regional or local impact assessments or targeted policy development on European and member state level. Investment decisions in infrastructure profit from reduced uncertainties. Among others, those contributions accommodate clarity in the field and bear the potential to support the acceleration of lignocellulosic advanced biofuel rollout in the EU.

2. Theoretical Background

This chapter focusses on depicting the theoretical framework for grasping the research topic at hand. Due to the explorative nature of this thesis topic's intricacies, a combination of concepts and frameworks will be used to approach the topic and make it tangible. Firstly, the key terms *advanced biofuel* and *lignocellulosic advanced biofuel* will be explained, defined and contextualized. Subsequently, Energy System Modelling (ESM) will be explained. Those allow for a macro-perspective view on European wide energy considerations, both predominantly and in the future. Furthermore, they provide intrasectoral insights, which allow to get a clearer picture for the transport sector and the respective renewable fuels. Following on that, the industrial location theory, originating from Alfred Weber and advanced by other scholars is explained. It provides the framework for current plant location analysis and allows for a stringent observation of the investigated research gap throughout the work. Finally Supply Chain (SC) modelling is explained. By explaining how state-of-the-art SC modellings have evolved from industrial location theory and how they nowadays complement the theory's intentions, makes it possible to close the loop and provide a solid frame to approach the research gap. Circular Economy and Bio-based Economy are introduced as an overarching concept and baseline of the research at hand. Just like TRL and FRL, it will be picked up and contextualized. Those will play a minor role in executing the research but are crucial for framing and understanding the topics inherent complexities. They are therefore included in the Appendix.

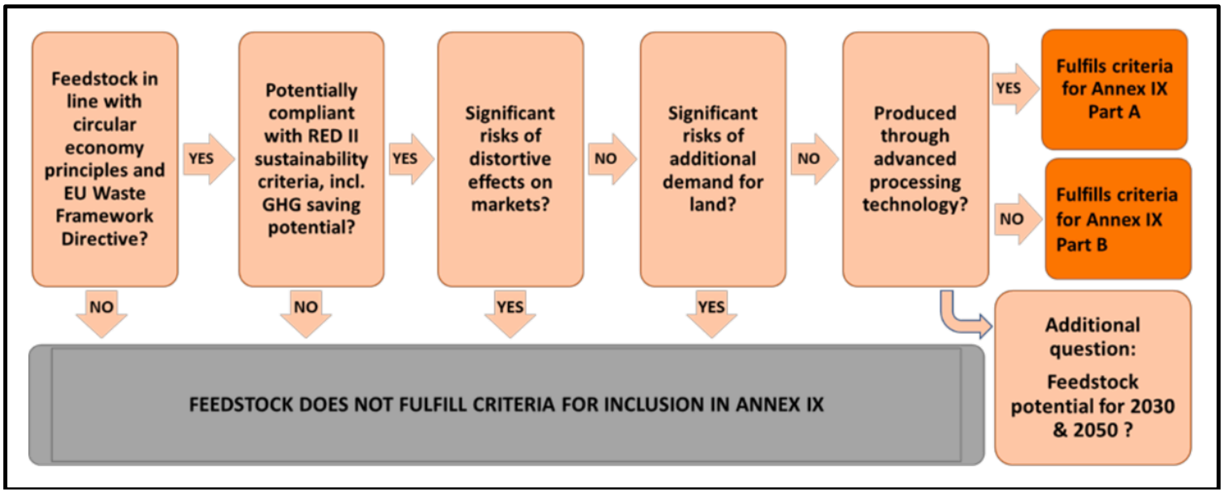
2.1 Biorefineries and advanced biofuels

The IEA Bioenergy Task 42 describes biorefining as "the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)" (Geoff Bell et al., 2014). Depending on the definition, respectively the different characteristics of a biorefinery (e.g., TRL, multi-input, single-output, feedstock etc.), a vast range of biorefineries in existence can be found in the literature (European Commission, 2023a; IEA, 2020b; NOVA Institute, 2017).

Referring to the European Commission (2022, p. 1), advanced biofuels are defined as "those fuels produced using only feedstocks which have no direct or indirect land use change". More precisely, refer to advanced biofuels as biofuels from Annex IX-A feedstock, thereby excluding Annex-B, which comprises used cooking oil (UCO) and animal fats as feedstocks (ETIP, 2020). Lignocellulosic advanced biofuel is in fact a term referring to feedstock within Annex IX-A, which is informed by lignocellulosic characteristics. Next to straw and lignocellulosic wastes and residues from agriculture, forestry and forest-based industries (e.g., bark, branches, stover, saw dust, etc.), Annex IX-A comprises feedstock, including Algae, Biomass fraction of mixed municipal waste, bagasse, tall oil pitch and also, among other feedstocks listed, palm oil mill effluent and empty palm fruit bunches and Animal manure and sewage sludge (ETIP, 2020). *Figure 1* portrays an overview of the evaluation process for advanced biofuels feedstock and the distinction between advanced biofuels (Annex IX-A) and fuels without advanced processing technologies (Annex IX-B), which was adopted by the European Commission report in the context of assessing the potential for new feedstocks eligible to produce advanced biofuels.

Figure 1

Overview of the evaluation process for advanced biofuels feedstock



Source: (European Commission, 2021, p. 58)

2.2 Technologies for advanced biofuels

Technologies for advanced biofuels are mainly represented by oleochemical, thermochemical and biochemical processing technologies. Depending on the feedstock and its individual characteristics, multiple transformations are possible to obtain advanced biofuels (European Commission, 2022). As shown in *Table 1*, it is usually differentiated between pretreatment processes that produce so-called *intermediate bioenergy carriers* and conversion, respectively processing technologies that conduct *fuel synthesis or upgrading,* resulting in the final advanced biofuels. The lack of technological maturity represents a significant burden towards dispersal of advanced biofuels within the respective industries. The only technologies that are currently deployed at a commercial level are *hydroprocessing* of oils, fats and bioliquid intermediates as upgrading technologies and *pyrolysis* and *enzymatic hydrolysis* as pretreatment technologies (European Commission, 2022). The former technology represents the established conversion process of creating renewable fuel out of UCO and HEFA feedstock, which incorporates the vast share in currently deployed renewable diesel and biodiesel. The latter in turn represents the conversion technology needed to turn starch crops into conventional bioethanol (IEA, 2011), thereby also representing a conventional and established technology. Pyrolysis is the most developed technology for converting biomass intermediate liquid products into drop-in hydrocarbon biofuels, oxygenated fuel additives and petrochemical replacements (U.S. Department of Agriculture, 2021). Biomethane from biogas upgrading also has a commercial TRL and is understood to be one of the most promising technologies in the LABF field (European Commission, 2022). Other technologies are shaped by immaturity and need further research and development for constituting a viable alternative in the future. *Table 1* summarizes the state-of-the-art technologies and their respective TRLs (European Commission, 2022) (see Appendix I for explanation of TRL).

Table 1

State of the art technology and corresponding TRL

Fuel Synthesis and Upgrading	TRL
Hydroprocessing of oils, fats and bioliquid intermediates	9
Fermentation of syngas to biomethane	4-6
Gas fermentation through microorganisms to alcohols	8-9
Aqueous Phase Reforming of sugars to hydrogen	5
Transesterification of triglycerides	9
Biomethanol synthesis	8
Methanol to Gasoline synthesis	8

Pretreatment Technology (Intermediate Bioenergy Carrier)	TRL
Pretreatment and enzymatic hydrolysis to sugars	8-9
Pyrolysis of biomass to pyrolysis oil	8
Gasification of biomass and pyrolysis oil to syngas	7-8
Hydrothermal liquefaction to bio-crude	5-6

Promising Pathways	TRL
Biomethane from biogas upgrading	9
Catalytic methanation of syngas for SNG production	7-8
Fast Pyrolysis & Thermo-Catalytic Reforming to drop-in fuels	6-7
Lignocellulosic biomass to FT fuels	6-7
Lignocellulosic biomass to ethanol	7-8

Source: (European Commission, 2022)

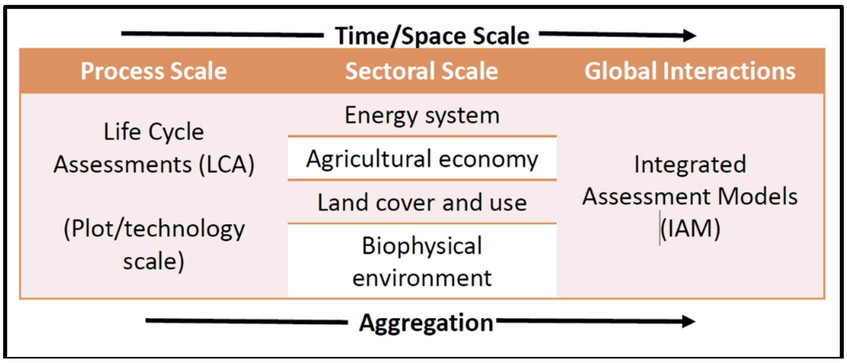
2.3 Modeling tools to assess the future role of advanced biofuels

Modeling tools are a recognized within the realm of energy assessment and energy projection. They support organizations, cities or countries with the elaboration and implementation of decarbonization plans (Martins et al., 2021). There are various modelling tools applied in the world of energy assessment and energy projection in general, but also concerning the field of bioenergy (Martins et al., 2021). For the research at hand, the most important tools to elaborate on are Energy Systems Modeling (ESM) and supply chain modelling (SC modelling). ESM is used to improve policy decisions through evidence based least cost and technology rich energy system pathways. By focusing on the entirety of a system, and by "comprising the demand component (energy service demands), the supply component (resource potential and costs) and the policy component (scenarios)" (Chiodi et al., 2015), inter- and intrasectoral comprehension of technology and energy circumstances is facilitated (Chiodi et al., 2015). The scope of ESM usually diverges, depending on the energy system of interest and on the model generator in use. They can be applied to model "local, national or multi-regional energy systems, providing a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon" (Chiodi et al., 2015, p. 5). In the case of the research at hand, ESM underlies the future projections on advanced biofuels deployment in the EU.

Against the background of the fluctuating nature of biomass supply and their vast range of sources, supply chains and their management play a vital role in effectively providing biomass resources for energy production (Mafakheri & Nasiri, 2014). Especially in the field of bioenergy, biofuels, and especially advanced biofuels, and due to its inherent dependence on vast amounts of biomass and complex steps along the supply and value chain, the use of supply chain management is of big importance (Mafakheri & Nasiri, 2014, p. 117). It allows for "integrated management of bioenergy production from harvesting biomaterials to energy conversion facilities" (Mafakheri & Nasiri, 2014, p. 117), provides relevant insights in decisive factors of future supply chains (Mafakheri & Nasiri, 2014). Building up on that, SC modelling involves the simulation of different scenarios within the biomass supply chain. This approach addresses inherent decision challenges and ultimately leads to arriving at a viable solution for the specific problem at hand (Mafakheri & Nasiri, 2014). Referring to *Figure 2*, supply chain operations studies are similar to Life Cycle Assessment (LCA) on the process scale, however they lack sectoral scale details, such as the development of transport fuels, competing demand and alternatives or global interactions, such as international trade of energy carriers. Therefore, the modeling approaches described allow to approximate to the research gap described in chapter 1.2.

Figure 2

Common modeling tools for energy projection and energy assessment



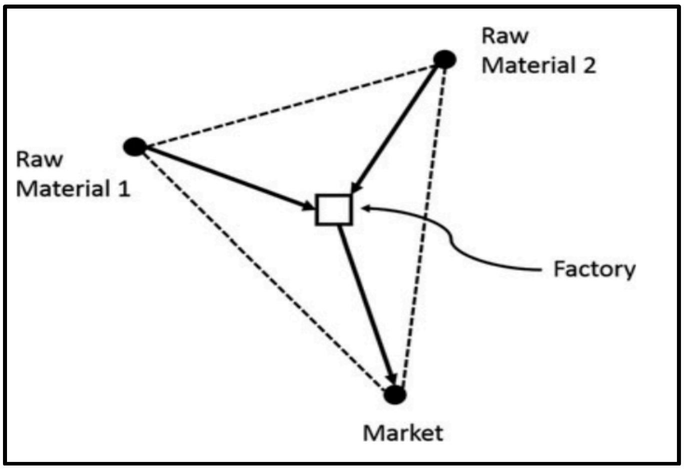
Source: (Daioglou, 2023)

2.4. Industrial location theory

The industrial location theory originates from Alfred Weber, 1909, and has been picked up by scholars ever since. It is concerned with the spatial distribution of manufacturing activity and centers on the factors influencing the selection of sites for new facilities, respectively factories (Chapman, 2009). It originates from the assumption that for every industrial process, be it production, distribution or consumption, there must be a "somewhere" and a "somehow" (Church, 2019, p.69). In the theory's original intend, Weber approached the topic of locating a company that needed two raw materials and a market. The raw materials are sourced at specific locations, whereas the market is supplied by what is produced out of the raw materials (Church, 2019). To come up with a solution Weber created the so called "locational triangle" respectively "locational figure" (*Figure 3*).

Figure 3

Depiction of a classic location triangle with two raw materials and one market



Source: (Church, 2019)

The original theory's central issue was to determine how transportation cost influences distribution of industries. Therefore, Weber's central assumption underlying his locational Figure was, that industries are attracted by locations that have the lowest costs of transportation (Church, 2019). All of this pertains to the transportation of necessary materials for manufacturing a product, along with the transport cost related to shipping the final product to the market (Church, 2019). According to Weber, transport cost constitutes the largest factor in determining industrial location. To determine the cost of products, Weber combined economic and spatial parameters, such as transport cost, production cost, labor cost and agglomeration effects to arrive at a profitable location for industries (Church, 2019).

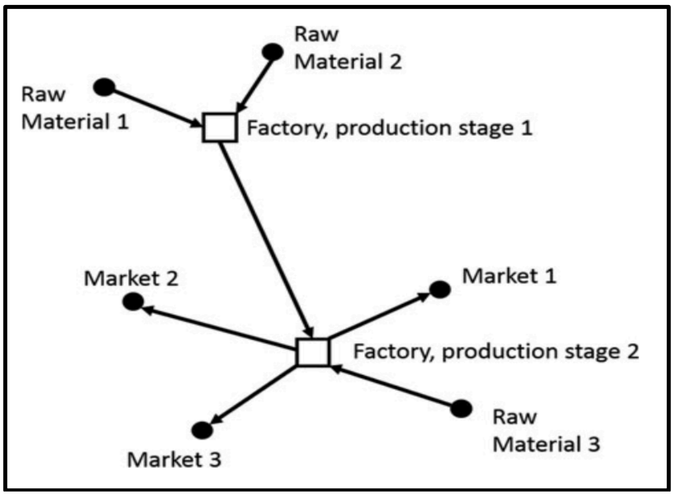
Agglomeration, as defined by Webber et al. (1985), is "a point on the earth's surface at which economic activity is particularly dens". Economies of agglomeration are defined as "those savings in production costs that occur when factories locate near one another" (Webber et al., 1985, p. 50). Profiting from those infrastructural proximities and industrial adjacencies mainly includes cost savings due to scale (Webber et al., 1985). More precisely, this aspect describes that multiple firms provide and make use of services in this area of agglomeration (Webber et al., 1985). The so-called economies of massed reserves play a crucial role since they give meaning to the demanded amount and efficiently use capital and inventories. In case of an overall economic demand rise, dynamics of economies of massed reserves cause the demand for needed inventory to increase, but at a slower rate than in dispersed areas of industry, meaning that a well-established industrial systems or industrial areas (e.g., production- and transportation infrastructure) can compensate the required increase in production by system immanent interrelations and interdependencies. (Webber et al., 1985). In this context, railroads and highways but also banks and commercial facilities are described as social fixed capital, which is “evidently expensive to produce” (Webber et al., 1985, p. 51), thus, minimizing transport and production costs, if already present. Chapman (2009) emphasizes newly developed tendencies in agglomeration dynamic and stresses that “the tendency for firms involved in relatively new sectors such as biotechnology and nanotechnology to cluster in particular regions has been widely noted and seems to confirm the significance of localized knowledge-circulation systems in promoting agglomeration” (Chapman, 2009, p. 399-400).

In addition to *transport cost* and *economies of agglomeration*, *production cost* also varies depending on locations of industrial sites. When considering a certain location, the theory underlines that discovering the location dependent transport cost should be the first thing to do, followed by adding the respective transportation cost and finally deciding on a location where both combined are minimized (Webber et al., 1985).

Even though Weber’s basic model is very simple and shaped by various underlying assumptions, such as, among others, ubiquitous and fixed raw materials and transport cost increasing with greater weight and distance, he concomitantly provided expansions and adaptations of his locational decision models and their variables to better come up for real life circumstances (Singh, 2023). Those expanded models include “Multi-Plant Location Problem“, “Single Plant Location with Alternate Sources of Raw Materials“, or “Multi-Plant Location with Resource Constraints” (Church, 2019, p. 77-84). Moreover, the theory comes up for multiple stages of production in which a product is manufactured in multiple locations at different points in time (Church, 2019). Additionally, the theory covers diverging characteristics of raw materials, thereby distinguishing between weight-gaining and weight-losing materials, thereby expanding the original theoretical stance that more material transported automatically leads to higher costs. In this course Weber emphasized that for weight-losing raw materials (coffee beans in his example), locating the first processing step close to the raw material and then transporting the pre-processed material to the market would be the best approach (Church, 2019). *Figure 4* depicts this distributed supply chain approach by Weber.

Figure 4

Expanded locational figure covering two stages of production

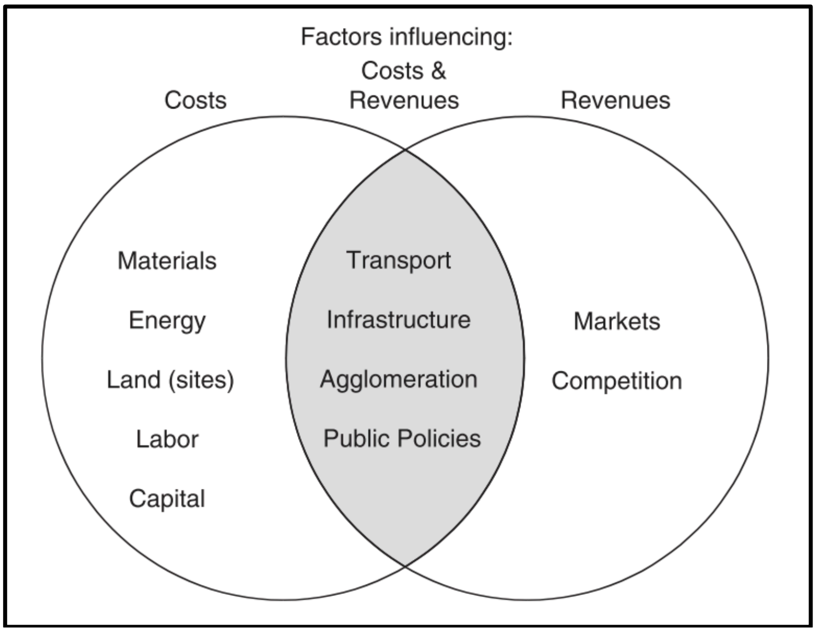


Source: (Church, 2019, p. 84)

Looking at Weber's foundation, Chapman (2009) describes the logic of industrial location factors as finding a middle ground between the cost of production and factors influencing revenues made from selling manufactured goods. Just reducing cost cannot be the major point of focus since profit has to be considered as well. Therefore, refinements of the industrial location theory tried to accommodate the complexities of this issue by stressing that cost and revenue "variables are not necessarily independent of one another" (Chapman, 2009, p. 398). In this turn, better transport and infrastructure facilities may not only relatively reduce operating cost between different production sites, but also enhance market access and finally revenues (Chapman, 2009). This refined approach, depicted in *Figure 5*, shows transport, infrastructure agglomeration and public policies as overlapping factors of cost and revenues. Against the background taking those aspects as a base, the thesis at hand investigates their influence on locational factors, relevant for the future rollout of advanced biofuels.

Figure 5

A typology of industrial location factors



Source: (Chapman, 2009, p. 397)

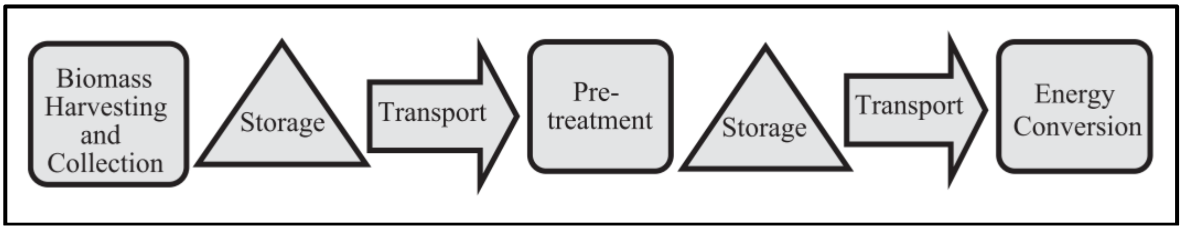
2.5 Industrial Location theory, advanced biofuels, and its supply chain models

As described in the previous subchapters, industrial location theory is concerned with finding a cost- and revenue-optimal location for an industrial facility. Transport cost, infrastructure, agglomeration, and public policies are considered to represent deciding terms combining the focus on cost reduction and revenue maximization, thereby representing and advancement of the industrial location theory, and thus having an influence on industrial locations (*Figure 5*). Looking at industrial location theory, the word "supply chain" is not mentioned. Nevertheless, the importance of locations for certain steps in a production process is emphasized, thereby laying emphasis on supply chains, supply chain management and finally supply chain modeling as being vital within the realms of future location decisions.

As mentioned, Weber considered different characteristics, of raw materials, such as weight-gaining and weight-losing, as having major influence on certain production steps and concomitantly on location decisions within the supply chain. Biomass in this turn represents a weight-losing raw material suggesting that this impacts respective supply chains. Lignocellulosic biomass and its characteristics, comes with a number of challenges for collection and processing, such as low energy density, high logistic costs, and high water content (Rajendran, 2017;Mafakheri & Nasiri, 2014). Depending on the technology and the aspired final product, diverging intermediate processing or pretreatment steps must be executed, thereby significantly impacting cost and structure of the respective supply chain (Mafakheri & Nasiri, 2014). This is depicted by *Figure 6*, representing a typical biomass supply chain. Choosing an adequate harvesting and collection plan, and optimally locating bioenergy plants needs to consider biomass-, transportation- and logistics factors. Moreover, according to Mafakheri & Nasiri (2014), the configuration of biomass supply chains and the bioenergy production is depending on the decision between a centralized supply chain with a large conversion plant, or a distributed supply chain with several distributed small plants. Yet, "where?" and "why there?", constitutes the research gap of the thesis at hand, emphasizing the adequateness of using industrial location analysis in combination with modern approaches and expert opinions to approximate the gap in knowledge.

Figure 6

Operational components of a biomass supply chain



Source: (Mafakheri & Nasiri, 2014)

3. Methods & Input data

3.1 Research Design

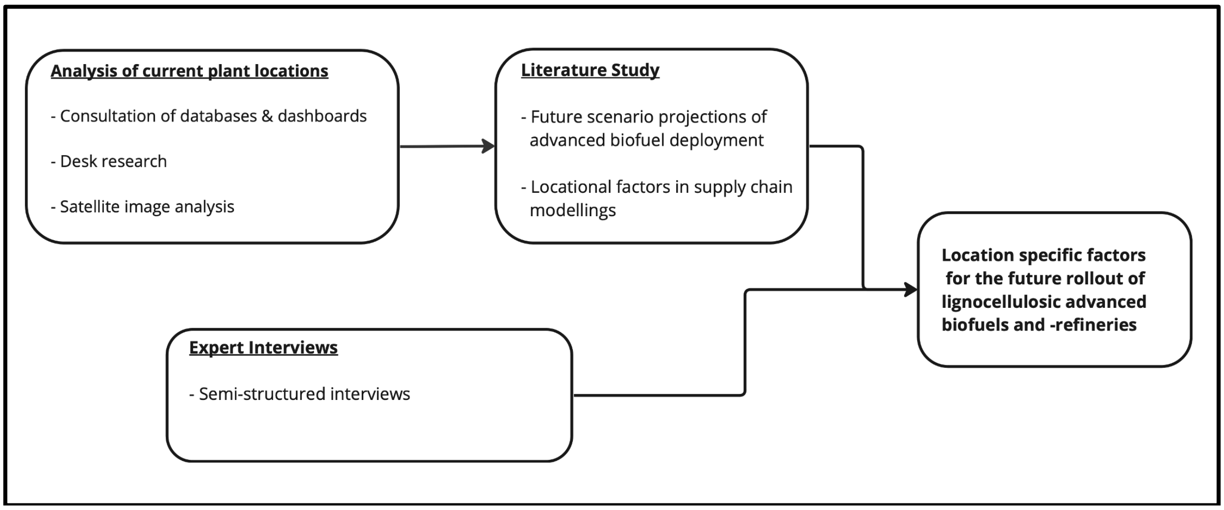
The aim of this research was to improve the understanding of the location specific factors that are going to be relevant towards the future roll-out of lignocellulosic advanced biofuels and the designated biorefineries in the EU. The field of advanced biofuels is informed by uncertainty, technological immaturity, and complexities, ranging from feedstock characteristics up to political and legislative framing conditions. In the following sections, the methodology for finding an answer to the research question and its sub questions is outlined. Due to the application of existing theory (industrial location theory) to a new field (location specific factors for lignocellulosic advanced biofuel refineries), the research was of abductive nature. A combination of inductive and deductive approach was chosen, depending on the research step.

Three research steps were undertaken to address the research gap and advance validity and reliability of the research design. The diversity of the individual research strands and approaching the research gap from three different angles fostered validity and suitability by identifying and scrutinizing various accessible data sources (Bryman, 2012), considering the overall immature state of development of the field. Moreover, Reliability was ensured by delineating each individual research step throughout the individual methods, and especially by adding the foundational data assembled and used to deduce the results.

Firstly, an analysis of current plant locations was conducted. Secondly, a literature study addressed the future oriented perspective by investigating the state-of-the-art future projections for advanced biofuels on the one hand, and what current supply chain modellings reveal about the role of locational factors on the other hand. Simultaneously, expert interviews were conducted in the field of bioeconomy, (advanced) biofuels and relevant industries (e.g., Oil refining companies). The participants perspectives were essential for recognizing and contextualizing in-field perspectives with the study's underlying theory, therefore backing up findings and conclusions (Bryman, 2012). By combining those research steps, locational factors that are relevant for the future rollout of advanced biofuels in the EU could be deduced.

Figure 7

Research Design



3.2 Analysis of current plant locations

The analysis of current plant locations aimed at approaching the geographical state-of-play of biorefineries that produce advanced biofuels and that use lignocellulosic material at least as part of their input materials. By analyzing the locations of the respective biorefineries, insights towards locational factors that surround the already existing and relevant plants in the advanced biofuel cosmos could be gained and allow for deductions about possible relevance of similar locational factors for the future rollout (Fortenbery, Deller & Amiel, 2013). External reliability and replicability is ensured by the detailed delineation of the three individual steps to conduct the location analysis at hand. External validity refers to the representativeness of the sample size (Bryman, 2012) and is thoroughly met due to encompassing all the commercially operating plants in Europe that partly use lignocellulosic material as an input material. The following three steps were executed to approach the location analysis.

Step 1: Three databases, stated in *Table 2*, were examined for their applicability to biorefinery processing. Due to the limited prevalence of biorefineries exclusively centered around lignocellulosic feedstock, plants that incorporated lignocellulosic feedstock as part of their overall input were investigated according to this approach.

Those databases have been selected on the following criteria:

- Focus on advanced biofuel production or pretreatment plants
- Possibility to filter for input and output
- Status of plants was visible (planned, under construction, operational)

Table 2

Databases used for analysis of current locations

Database	Source
ETIP Bioenergy – Production Facilities	ETIP (2023)
Interactive Dashboard – Biobased Industry EU	European Commission (2023)
Database on facilities for the production of advanced liquid and gaseous biofuels for transport	BEST Energy (2023)

Step 2: Desk research complemented the previously mentioned databases, to investigate for plants that might have been omitted in the databases but were yet relevant. The studies depicted in *Table 3* have been selected because:

- They provide a detailed list of existing biorefineries
- They mention feedstock and process technology
- They differentiate between different kinds of biorefineries

Thus, they allow for an adequate complementary investigation in addition to step 1.

Table 3

Publications investigated to complement the dashboard analysis

Study	Source
Distribution of the bio-based industry in the EU	Parisi (2020)
Current Status of Advanced Biofuels Demonstrations in Europe	ETIP (2020)
Biorefineries in Europe	IEA (2020)

<u>Step 3:</u> <u>Final selection of relevant plants and Google Maps/Google Street View Analysis</u>

In Accordance with the steps executed, 19 biorefineries could be found. All those biorefineries hold at least TRL 8, use lignocellulosic material at least as part of their input and produce at least an intermediate or a final fuel. The finally selected plants relevant for the research question were then investigated via a manual satellite image analysis (Google Maps and Google Street view). This was done to shed light on the plant's exact locations, their adjacent infrastructure and potentially existing agglomeration economies. The 19 biorefineries eventually relevant for the location analysis are depicted in *Table 4.*

Table 4

Current plants producing advanced biofuels from lignocellulosic material

Location	Input (feedstock)	Output (product)	Technology (process)	Production capacity	Status
Crescentino (Italy)	Agricultural waste (wheat straw, rice straw) and energy crops (Arundo donax, miscanthus).	Ethanol, animal feed, power and heat.	Hydrolysis, Fermentation.	50 Ml/y	Shut down (to be confirmed).
Kajaani (Finland)	Woody biomass (sawdust).	Ethanol and animal feed.	Hydrolysis, Fermentation.	10 Ml/y	Operational. Expansion planned
Strazske (Slovakia)	Agricultural waste (wheat straw, rapeseed straw, corn stover) and energy crops (switchgrass).	Ethanol and animal feed.	Hydrolysis, Fermentation.	70 Ml/y	Under construction
Leopoldov (Slovakia)	Agricultural waste (wheat straw)	Ethanol, fertilizers, power and heat.	Hydrolysis, Fermentation.	63 Ml/y	Under construction.
Pietarsaari (Finland)	Woody biomass (forest industry residues)	Ethanol and animal feed.	Hydrolysis, Fermentation.	50 Ml/y	Investment decision in 2018.
Hønefoss (Norway)	Woody biomass (forest industry residues)	Ethanol and animal feed.	Hydrolysis, Fermentation.	50 Ml/y	Investment decision in 2018.
Holstebro (Denmark)	Agricultural waste (straw)	Ethanol, fertilizers, power and heat.	Hydrolysis, Fermentation.	73 Ml/y	Planned.
Joensuu (Finland)	Forest residues and other wood-based biomass.	Bio-oil, power and heat.	Pyrolysis.	50,000 t/y (~41.6 Ml/y)	TRL 9 Commercial; operational
Podari (Romania)	Agricultural residues; Wheat and other cereal straw	Ethanol	Fermentation	50,000 t/y (~63.35Ml/y)	TRL 9 Commercial; operational
Hallein (Austria)	Lignocellulosics; Sulfite spent liquor from spruce wood pulping	Ethanol	Fermentation	30,000 t/y. (~38 Ml/y)	TRL 8 First-of-a-kind commercial; operational
Enschede (Netherlands)	Forest residues; Clean wood residues	Pyrolysis oil, steam, power	Fast Pyrolysis	24,000 t/y (~20 Ml/y)	TRL 9 Commercial; operational
Hengelo (Netherlands)	Organic residues and waste streams ; wood pellet processing	Pyrolysis oil, steam, power	Fast Pyrolosis	24,000 t/y (~20 Ml/y)	TRL 8 First-of-a-kind commercial; operational
Södra (Sweden)	Forest residues	Methanol	Andritz Technology. What does that mean? A-Recovery+ concept from ANDRITZ	5,250 t/y (~ 6.6 Ml/y)	TRL 9 Commercial; operational
Sarpsborg (Norway)	Lignocellulosics; Sulfite spent liquor from spruce wood pulping	Ethanol	Fermentation	15,800 t/y (~20 Ml/y)	TRL 9 Commercial; operational
Gavle (Sweden)	Organic residues and waste streams; Saw dust	Pyrolysis oil	Fast Pyrolysis	24,000 t/y (~20 Ml/y)	TRL 9 Commercial; operational
Ornskoldsvik (Sweden)	Lignocellulosics; Primary wood chips; Sugarcane bagasse, wheat, corn stover, energy grass, recycled waste etc. have been tested	Ethanol	Fermentation	160 t/y (~0.2 Ml/y)	TRL 8 First-of-a-kind commercial; operational
Pitea (Sweden)	Forest residues; Tall oil from pulp and paper industry	Renewable diesel (HVO)	Hydrotreatment	39,000 t/y (~49.4 Ml/y)	TRL 9 Commercial; operational
Lieksa (Finnland)	Residues from forestry industry, such as sawdust and crown trunks	Pyrolysis oil	Fast Pyrolysis	24,000 t/y (~20 Ml/y)	TRL 9 Commercial; operational
Amli (Norway)	Residues from forestry industry, such as sawdust ad crown trunks	Pyrolysis oil	Fast Pyrolysis	(100,000 t/y) (~83.3 Ml/y)	TRL 8 First-of-a-kind commercial

Due to the ambiguous definitions of agglomeration and due to the nature of (lignocellulosic) advanced biofuels and the respective refineries still being an industrial niche sector, a definition for agglomeration was needed. Therefore, agglomeration was given a frame by the researcher for the location analysis at hand. Agglomeration was to be in place, if two or more industrial activities prevalent in one area could be observed. Potential synergies or interdependencies, such as a logistics and transport company adjacent to a biorefinery, needed to be observable and respective synergies to be conjecturable. The two satellite images, *Figure 8,* and *Figure 9*, show exemplary images of biorefineries investigated in the research at hand. The added arrows underline predominant agglomeration economies in the respective area.

The first Biorefinery shown in *Figure 8* is a plant located in Gavle, Sweden. It uses around 85,000 t/y of saw dust, plus organic residues, and waste streams to produce around 24.000 t/y (~20 Ml/y) of pyrolysis oil. It is operating with TRL 9 and is commercial.

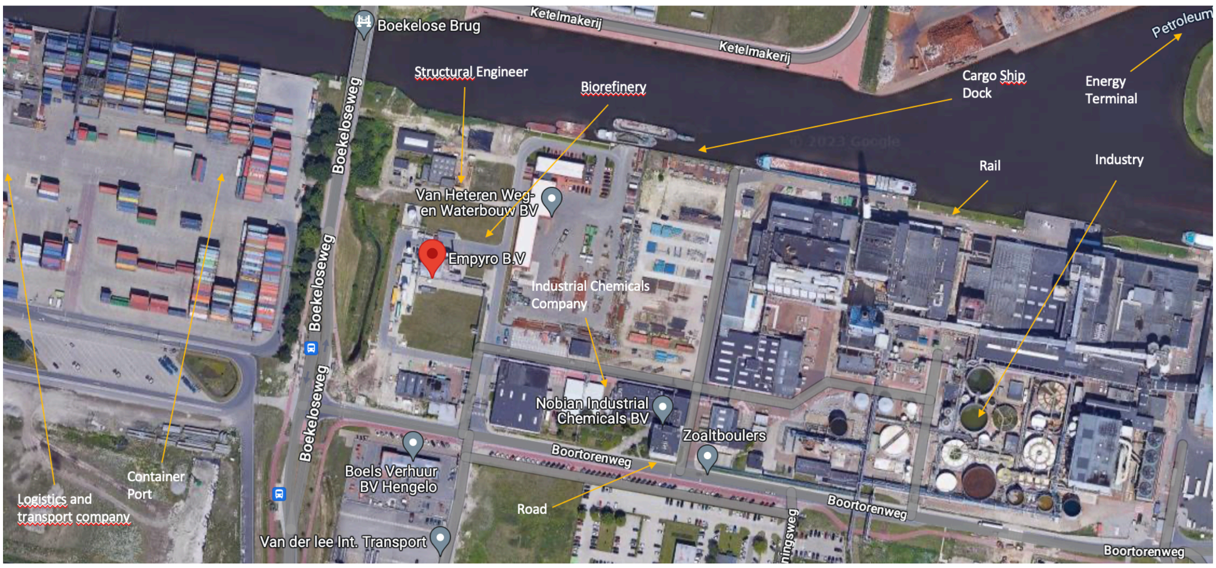
The second satellite image *Figure 9* shows a plant located in Hengelo, NL. The plant holds TRL 8 (First-of-a-kind commercial) and is operational. Its main input is organic residues, waste streams and wood pellet processing waste (5,000 kg/h). Its main output is pyrolysis oil (24,000 t/y, or ~20 Ml/y), steam and power (electricity).

Figure 8

Exemplary location in of existing plant with agglomeration economies in Gavle, Sweden.

Figure 9

Exemplary location in of existing plant with agglomeration economies in Hengelo, NL



3.3 Analysis of future plant locations

The analysis of future plant locations was approached using two distinct methods. Initially, a study of future scenarios for advanced biofuel deployment aimed to identify commonalities among projections. This examination aimed at assessing projection details, including its treatment of location-related factors. Following this, a literature review of supply chain modelling studies was conducted to ascertain, which location factors were incorporated in such models and if patterns would be observable. Detailed explanation of identification criteria for suitable projections and supply chain models as well as depiction of the final input data eventually used assured confirmability and external reliability and replicability (Bryman, 2012). External validity however was impacted, especially concerning the supply chain modellings. Even though valid reasons for the model selection were invoked, they yet represent a selection and are not based on a thorough and systematic literature review. The objective was to compare factors found in deployment projections and supply chain modellings with findings from current plant locations and insights from experts, thereby facilitating internal validity, which refers to the development of theoretical ideas, along in-field observations (Bryman, 2012) aiming to identify areas of alignment and significance.

3.3.1 Future scenario projections of advanced biofuel deployment

The analysis of future plant locations aimed at shedding light on the state-of-the-art projections for 2nd generational-, respectively advanced biofuels. Projections were ought to be investigated for deployed advanced biofuels on the European- and on the member state level, aiming to provide insights into overarching and individual targets. By comparing these projections with the quantities of advanced biofuels currently deployed, potential mismatches could be identified. These mismatches might highlight vulnerabilities and ultimately emphasize possible areas of influence.

Different studies have been examined to provide a state-of-the art insight in the expected market development of advanced biofuels in the EU up to 2050 under different scenario conditions.
Starting point was the recent meta-analysis by Chiaramonti et al. (2021), who reviewed published scenarios on the role of biofuel in EU transport decarbonization until 2050.

Following up on Chiaramonti's study, a screening of studies was done to identify studies that could provide similar detailed insights into future scenarios. The screening considered publications including the following criteria:

- Consideration of Europe
- Future perspective (2030-2050)
- Advanced biofuels

In the beginning, a multitude of studies and publications were screened according to if they cover the mentioned above aspects. This resulted in 10 publications (see *Appendix III*, *Table 10*). Out of those studies, just one projection (JRC, 2020) covered detailed scenarios until 2050. Since a lack of information still prevailed, another screening has been done, after which one more study could be identified that entailed the relevant information, resulting in the three studies listed in *Table 5.* Those studies provide detailed scenario-dependent projections across the most relevant time horizons, namely 2030, 2040 and 2050. By having clear insights into these outlooks, ranges can be deduced that can be contrasted with the state-of-play.

Table 5

Scenario projections studies for advanced biofuel deployment

Study	Scenario	Definition of advanced biofuel	Level of detail included
Chiaramonti et al. (2021)	2030, 2040, 2050	Biofuels produced from Annex IX-A feedstock	Total Final Energy Consumption in the Transport sector **Three scenarios:** Low, Medium, High
Padella et al. (2020)	2030, 2040, 2050	Biofuels produced from Annex IX-A feedstock	EU28 plus Switzerland, Iceland and Norway; **Three scenarios**: Baseline, Diversified, ProRes (for Demand & Supply)
Uslu et al. (2019)	2030, 2050	Liquid fuels produced from lignocellulosic feedstocks from agriculture, forestry, and waste	**Two scenarios:** Scenario Road ZERO, Scenario Transport BIO

3.3.2 Location specific factors in supply chain modellings

Following the future scenario projections and considering the backdrop of industrial location theory, it's evident that supply chain models play a vital role. When examining the operational elements of a biomass supply chain, which are pivotal for advanced biofuel production, it's apparent that supply chain models both build upon and expand the industrial location theory's considerations. They provide insights into optimal solutions for individual supply chains thereby focusing on infrastructure, logistics, supply chain related dynamics and actor interdependencies. Studying multiple supply chain models in this regard is at least comparable to a comparative case study by analysing multiple cases (SC models) and identifying patterns, differences, commonalities and finally drawing conclusions for a broader objective (Goodrick, 2014). Different supply chain models as case studies were chosen, as it is appropriate for examining "how"- and "why"-issues in addition to the research being focused on current phenomena (Yin, 2011). Furthermore, according to Bryman (2012), the comparison of cases themselves can reveal concepts that are relevant to an emerging theory and can determine the conditions under which a theory does or does not apply.

To come up with suitable supply chain models a multitude of supply chain models have been examined. The final selection of 15 studies has been done based on the following content of the studies:

- Include cost factors in their model purpose
- Consider different transport options
- Touch upon infrastructure and agglomeration effects
- Cover supply chain logistics and its design modelling
- Focus on specific location problems of facilities (pretreatment, storage or conversion),
- General supply chain design simulation and/or optimization

Results of the supply chain modellings are largely based on Multi Integer Linear Programming (MILP) models (De Mol et al., 1997; Ng & Maravelias, 2017; Zhu & Yao, 2011). MILP is the most used optimization model in the literature and can effectively tackle large scale problems and complexities, as inherent in advanced biofuel supply chains, such as harvesting point, storages, biorefineries and the respective transport connections (Moretti et al., 2021). The different modelling studies allowed to deduce commonalities within the modelling studies that could be compared with the findings of the other research strands. This facilitated the validity of the overall results and emphasized the relevance of such factors for the new field of lignocellulosic advanced biofuels and in accordance with the underlying theory. Finally, *Table 6* depicts the 15 supply chain model studies reviewed in detail. This approach bridged the research gap through a deductive approach, while interviews contributed to an inductive perspective.

Table 6

Selection of relevant supply chain model studies

Study	Model purpose	Infrastructure	Agglomeration	Logistical system(s) considered
De Jong et al. (2017)	Cost optimization of biofuel production	Existing transportation infrastructure, feedstock handling infrastructure assumed to be in place	Integration, co-locating and using industrial by-products, economies of scale	Intermodal transport, distributed supply chain configuration
Bojic et al. (2017)	Minimization of both internal and external biomass transport costs; selection of optimal plant location	Existing road and inland waterway infrastructure considered; rail not considered due to bad condition in Serbia	Port vicinity for plant locations considered	using the inland waterway transport for main haulage and road transport for pre- and post-haulage.
Morrow, Griffin & Matthews (2006)	Distribution cost minimization of various ethanol fuel blends	Road, rail, pipeline	Not mentioned	Using inland waterways and multimodal transport
Akgul et al. (2010)	Total supply chain cost minimization; optimization of facilities' locations, number of transport units	Available modes of transport: trucks, rail, barge, and ships; internal depots used for conventional fuel storage are assumed to be the actual demand centers for biofuel	Not mentioned	Intermodal (no indication of pre-treatment plants, but just rail as optimal solution)
Zamboni, Shah & Bezzo (2009)	Cost and GHG emissions minimization	Not touched upon in detail, yet rail and existing bioethanol plants are considered for the model	Not mentioned	Distributed (Hub and Spoke)
Kim, Realff & Lee (2010)	Maximizing overall profit by selection of biofuel conversion technologies, processing capacities and locations, and the logistics of transportation from the locations of forestry resources to the conversion sites and then to the final markets	Infrastructure is not considered to be in place, as it is an outcome of this modelling study.	No agglomeration assumed in advance.	Evaluation: Centralized vs. Distributed supply chain
You & Wang (2011)	Minimization of annualized total cost	Supply chain network structure is given but not specified	Supply chain network structure is given but not specified	Evaluation: Centralized vs. Distributed supply chain
Zhu & Yao (2011)	Logistics system design optimization	Existing storages, roads and rail are assumed to be in place	Not mentioned	Using storages both integrated in the biorefineries, but also close to the feedstock to exploit biomass and supply chain efficiency => Mix of hub and Spoke and Integration is drawn

Kim, Realff & Lee (2011)	Overall profit maximization	Rail or road assumed, because not given as cost factor; Range of existing pretreatment and conversion plants assumed	Not mentioned	Distributed (Hub and Spoke) system is depicted, ranging in the number of plants utilized, depending on the model details
Kostin et al. (2018)	Maximizing net present value (NPV)	Ethanol is assumed to share infrastructure with sugar industry	Port areas used for market access	Distributed (Hub and Spoke)
Ng & Maravelias (2016)	Minimize Total Annual Cost (TAC)	regional depots and biorefineries considered to be in place and used	Not mentioned	Distributed (Hub and Spoke)
Lin et al. (2014)	Minimization of annual biomass–ethanol production costs by optimizing both strategic and tactical planning decisions simultaneously; development of biomass production, storage, preprocessing, and conversion infrastructure and the selection of existing ethanol blending infrastructure	Current blending infrastructure considered; no newly built blending facilities	Not mentioned directly but locating plants close to cities has been considered	Large scale centralized biorefinery close to potential high yield areas to profit from economies of scale
De Mol et al. (1997)	Simulation and optimization of the logistics of biomass fuel collection	Given network structure is assumed; So-called network structure includes the different nodes which represent certain infrastructural circumstances	Not mentioned	Transport, storage, handling and pre-treatment are modelled in different ways to observe costs
Jåstad et al. (2023)	Least-cost combination of biorefineries and pretreatment plants in a certain geographical region	Depending on the scale of the model it is very important. Especially for middle and large scenarios, Infrastructure is important and reduces costs	Especially in the middle and large cases of a rollout, harbor areas and existing industrial areas will attract Biorefineries. In those areas, agglomeration effects will happen and help to reduce costs	Small case: Centralized individual case; with growing system, integrated and hub n Spoke will become more viable
Martinkus et al. (2018)	Cost minimization between biomass (feedstock) sources, depots, biorefineries, and end user	No uniform infrastructure assumed	Due to using infrastructure at saw- and pulp mills, agglomeration plays an implicitly important role,	Distributed (Hub n Spoke => two satellite pretreatment depots and one central biorefinery)

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3.4 Expert interviews and workshop

Conducting interviews constituted a major part of the data collection for the research at hand. Semi-structured interviews were chosen because they allowed for beginning the investigation with a relatively clear focus (Bryman, 2012), yet having some flexibility to adjust and adapt the dynamic of the interview and the interview questions (Bryman, 2012). Since the locational factors important for the future rollout of advanced biofuel refineries represent a blind spot, emphasis had to be laid on how the interviewees perceive the issues and events inherent in the respective system of advanced biofuels. Therefore, it was relevant, how the experts that were interviewed explain and understand events and patterns, but also predominant dynamics and behaviour (Bryman, 2012), in the field of the bioeconomy in general and of course especially related to advanced biofuels and lignocellulosic advanced biofuels. Relevant interview partners were chosen and approached based on purposive sampling and snowball sampling. Purposive sampling allowed the researcher to select relevant people from within the field with his research goal in mind (Bryman, 2012). Initially, the strategy included to conduct interviews with policy experts and experts working in the field of (advanced) biofuels or research organisations concerning themselves with those topics. Furthermore, it was attempted to conduct interviews with several experts from the industry itself, meaning for instance biorefinery supply chain managers. Due to difficulties and partly a lack of responses, snowball sampling helped to complete the aspired participant number. Snowball sampling refers to sampled participants proposing "other participants who have had the experience or characteristics relevant to the research" (Bryman, 2012, p. 424).

Finally, 15 interviews were conducted with an overall of 17 interviewees, due to two interviews including two interviewees respectively. Furthermore, a panel discussion with four renown experts from the field of advanced biofuel was attended. Chapter 3.4.1 touches upon that in more detail.
The following list portrays the interviewees and their fields of expertise, respectively the industry they are working in.

- Policy experts: 1
- Pulp & Paper; Chemicals: 1
- Sustainable Aviation Fuel (SAF): 1
- Transport Fuel Trade: 1
- US-American Biofuel industry: 1
- Oil refining industry: 5
- Fossil Energy: 1
- Research & Consultancy: 6
- Panel Discussion: 4

The interview questions asked covered the topics of advanced biofuel with a special focus on lignocellulosic advanced biofuel. In order to put special focus on the locational aspects and factors, the interviewees were asked for drivers, burdens, uncertainties and about important locational factors for the future rollout (see interview guide in *Appendix IV*). The conducted interviews were then transcribed and coded. An inductive approach was taken using the in-vivo coding method. The resulting codes were then summarized into the code group's overarching topics over multiple rounds of iteration. Subsequently, these topics were then summarized to overarching categories to make them tangible. Those overarching categories allowed the researcher to grasp the complex and multi-level intricacies and portray the results as concisely as possible.

3.4.1 Workshop - Technical University of Darmstadt

In addition to the LR and the interviews, the researcher attended a workshop at the Technical University of Darmstadt, called *"Enabling the Clean Energy Transition with 2nd Generation Biofuels"*, hosted by the European Technology and Innovation Platform (ETIP) and the CLARA consortium. The agenda of the workshop (see *Appendix V*) included, among various presentations and expert talks, a panel discussion and visit of the 1 Mega Watt (MW) pilot plant located and operated on the university campus. The researcher seized the presentations and especially the breaks of the workshop to network, get in touch with the experts and other attendants that also work in the field to ask relevant questions for the topic at hand. A core agenda item for the research at hand was represented by the panel discussion. 4 experts from the field of advanced biofuels were asked several questions by a moderator. Questions of the audience were allowed at any time. The researcher placed the RQ at hand in the panel discussion.

The main and guiding question of the panel discussion was: "How can 2nd generation biofuels enable the clean energy transition?". Experts discussing were:

- Christian Aichernig – Chairman of BEST Energy and Managing Director of Aichernig Engineering GmbH
- Juan Adanez – CSIC, Spain
- Edgardo Coda – Sumitomo SHI FW
- Nicolaus Dahmen – KIT, Germany

Lastly, by visiting the pilot plant, the researcher tried to gain a better and more thorough understanding of the research field in general and the technological intricacies and context surrounding and underlying the topic of advanced biofuels. By doing that, interview questions asked in the following interviews could be refined and better directed.

4. Findings from the Expert Interviews

This section presents the findings of the semi-structured expert interviews. The findings relate to ***RQ1.4:*** *How do experts perceive this upcoming market and what factors do they consider crucial for the future rollout?*

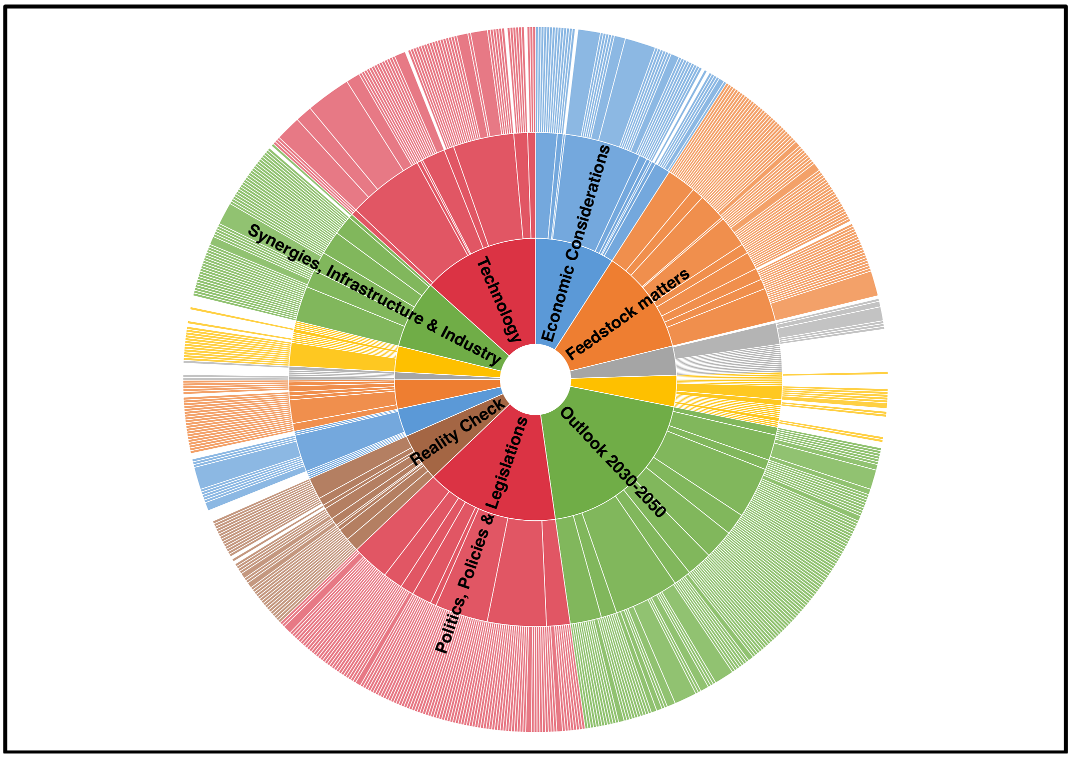
After inductive coding and multiple rounds of categorizing, out of the 961 codes, the following 13 categories were deduced:

Using synergies, infrastructure & industry, Technology, Sustainability concerns, Supply chain logistics as important factor, Social considerations, Regional considerations, Reality check, Politics, policies & legislations, Outlook 2030-2050, No one-fits-all-solution, Important stakeholder, Economic considerations.

From those 13 categories, the seven categories pointed out in *Figure 10* represent the topics mainly mentioned. The following points out the most relevant findings for answering the research question. The reader is encouraged to go to *Appendix VI* for a more detailed overview and elaborations of the final categories deduced. There, exemplary quotes, contextualization, and elaborations on subcategories are provided in more detail.

Figure 10

Sunburst-Diagram with focus on the largest categories from interviews



Politics, policies, and legislation-related topics were prominent answers to the questions asked. While these points may not be directly focused on locational aspects and factors for the future rollout of advanced biofuels, experts consider them to form the essential and foundational starting point. One crucial aspect involves the necessity for well-defined policies that establish stable conditions and encourage long-term financial investments. The existing policy landscape often contributes to an environment of uncertainty. Furthermore, experts emphasize the significance of policy adaptation, advocating for a specific legislative granularity and the establishment of more ambitious targets. Even though not directly addressing locational elements, these points are perceived by experts as pivotal framing conditions for the successful future implementation of advanced biofuel initiatives.

Economic considerations have been pointed out as immensely important and building on political circumstances. It was strongly emphasized by almost all interviewees that sufficient financial resources in the field are currently lacking but are yet and will be decisive for the future rollout. Looking at the mostly immature technology in the field, more investment would facilitate research and development, which in turn would foster the needed competitiveness with fossil fuels. Experts stress the "lock-in-situation", the field is currently caught in. Short term profit orientation of investors hinders investment. Simultaneously, investments are needed to drive the technologies and market establishment to guarantee quicker returns for investors. This "chicken-and-egg"-problem is overarching and slacking the whole industry.

Technology circumstances have been mentioned by experts as having direct and indirect implications for location decisions due to the interrelatedness with feedstock matters. The maturity of technologies is a primary concern; specifically, the insufficient development of technologies for lignocellulosic-based fuels hinders their widespread adoption. These fuels entail intricate characteristics necessitating specific processing methods. Densifying biomass is highlighted as essential, adding a significant processing step. To make the transportation of such feedstock economically feasible, experts emphasize initiating pretreatment near the source. Simple technologies are suited for remote locations, while complex ones for biomass processing require proximity to existing industrial zones or areas with relevant infrastructure. For instance, Fischer-Tropsch-Fuels and pyrolysis hold promise but need enhanced efficiency and affordability.

Local and regional conditions are mentioned by experts in this context. Conditions prevalent at a certain location or region of consideration are crucial to evaluate the feasibility and cost aspects of a potential future supply chain to be in place. Aspects such as feedstock, renewable energy available, hydrogen access, policy and legislations in place, relevant stakeholder in the region, availability of skilled personnel and existing infrastructure were pointed out as vital to be considered in this regard.

Supply chain logistics and feedstock considerations play a crucial role in cost reduction. Notably, "feedstock availability" and "feedstock proximity" are key sub-categories, followed by "competition for feedstock" and "feedstock intricacies." Experts emphasize that securing a consistent supply of feedstock is pivotal, as the industry builds on biomass. Given the potential competition with other industries building on biomass, industries must consider the feedstock supply: "If any industries start to think about using biomass, they really have to think about where they're going to secure the long-term supply of feedstock", as one expert stressed. A central theme highlighted is the need to efficiently transport feedstock from its generation or production point to the fuel production site. Even though import will play large role according to experts, European focus throughout the supply and value chain is stressed not to be neglected, underscoring the importance of utilizing local resources rather than solely relying on external sources.

Making use of existing industrial areas, infrastructure, as well as creating and seizing synergies was emphasized by every respondent. Underlying these statements is the need for cost reduction throughout the supply- and value chain and stressed the significance of leveraging existing industrial areas, infrastructure, and synergies in facilitating the future adoption of advanced biofuels across the European Union. Specialists implicitly pointed out the need for utilizing existing resources, as an expert from Austria stated, "When thinking about building a plant, you should always examine if you can create synergies with existing plants or make use of existing industries." A policy expert underlined the considerable advantage of "industrial clusters" in terms of positioning. Throughout these discussions, key sub-categories emerged organically: Co-processing and co-locating involve optimizing processes by combining facilities or affiliating production processes to existing factories. According to the experts, making effective use of industrial areas can significantly enhance operational efficiency as well as harnessing synergies to create mutually beneficial relationships. Employing retrofitting and repurposing strategies will be crucial to utilize existing infrastructure for biofuel needs. Generally, leveraging the infrastructure already in place was emphasized to foster the implementation process. These approaches were repeatedly highlighted as crucial for capitalizing on existing infrastructures and industries, aligning with the experts' overarching goal of cost-effective advancement.

An Outlook for 2030-2050 was provided by the respondents, who most generally agreed on advanced biofuels incorporating a crucial role in the energy transition especially in sectors that are difficult to electrify. An expert in the field of SAF stated: “We do see in our growth strategy that there will be a large role for lignocellulosic biomass […] these areas that are difficult to electrify, we simply need liquid energy sources with a high energy density. I think this is slowly seeping through that this is really necessary, that we need this”. In terms of envisioning the potential rollout, insights from the interviews indicate a prevailing consensus among experts. They envision a developed advanced biofuel system characterized by a combination of smaller-scale biorefineries or pre-treatment facilities located near feedstock sources, alongside larger plants or biorefineries strategically positioned for international market access and blending capabilities. Finally, experts pinpointed ***hot spot areas*** to be regions in Europe that are shaped by abundant feedstock and opportunities to sustainably exploit it. The dominant sub-categories that could be deduced are for example. “The Nordics”, “Eastern Europe” “Forestry rich regions”. In this regard was the pulp and paper industry mentioned explicitly to provide suitable conditions for co-locating and co-processing in the future. “Harbours” were stressed as a hot spot for industries to accumulate.

Finally, the concept of **No one-fits-all-solution** arises from a significant number of interviewees who emphasize the intricacies of addressing diverse solution pathways. The aspiration for a financially efficient, technologically effective, and broadly applicable solution represents an ideal scenario, but does not align with the complex realities of the industry. Subsequently, experts underscore the unavoidable need for individual, case-specific solutions. They stress that different situations demand diverse approaches, that the choice of location depends on factors like technology, feedstock, and process, and that there's no universal solution, pointing back at the regional and local circumstances to be considered. Additionally, experts advocate for using and leveraging all available resources to tackle the complexities of the industry. “We don't believe that there is a silver bullet to replace all the energy in all the sectors“, as one interviewee emphasizes. Another expert followed by sying that “there is not this one optimal scenario” for biorefineries. “There are a number of factors that add to it, and I don't think you can give a general answer to that, because it has to be considered individually in each application”.

In the following chapter, findings of the other research strands will be backed up by direct and indirect quotes of the experts interviewed

5. Context conditions and locational factors of advanced biofuels deployment

This chapter presents the findings of this research with regards to tackling the problem statement and support answering the research questions stated in chapter 1.2. Context conditions for current and especially future deployment of advanced- and especially lignocellulosic advanced biofuels are complex and shaped by various interrelationships of individual aspects in the supply- and value chain. Political and economic circumstances represent the underlying foundation for the development of advanced biofuel markets (IRENA, 2019; IEA, 2011; Lieu et al., 2018). Elucidating their development in the previous years, in combination with expert's insights, allows for inferences of future policies and respective investment situations. Whereas *current deployment* subsequently depicts the state of play of advanced biofuels, *future deployment* summarizes state-of-the-art projections of deployment situations until 2050. Both are contextualized and supported with interview findings. Finally, *locational factors for advanced biofuel production* can be deduced, by bringing together *locational factors of current* advanced biofuel refineries with future locations. *Future locations* are in turn framed by industrial location theories' major aspects and supported by findings of a supply chain model review and expert interviews.

5.1 Policies and Investments

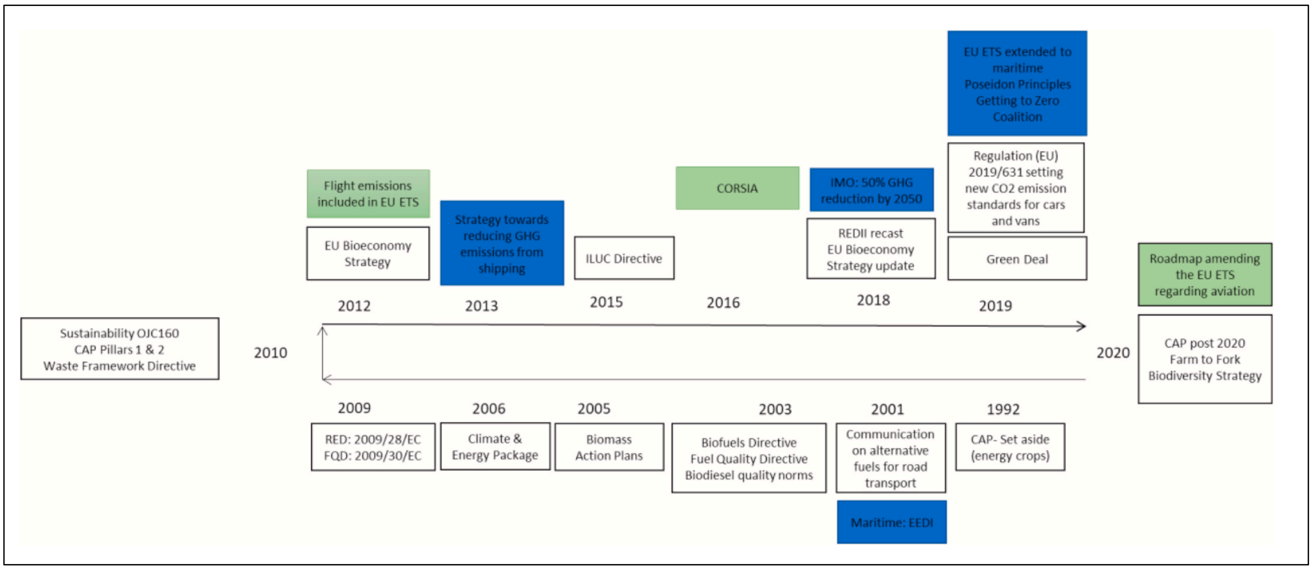
5.1.1 Current Policies and Investments

The importance of climate legislations and policy roadmaps, such as the Green Deal and the Renewable Energy Directive (RED, RED_II and soon RED_III) constitute a crucial pillar for the energy transition. They provide the foundation and ambitious targets for the EU and its member states to approach and reach the stated climate goals. Yet, general climate policies per se do not lead to renewable liquid fuel deployment, because they cannot overrule the underlying profit oriented dynamic of the markets. The development of advanced biofuel production and -deployment will always have to find a way to penetrate the markets by being competitively superior or at least being technologically and/or economically equally viable to other alternatives on the market. Hence, sector specific policy instruments such as blending targets, sub-targets and quotas are needed to support steering this dynamic in the intended direction. Since advanced biofuels and especially lignocellulosic advanced biofuels are far from being cost-competitive with conventional fuels (IEA, 2020a; IRENA, 2019), those sector specific policy instruments are the only option for policy makers to have an impact, influence the markets and enable long term planning for investors.

Figure 11 depicts the policy evolution of biofuels and advanced biofuels in the EU from 1992-2020. Underlying that policy development is a continuous policy cycle, respectively the continuous iterations of policy developments that occur naturally to adapt and adjust policy instruments and thereby approach the intended outcomes step by step, as described by Lieu et al. (2018, p. 3). They outline the continuous policy cycle as consisting of four key stages, namely "Policy development (problem definition & agenda setting)", "Policy implementation in a policy mix", "Policy evaluation (policy performance & stakeholder response)" and "Policy redesign in a policy mix", all constantly repeating themselves in this order. Specifically, the constant development of the RED is a good representation of the latter in this regard, however all developed policy instruments are shaped by this continuously ongoing dynamic.

Figure 11

Biofuels & Advanced biofuels policy evolution (1992–2020)



Source: Panoutsou et al. (2021, p. 4)

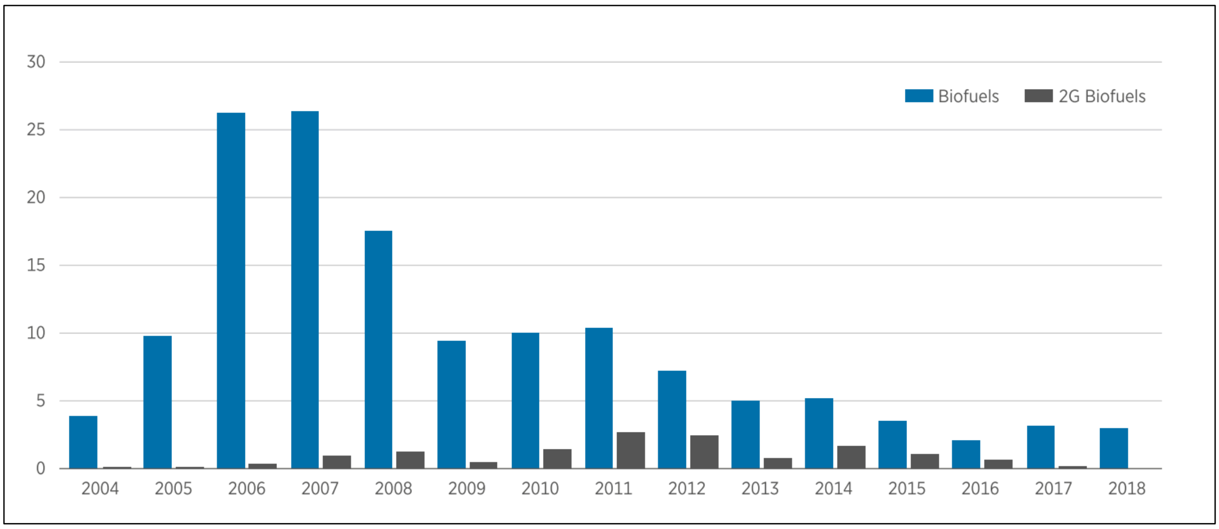
The impact of such continuous development of policy instruments on economic aspects such as investments in the market can be observed by reconciling *Figure 11* above with *Figure 12* below. Generally, investments, respectively economic circumstances represent a crucial driver for the needed transition (Panoutsou et al., 2021). Starting up the needed climate- and environmental actions and meanwhile avoiding lock-ins into unsustainable practices will require massive public investment and large amounts of public and private capital, as the European Commission (2019) emphasized. This was also underlined by the experts interviewed for the research at hand, who pointed at policy and economic circumstances as important trendsetters for the rollout of advanced biofuels (see chapter 4, *Figure 10*). Representatively for that, one respondent emphasized in the interview conducted, that “policies determine everything”. When deciding on an investment, “investors always ask for a foreseeable future for 10-15 years and that's not always possible“, as an expert stated. The uncertainty created by the political circumstances represents a major burden for investors. “Many things are currently highly uncertain. This high uncertainty leads to the fact that at the moment no decisions can be made”, as an interviewee stated with regards to the slack in current development of advanced biofuels. Looking at the investments made in the field of biofuels and advanced biofuels from 2004-2018, the mismatch between stable policies needed for deliberate investments and the erratic policies prevailing and creating vast uncertainties for investors, becomes obvious.

As depicted in *Figure 12*, global investments in advanced biofuels started to pick up speed in 2009, peaked in 2011 and reached zero by 2018. The graph shows global developments and not just solely the EU, nevertheless developments can at least partly be traced back to the introduction of the first RED and the FQD in 2009. The first RED imposed an EU target of 20% renewables by 2020 and binding targets on the member state level. The FQD imposed, among other aspects, a reduction of the life cycle greenhouse gas emissions from fuel (ETIP, 2023a). Double-counting of Annex-A and Annex-B type fuels around the same time represented an incentive for investment in advanced biofuels (Peters, Alberici, & Passmore, 2015). The outcome can clearly be observed in the increase from 2009 until 2011 and 2012 and be explained by a foreseeable market for investors that in turn incentivize them to invest in this field. In and after 2012, market uncertainties, sustainability concerns (mainly triggered by the ILUC Directive) and the lack of long-term planning opportunities can be invoked for the decline in investment.

Yet, implemented policy instruments did not anticipate that lignocellulosic fuels would be neglected by this dynamic of increasing investment and development of advanced biofuels. This was due to UCO and HEFA being significantly easier and cheaper to process into advanced biofuel than cellulosic feedstock (IRENA, 2019) and therefore attracted most of the investment. In this case, policy adaptations are covered by a cap on Annex-B type of fuels that has been imposed in the RED_II. Since the Annex-B (UCO & HEFA) production system was already saturated at the time of the cap, investment decreased significantly, because no new investments were needed. Additionally, the development of the RED_III started, constituting another uncertainty about future developments, resulting in investors holding still and waiting for the new legislations to be implemented, so a certain planning horizon exists.

Figure 12

Global annual investments in biofuels 2004 - 2018 (USD billion)



Source: IRENA (2019)

5.1.2 Future Policies and Investments

Future policies and investments will most likely be shaped by the exact same dynamic described in the previous chapter 5.1.1, meaning continuous development of policy instruments. Nevertheless, to facilitate investments in the future, detailed and target specific policy instruments will have to be combined with enabling a longer planning horizon for investors (Panoutsou et al., 2021). This dynamic is also recognized by the experts interviewed. In this regard, it was stressed by multiple interviewees that *need for change, policy adaptation, higher targets, and a certain granularity in the regulations* "is not recognized to sufficient extent by politics". Creating more stability and certainty in this market to attract investments is highly demanded by experts. One respondent criticized that apart from "Refuel Aviation", which does provide some certainty for the next 25 years, no clear perspective for any kind of technology or fuel is provided for the time after 2030. Moreover, it was clarified by various experts that current policies do not prevent established market participants, especially from the fossil fuel industries, from exploiting regulatory loopholes and by that just reinforcing the status quo: "If you ask these companies off the record, they all will say that the government has to put much higher targets into place", as an expert in sustainable fuels stated.

Moreover, the current system allows for loopholes, respectively does not thoroughly mitigate fraud. The European Commission (2021, p. 10), depicts exemplary cases, such as the „fraudulent creation of biofuel credits/certificates or soy biodiesel being fraudulently sold as used cooking oil methyl ester (UCOME)". The European Commission (2021, p. 11) also underlines the length and complexity of supply chains, as well as feedstocks that can be easily collected and traded globally, such as UCO and processing residues, "which feed into international fuel and chemical markets (e.g., methanol)", are prone to fraud. In this sense, and looking into the future, the risk for feedstocks having similarities with UCO, like other waste fats and oils, could face similar fraud risks". This could also constitute a risk for the future rollout of lignocellulosic advanced biofuels and the traded intermediates that are projected to consist of bio-crude oils as a large part, as interviewees have also emphasized. As long as those gaps in legislation can be exploited, the development will stagnate. This is why the experts interviewed expressed the *need for more case specific and precise regulations.*

The RED_III, which is currently under development, is ought to provide more clarity and higher sector specific targets, such as 5,5% share of Annex-A biofuels, of which 1% is ought to be covered by RFNBOs (European Commission, 2023b). Even though higher targets are important in the broader picture, one expert still pointed out that the rapid change from RED_II to RED_III creates uncertainty for investors. Finally, the rollout of (lignocellulosic-) advanced biofuels depends on climate policies and policy instruments, such as sector specific support and quotas on blending targets. Those are the factors that can really impact the development and steer guide it in the intended direction.

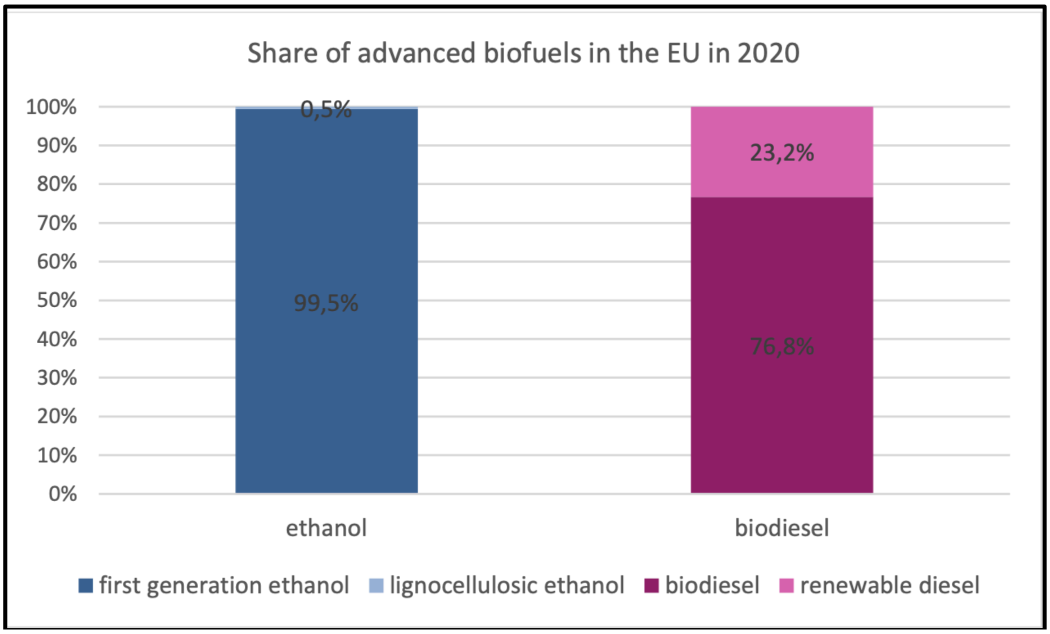
5.2 Advanced Biofuel Deployment in the EU

5.2.1 Current Deployment

The exemplified context conditions in the previous section 5.1, provide part of the explanation for the status quo of advanced biofuels in the EU and the low quantity currently produced and deployed. As *Figure 13* portrays, in 2020, the share of lignocellulosic ethanol in the EU was at 0,5% (European Commission, 2022). The largest share in the overall advanced biofuel production (23,2%) still comes from renewable diesel, produced from feedstocks listed in the Annex IX-B of the RED_II, which is mostly represented by used cooking oil (UCO).

Figure 13

Share of advanced biofuels. Use in the EU in 2020

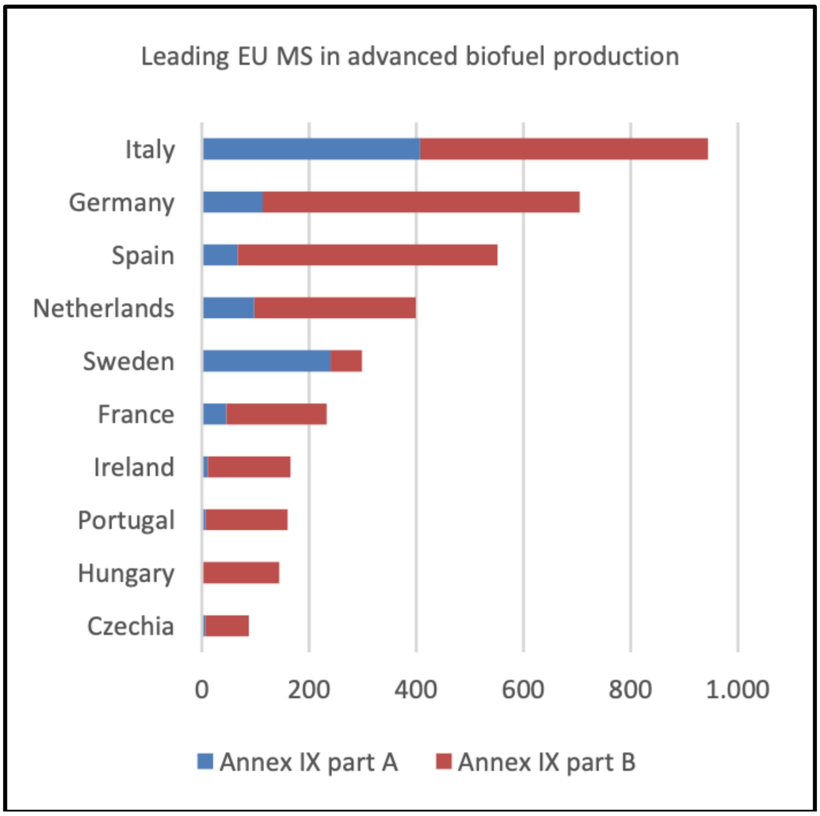


Source: (European Commission, 2022, p. 22)

The production capacity per member state level allows for further insights into the distribution of production within the EU and which countries are currently leading the change in the European renewable fuel production. As the numbers depicted in *Figure 14* show for 2020, Italy was the leading country in overall biofuel production, producing almost 1 Mtoe of biofuels and being in the lead especially for producing the most Annex-A-type biofuels (~ 400 ktoe/year). Germany was the country producing the second most biofuels, (~700 ktoe/y, or 0.7 Mtoe/y), of which around 600 ktoe/y was biodiesel, thereby being the leading country in Annex-B-fuel production. Even though Sweden produces the fifth most biofuel overall, it is on second place, when it comes to Annex-A-type fuel production. (European Commission, 2022).

Figure 14

Biofuel production capacity per member state and type in the EU (in ktoe/year)



Source: (European Commission, 2022, p. 22)

The mismatch between overall decreasing investment in advanced biofuel since 2011 (*Figure 12*) and the increase in use of advanced biofuel in the EU since 2011 (*Figure 15*) is conspicuous and can be attributed to the constant development of policy instruments since 2009 (*Figure 11*) that incentivize the use of advanced biofuel and especially lignocellulosic advanced biofuels in the EU (Chapter 5.1.1).

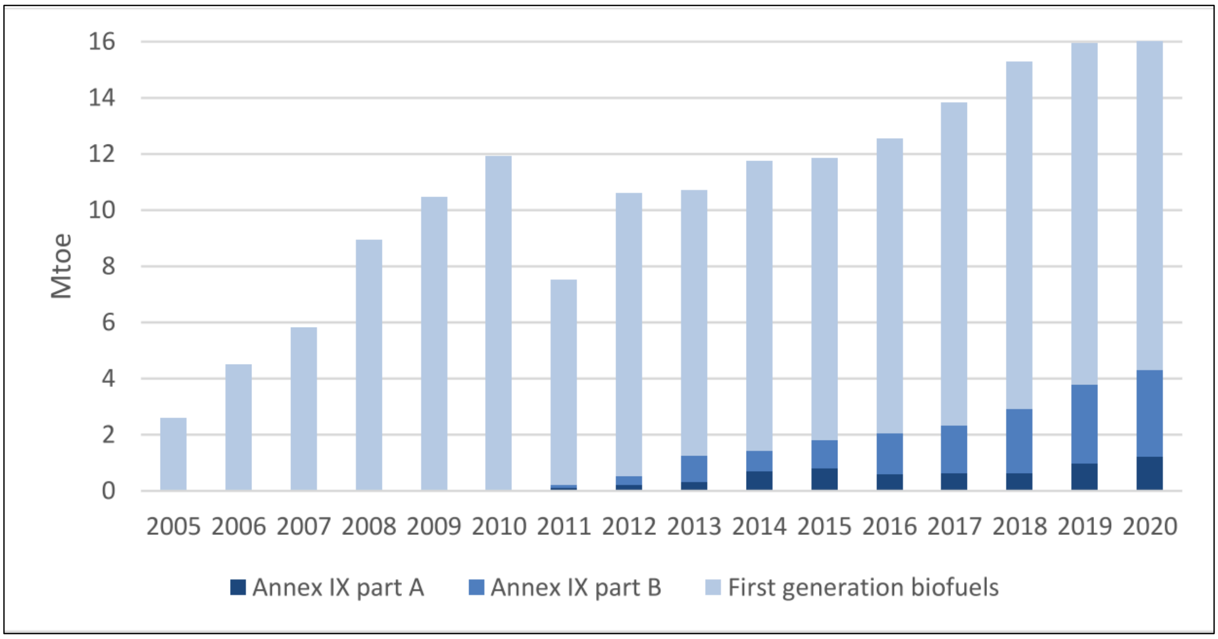
The consulted experts mentioned a diverse range of arguments for the slack in advanced biofuels development. An argument that has been mentioned by a range of different specialists in the field is the phenomena of *picking the low hanging fruits* when it comes to stepwise approach of investigating solutions for system immanent problems. Solutions are perceived as best-case solutions, when short term feasibility and short-term cost minimization of potential solutions are given. "Barriers are that we still find a lot of low hanging fruits. Options with low costs, which are fairly easy to turn into fuels" are preferred, as an expert in advanced biofuels claimed. This is underlined by another expert who strengthened this argument by pointing at HEFA and UCO constituting the vast majority of advanced biofuels feedstock, even in terms of feasible technology, because "the technology is already there". Implicitly, a critique of the capitalistic short-term profit orientation runs through the respondents' arguments when explaining their perception of stagnating dynamics in the field. "We try to get the cheapest way to help support the markets to contribute the cheapest renewable energy source into the market", as one respondent emphasized in this regard.

Another aspect, subsequent to the phenomena of picking the low hanging fruits, is mentioned by the experts interviewed, and pointed out in the literature. It is the prevalence of *lock-in effects* that constitute a major burden for the development of advanced biofuels (IRENA, 2019). Lock-in effects, respectively the prioritization of the, easy, and cheap solutions constitute an underlying impediment:

"The system does not exist without effort. But this effort was made at some point in the past and the system exists now. This makes it more difficult to change it“, as a specialist in CtL emphasized. Another expert, working in the fossil fuel industry claimed that using existing type of refineries and storage facilities creates a lock-in effect, "because it is just cheaper to keep using it". This is also confirmed by the literature (IRENA, 2019). Respondents of a survey regarding the major burdens for advanced biofuels have stated, among other aspects, that "supply chains for UCO and animal fats are challenging by being wide and dispersed" (IRENA, 2019, p. 23). This significant predominance of Annex IX-B fuels and technologies and the lack of mature technologies for Annex IX-A fuels was a matter of consideration for experts: "The only Annex-A advanced biofuel that we can really produce ourselves to a certain extent at the moment is biomethane and, to a certain extent ethanol", as a specialist in advanced biofuels emphasized. The same expert emphasized that he was accompanying demonstration projects in this field for over 20 years, concluding that lack in progress of those projects as opposed to the original aspirations by the project's participants, prevailed. Looking at the use of advanced biofuels in the EU allows to depict the current situation more thoroughly. As shown in *Figure 15*, consumption of advanced biofuels started to ramp up in 2011 and reached around 1 Mtoe by 2020.

Figure 15

The evolution of the use of biofuel, including advanced biofuels in the EU

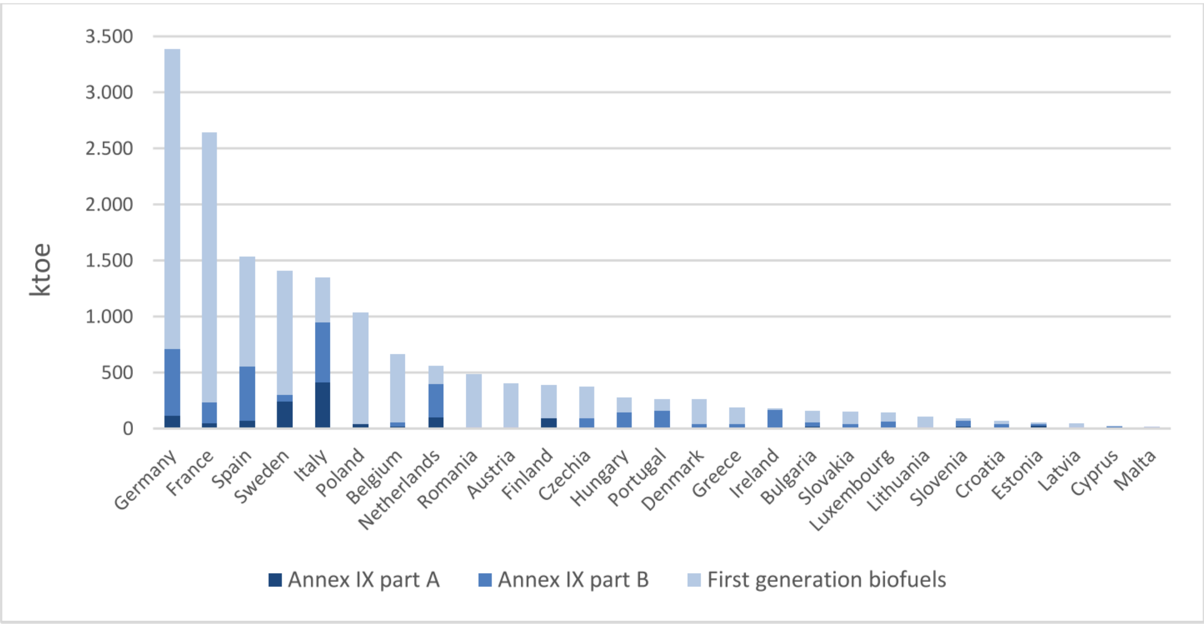


Source: (European Commission, 2022, p. 23)

Looking at the consumption of biofuel and advanced biofuel by individual member states (*Figure 16*), it can be concluded that Germany consumed the most biofuel in 2020 with almost 3.5 Mtoe, of which just under approximately 0.1 Mtoe was advanced biofuel. Just like Germany, no country in the EU even reaches 0.5 Mtoe in biofuel consumption, with just two countries consuming but also producing noticeably more than other countries. Italy is the frontrunner in advanced biofuel consumption, with about 0.4 Mtoe use and Sweden with around 0.25 Mtoe use of advanced biofuels (*Figure 16*). Explainable is this by both countries having specific policy support mechanisms in place that facilitated biofuel and advanced biofuel uptake relatively early (Giuntoli, 2018). Furthermore, the European Commission approved a 4.7€ billion public support scheme for biomethane and biofuels in Italy, which ran from 2018-2022 (EBA, 2023) thereby significantly supporting Italy's position in the field of advanced biofuel production.

Figure 16

The use of biofuel including advanced biofuels in member state of the EU (in ktoe/y)



Source: (European Commission, 2022, p.24)

As depicted above, the status quo for advanced biofuels in the European Union is quite clear and transparent. When it comes to the projections of future deployment, especially on the member state level, this appears differently. The Green Deal (2019), in its nature of a policy roadmap, takes the European Commission and the member states in charge and avers the enforcement, delivery and implementation of policies and legislations. Subsequently, experts likewise stress the importance, and the need of the respective member states to increase their targets, implement those targets on the national level and put them into practice respectively. Generally, "the policies and targets, indicated on EU level will have to be transferred to national law by the individual member states", as an expert emphasized to stress the multi-levelness of the issue. An expert in advanced biofuels policies confirmed that and stated that even if the directive needs to be implemented by the member states, those "member states have a lot of discretion and a certain freedom, how they implement the policies".

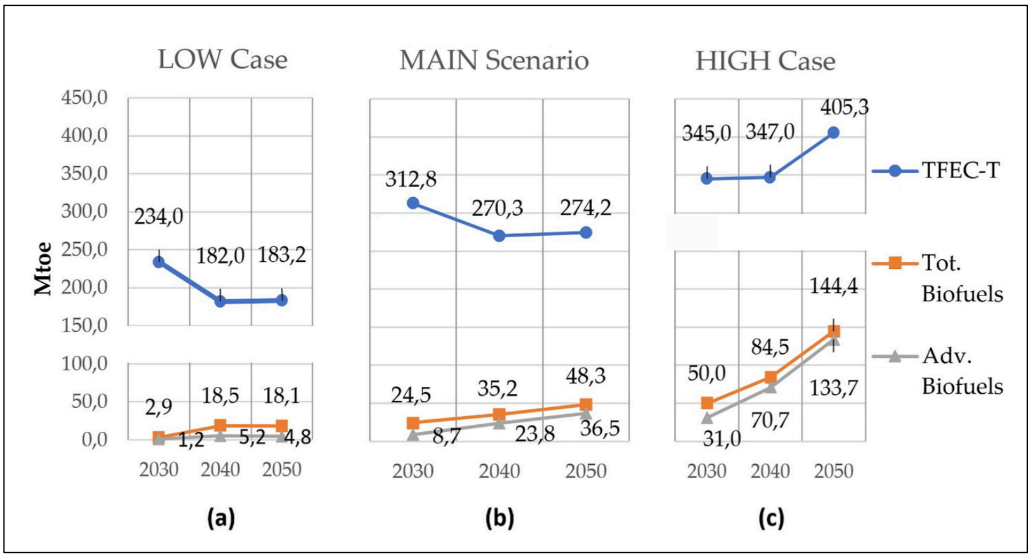
5.2.2 Future Deployment

As mentioned in the problem description in chapter 1.1, considering national and regional energy systems is crucial for the implementation of advanced biofuels. Therefore, this research aimed at depicting the targets and projections of individual member states, both, to check for individual member states accountability in reaching the respective goals and for providing a clearer and more detailed picture of the *future projections for advanced biofuel deployment in the EU*. Nonetheless, most scenario projections of advanced biofuel deployment, including EU PRIMES, are exclusively reported at the EU level and do not present details of individual member states. This is also confirmed by Chiaramonti et al. (2021, p. 10), who point out the difficulties in collecting data and underline scarcity of available and accessible information for the works of interest.

The publications and reports reviewed provided clarity on the lack of relevant information on both detailed projections of advanced biofuels in the EU at the macro level and comprehensive estimates and targets at the member state level. Out of the 15 publications reviewed, just 3 studies do provide projections from the last five years, cover entire Europe, and depict specific projections for advanced biofuels. Chiaramonti et al. (2021) has been mentioned in the problem description already and is one of the studies that show specific ranges, as depicted in *Figure 17*.

Figure 17

Total final energy consumption in the transport sector: Low-, main- & high case



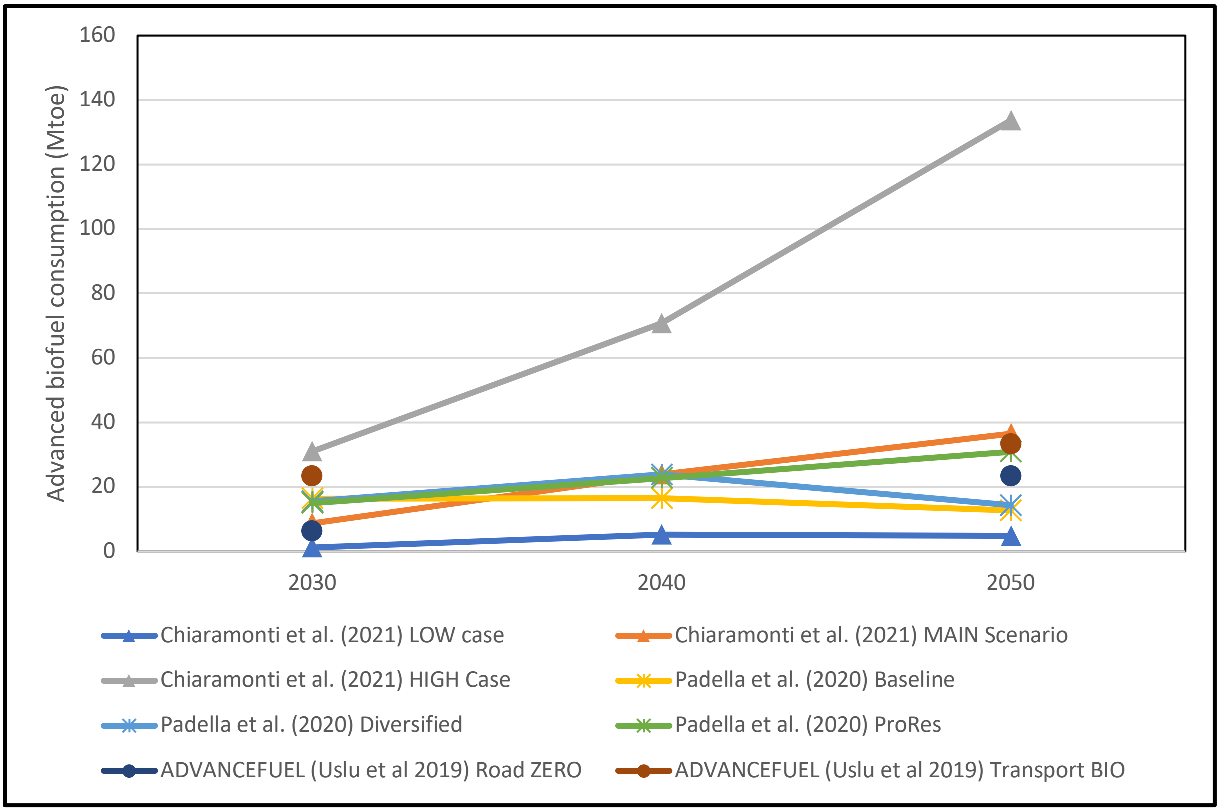
Source: (Chiaramonti et al., 2021, p. 7)

Chiaramonti et al. (2021) project a wide range of 1.2 – 133.7 Mtoe in demand of advanced biofuel in the period of 2030-2050. This vast range is conspicuous and can be explained by the prevailing uncertainty in the field of advanced biofuels, including mainly uncertainty about policy development and concomitantly stagnating investments as described in 5.1. Chiaramonti's projections are generally focused on Total Final Energy Consumption in the Transport sector (TFEC-T). The HIGH Case "displays a rising trend for TFEC-T, due to more expansive assumptions forecasting a general increase in transport activities" and share of advanced biofuels, "well above the expected effect of efficiency increase" (Chiaramonti et al. 2022, p. 6). The LOW Case depicts a situation in which "the REDII target for advanced biofuels is not expected to be met, with projections of 1.2% share of TFEC-T for total biofuels and 0.5% share for advanced biofuels by 2030" (Chiaramonti et al. 2022, p. 6). Due to the extreme nature of these scenario specific framing conditions, the high and low case are excluded for the average projections.

Figure 18 contextualizes Chiaramonti's projections with two other projections of energy system modelling studies on the EU level. Chiaramonti et al. (2021) and Padella et al. (2020) cover three different scenarios each. Additionally, two different scenarios drawn in Uslu et al. (2019) for 2030 and 2050 are also integrated in the figure. If Chiaramonti's *HIGH and Low Case* is excluded, estimated future demand for advanced biofuels, depending on the differing scenario conditions of the respective model, range from 8.7 – 23.2 Mtoe in 2030, 16.5-23.8 Mtoe in 2040 up to 12.7 – 36.5 Mtoe in 2050. By integrating those scenario projections in one figure, commonalities among those different projections can be portrayed.

Figure 18

Projected advanced biofuel consumption in state-of-the-art modellings



Finally, even though extensive, and detailed projections about advanced biofuels are limited, an indication about the range of demanded advanced biofuels in the future can be concluded. To put those numbers into context, the described future estimates for demand can be contrasted with the amount of consumed advanced biofuel in 2020, which was around 1 Mtoe *(Figure 15*, Chapter 5.2.1). If the average of each year is taken (Without Chiaramonti's High and Low Case) and contextualized with the consumption that prevailed in 2020, a clear picture of the required increase can be drawn (*Table 7*).

Table 7

Ranges, average demand projections and required increase compared to 1 Mtoe of advanced biofuel demand in the EU in 2020

Horizon	Range of projected demand (in Mtoe)	Average projected demand (in Mtoe)	Required percentaged increase (in relation to 2020)
2030	8.7 - 23.2	14.16	~1,400 %
2040	16.5 - 23.8	21.73	~2,100 %
2050	12.7 - 36.5	25.15	~2,500 %

Source: (Chiaramonti et al., 2021; Padella et al., 2020; Uslu et al., 2019)

Complemented by the also very limited information on projections on the member state level, it is immensely difficult, if not impossible for strategy developers and policy makers, to make a solid planning. This lack of planning in turn, leaves a gap of sufficient policy implementations in the respective member states. Member states cannot adapt the European policies and aim for designated goals and numbers of advanced biofuels to produce, if there is no idea and perception about the respective circumstances in the first place. Projections at the EU level can be used for long term planning, but not for deployment strategies or planning at member state level. This leaves a large gap in knowledge which could significantly and enduringly impact the rollout of (lignocellulosic) advanced biofuels.

The wide range of projections, respectively the scarcity in precise predictions is confirmed by expert's statements. Generally, there is no doubt amongst the interviewees that advanced biofuels and especially lignocellulosic advanced biofuels will play an important role in the defossilisation, especially in the transport sector, "we do see a large role for lignocellulosic biomass in our growth strategy", as an expert in SAF emphasized. Nevertheless, the general slack in development constitutes a major burden and is expected to prevail at least until 2030 according to projections for advanced biofuel use (Chiaramonti et al. 2021) or according to development projections of gross European biomass-for-bioenergy consumption (Hoefnagels et al., 2023). Interview findings pointed in the same direction. "Everything will take longer than planned and will be delayed, although there is a supposedly very clear roadmap until 2030 with the Green Deal package", as one respondent stressed. The same expert, who is specialized in advanced biofuel research and consulting, predicted that no significant roll-out will be observable.

Due to the slack in development, expanding the horizon beyond the EU's borders is unavoidable, both in terms of considering international competition for biomass, intermediates, and final fuels, as well as the importance of imports to satisfy the European demand (Andersen et al., 2021; European Commission, 2017; IRENA, 2014). Experts confirm that. One respondent stated: „We live in a rather free market. Import and export […] is already reality for normal biofuels, so I think it is also going to happen for the second generation. Either way, international competition will play a role". Another expert stressed the importance of imports even more clearly, by saying that it "will by no means be possible to fill that demand only by European sources". Either way, increasing international competition for feedstock and the fact that Ex-EU countries will also be interested in creating value in their own country, was emphasized: "Countries will probably also start to produce their own and they're doing it already", as one expert clarified. Another expert in the field of biochemicals underlined this motivation of Ex-EU countries by stressing the economic advantages of advanced biofuel production in the country of feedstock origin: "Whether one imports the product as bio crude oil, or whether the country that sends the crude oil decides to build the refinery themselves and then to sell the finished fuel to Europe, that would make a big difference, because the respective country would then earn much more money, than if it sells only the biomass to Europe. The value leverage and the margins would be considerably higher for the country of origin", as one expert in CtL stated in this regard. Concerning the predicted value creation in Ex-EU countries, an informant also emphasized that competition is to be acknowledged beyond trade of just fuel or intermediates, but rather be regarded more thoroughly, also in terms of policies, legislations and regulatories. „In other parts of the world […] they also develop policies, and they need advanced biofuels […] this could constitute the trigger for a dynamic being unfavorable for the future European advanced biofuels market".

Eventually, the interviewed experts are united by the belief, that the future rollout will have to be *approached step-by-step.* The complexity, uncertainty, and the previously mentioned intricacies cannot be solved contemporaneously. The European rollout "can never sort of emerge sort of all at once", as the SAF expert stressed in that context. With regards to future projections, it can be concluded that ubiquitous uncertainty is the overarching issue. Neither literature, nor experts have precise and well-founded ideas how advanced biofuels and especially lignocellulosic advanced biofuels will develop. Precise models from global, up until regional level are needed, to provide policy makers with guidance on making clear strategies for the future deployment. This clearly stresses the need for more detailed research and better structured and clearly outlined pathways, framed by the respective legislations. As outlined above, the projections especially underline the strong need for further development of advanced biofuels with regards to the member state level, because that is where the legislations are finally applied (European Commission, 2021c). The more clarity prevails on EU and member state level, the more efficient the rollout can be addressed. Right now, there is a large gap in knowledge and therefore a big mismatch between what is needed to come up with adequate and precise projections (e.g., detailed regulatories) and a clear picture depicting the requirements to come up with those projections (e.g., transparency on legislation implementation in the respective member states). And since those aspects are interdependent, for now the uncertainties prevail.

5.3 Locational factors for current advanced biofuel production

The previous subchapter concerned themselves with policy conditions, the resulting investment dynamics in the field of advanced biofuels and energy system modelling-based future projections with regards to advanced biofuel deployment until 2050. On the one hand, location specific information on advanced biofuel deployment on a member state level is missing, respectively not available. On the other hand, uncertainty still prevails about location specific factors that could influence the development of advanced biofuel deployment in the EU. The following subchapters aim at shedding light onto those uncertainties by first investigating *current locations and locational factors* of advanced biofuel refineries. Location specific factors that will be relevant in the future are addressed by investigating a range of supply chain models. Just as in the previous chapters, those findings are brought together with the insights from expert interviews.

The context conditions delineated in the chapter 5.1 provide the explanation for the stagnating development of advanced biofuels. As shown in chapter 5.2, the deployed number of advanced biofuels and especially lignocellulosic advanced biofuels is marginal. To get insights in the future locational factors of advanced biofuel refineries, light is shed on current plant's locations. Where current plants are located and what the surrounding conditions are, provides relevant information for the future rollout. This is also emphasized by Fortenbery, Deller & Amiel (2013), who make that point for current biodiesel plants and the respective insights that could provide for understanding locations of next generation biorefineries. The selection of facility location and decisions on aspired capacity of biorefineries are important long-term decisions, as Lin et al. (2014) state. The selected biorefineries were chosen based on their status.

Figure 19 depicts the status of the plants considered for this location analysis. Construction of plants are always based on strategic decisions. Strategic decisions cover decisions such as determining facility locations and capacities (Lin et al. 2014). Zhu and Yao (2011, p. 10937) describe strategic decisions as "long-term system plans that establish the system for years and are not subject to change in the near future e.g., the distribution strategy of either direct transportation or transshipment via intermediate warehouses, the locations and capacities of warehouses, and the composition and size of harvesting team" Therefore, it can be assumed that a thorough location analysis has been executed prior to the final location decisions of the respective plants. The location analysis executed and exemplified by the satellite images in chapter 3.2, resulted in the following findings. According to the industrial location theory, agglomeration describes a geographic location "at which economic activity is particularly dense" (Webber et al., 1985). The results shown in *Figure 19* portray the findings of the Google Maps and Google Street view analysis described in the methodology.

Figure 19

Status of considered biorefineries for the location analysis

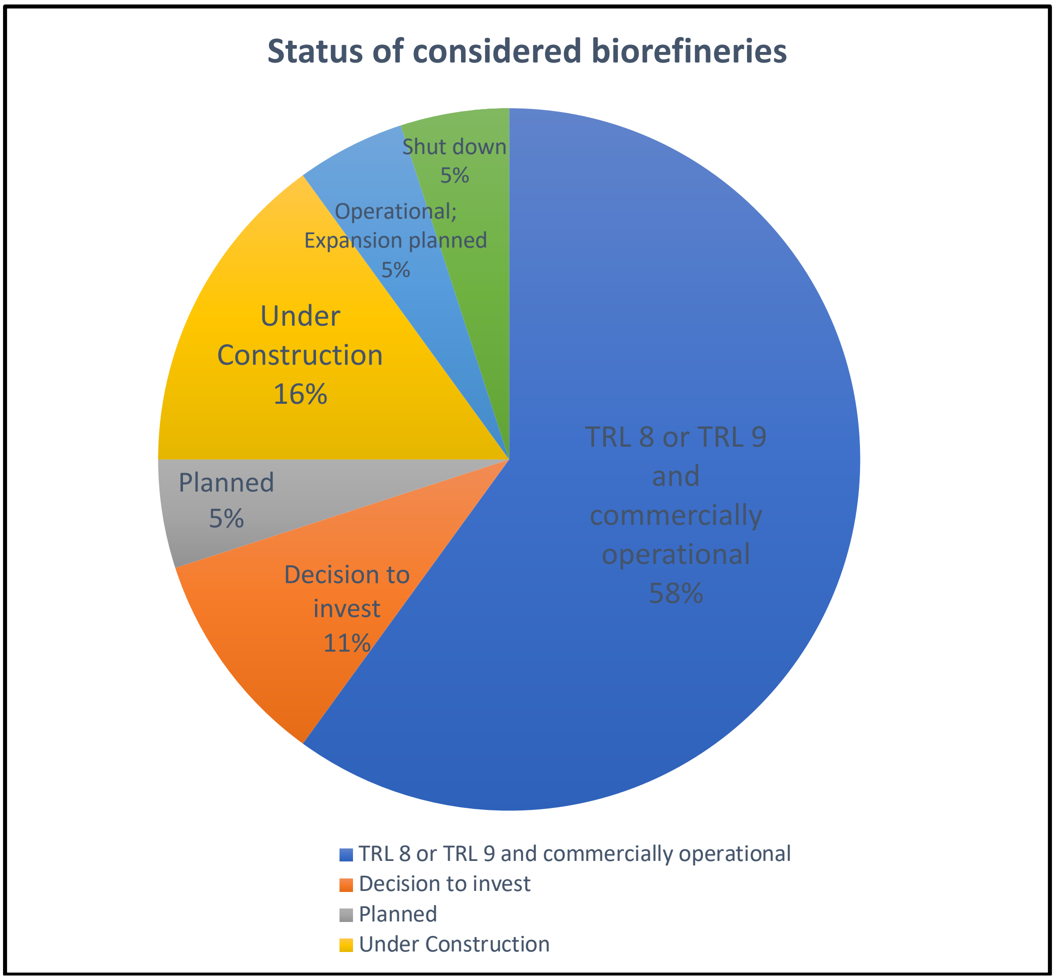
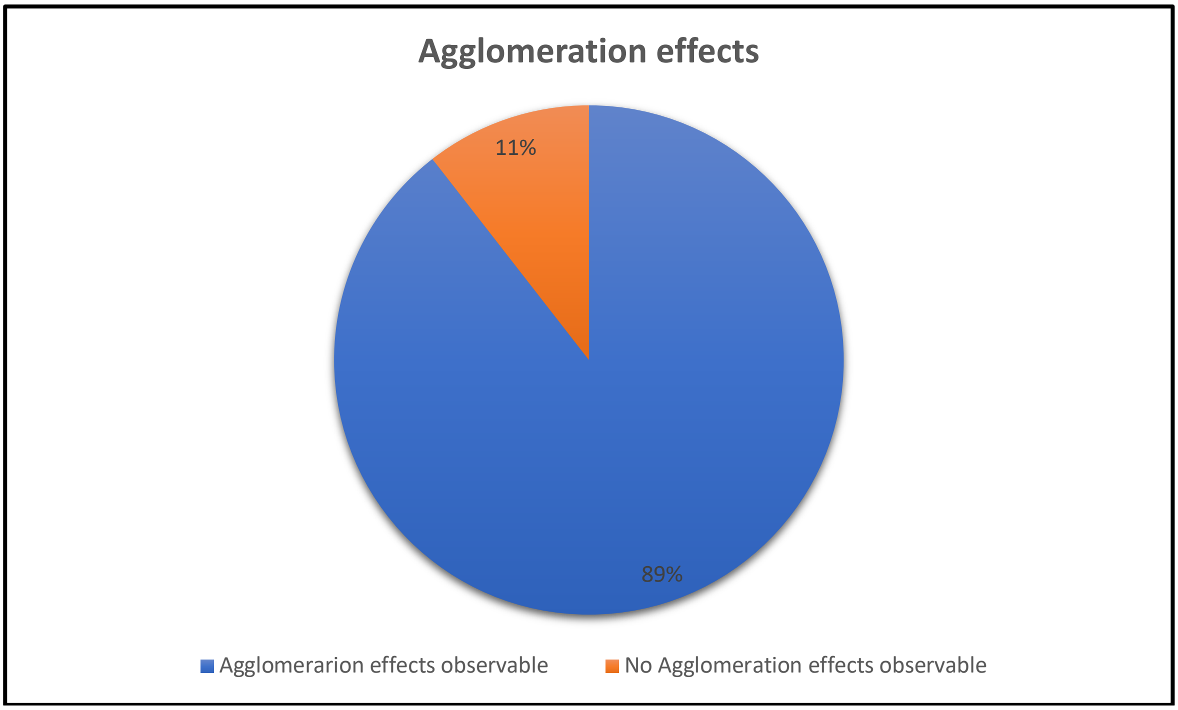


Figure 20 represents agglomeration effects that could be observed during the location analysis of current plants operating with lignocellulosic feedstock. Out of the 19 biorefineries that at least use lignocellulosic biomass as part of their feedstock and are currently working or being planned, 89%, so 17 plants are located in an area with ongoing industrial activity be that just one adjacent sawmill or a large harbour area with multiple adjacent industries. Just 2 plants, one in Italy and one in Romania, are built in an area or at a location where there are no adjacent firms or industries with which they would create synergies. Of the 17 plants located in an area with ongoing industrial activities, 10 are in Sweden or Finland and 1 in Austria. All 11 plants use forestry residues (saw dust, wood chips etc.) as feedstock. Satellite pictures clearly show the plants being located in areas together with other companies working in the wood or energy or industries, respectively companies that could create value in the supply chain, such as logistics or transport companies.

Figure 20

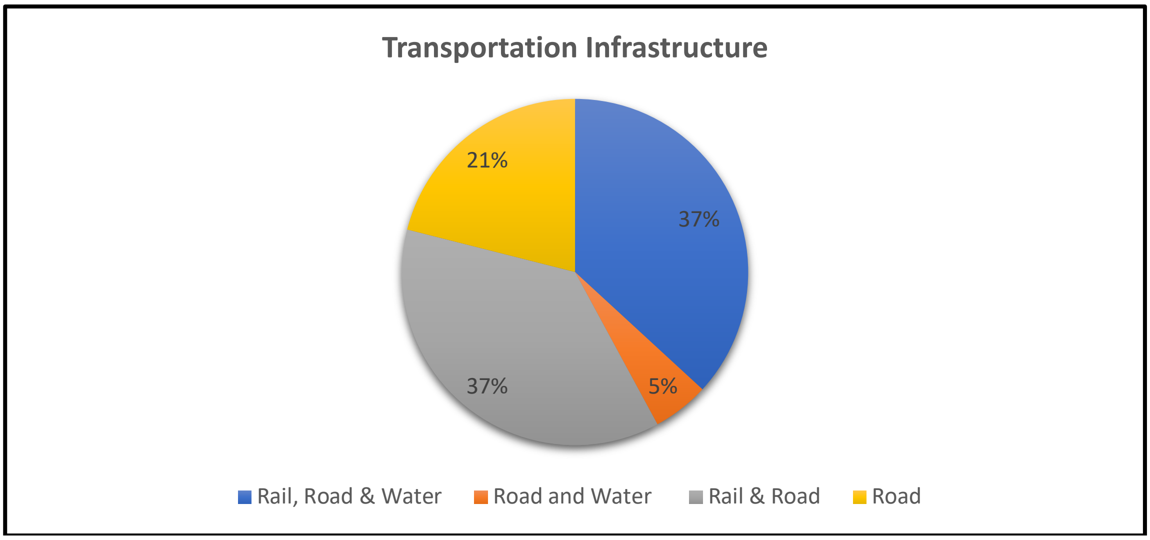
Observable agglomeration effects in the respective geographic area



The importance and advantages of such industrial areas for current, as well as future developments of advanced biofuels, was also stressed by interview respondents: "Crucial infrastructural locations like harbours or, for example Rotterdam have been and they will probably be most crucial for importing the energy dense materials and then either distribute them locally or finalize it to the to the end product and then just utilize what we have."
Since agglomeration dynamics could be identified for 89% of the existing plants that at least partly use lignocellulosic material as feedstock, a more detailed focus was put on the adjacent transport infrastructure, surrounding the biorefineries. Infrastructural connection to rail, road and waterways, or different combinations of those were checked for. Waterway access in this case is defined as having a designated loading and unloading port facilities at a cargo ship accessible river or lake system (that has access to the sea). *Figure 21* presents current plants' access to transportation infrastructure.

Figure 21

Current biorefineries and their access to transportation infrastructure



Most transport connections were represented by the respective plant either having access to all options, meaning rail, road and water, or being connected to rail and road infrastructure. Approximately a fifth of all plants (4 plants) just have a road connection, whereas 74%, or 14 out of the 19 plants have a connection to rail, road and waterways or just rail and road. 4 plants, or 21% just have road access and just one plant has access to road and waterways. This shows that existing infrastructure or the potential to connect newly build infrastructure to existing ones, either plays a crucial role in location decision or constitutes a prerequisite for successful operations of advanced biofuel plants.

5.4 Locational factors for future advanced biofuel production

Following the enhanced industrial location theory, *context conditions* in terms of policy and investment situation, *least cost transport*, and *supply chain aspects*, complemented by *infrastructural considerations and agglomeration effects*, represent deciding factors for locational decisions of industrial activities. From a *supply chain efficiency* perspective, Mafakheri and Nasiri (2013) stress the choice of an adequate harvesting site, including a proper collection plan, as well as optimal location decisions of bioenergy plants, transportation options and logistics costs, as crucial aspects to consider. The main purpose of the reviewed supply chain models revolves around either location problem of a conversion plant, pretreatment and conversion set-ups, optimization of supply- or production systems, or generally optimization or cost reduction strategies of advanced biofuel logistics. This allows for overarching conclusions in terms of all-uniting location-, logistic-, transport- and infrastructure factors to reduce cost and thereby yielding important locational factors. This subchapter combines the findings of the interviews with the results of the supply chain model review.

5.4.1 Feedstock supply cost & Logistics

The importance of feedstock supply cost and logistics for location decisions was already pointed out at the beginning of the 20th century in Weber's original theory of industrial location and was similarly mentioned by the specialists interviewed: "At the moment there are vast sources, but they are not being utilized or only to a very limited extent. And that's of course because of logistics, it's not easy to collect these agricultural residues and make them available for let's say production at large scale", as an expert in advanced biofuels highlighted the critical significance of logistics, encompassing infrastructure and transportation, in determining future production sites. Alfred Weber described the same in his theory, touching upon it as the necessary consideration of feedstock and market access (see chapter 2.4; *Figure 3*).

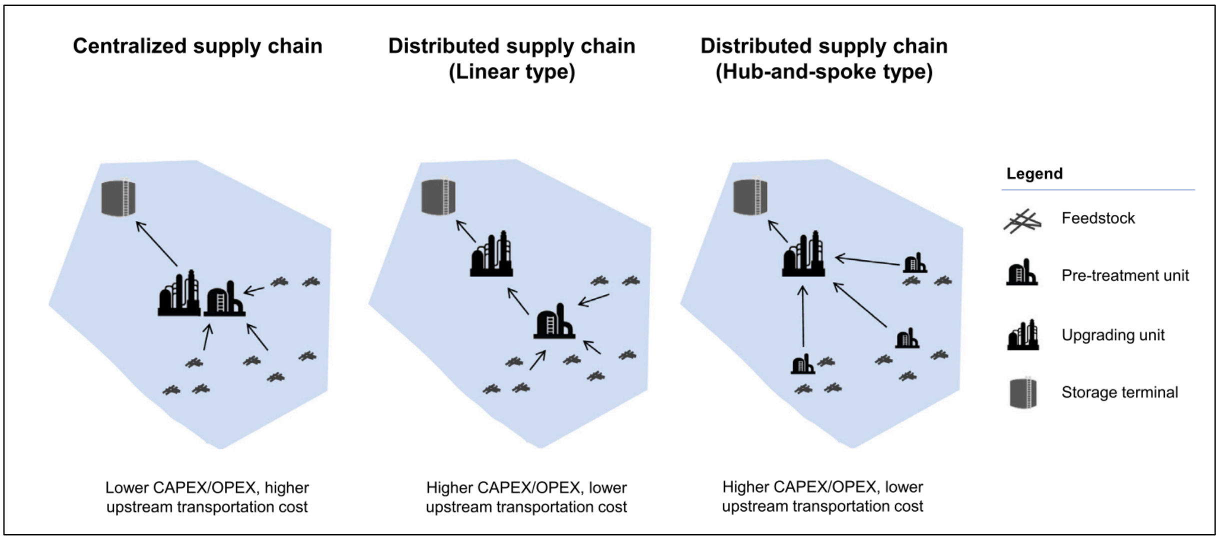
The significance of biomass availability and the challenges linked to feedstock collection and transportation for plant locations have been addressed by supply chain models (Akgul et al., 2010; Bojic et al., 2017; De Jong et al., 2017; Martinkus et al., 2018) and multiple interviewed experts. For instance, a biofuel industry expert in the US emphasized that "securing the long-term supply of feedstock" is a fundamental consideration when contemplating biomass utilization. This vital aspect of biomass availability shapes the foundation of supply chain configurations (Ng & Maravelias, 2016). Although experts rarely explicitly mentioned supply chain logistics in discussions about the future, they implicitly acknowledged their importance. A specialist in the oil industry highlighted that "logistics is a key aspect in this context" for the future rollout of advanced biofuels. *Feedstock matters*, encompassing distribution, characteristics, proximity, and underlying costs, are intrinsically linked to the dynamics of logistics (Zhu & Yao, 2011) and concomitantly linked to location considerations and by that to the future rollout at large. Feedstock intricacies are also confirmed and described by an expert from the SAF industry, who states that: "Cellulosic biomass is just a very challenging feedstock […] it's very spread out. So it's hard to collect hard to transport and then it's also quite heterogeneous in in terms of chemistry and composition and contaminants".
Looking at the literature, A wide range of available biomass is indicated by energy systems models (European Commission, 2017) , including the observation that the advanced biofuel requirement could be more than met by EU Member States, with suggestions that some states might even have over ten times the necessary amount (Searle & Malins, 2016). However, it's important to acknowledge that these models often neglect the economic viability aspect of advanced biofuel production.

Going beyond feedstock inherent characteristics contemplated in the modellings, experts added viewpoints that expand basic model assumptions, affect feedstock and transport cost, and hence economic viability at large. Thus, these aspects represent location specific- or regionally specific factors to be considered when evaluating potential location suitability that implicitly impact costs. Such added considerations touch upon *feedstock certification and its traceability* as well as *contractual situations with feedstock suppliers* and locally existing access to renewable process energy and hydrogen, available workforce and skilled employees, local political and economic context conditions. Together with aforementioned feedstock characteristics and its inherent complexities, such circumstances constitute a challenge looking at the needed development of the field.

To address those intricacies, especially in the future, Mafakheri and Nasiri (2014) stress that the configuration of biomass supply chains is greatly influenced by the choice between centralized bioenergy production (involving a large conversion plant) and decentralized bioenergy production (involving several distributed small plants). De Jong et al. (2017) depict the respective supply chain configurations as shown in *Figure 22*.

Figure 22

A schematic image of centralized and distributed supply chain configurations



(Source: De Jong et al., 2017, p. 1056)

Studying the relevant supply chains models yielded in corroborative findings. Supply chain models were chosen due to a general focus on logistics, transport and/or finding case specific solutions for supply chain optimization or cost minimization problems. Yet, a substantial number of supply chain modellings considered centralized or distributed supply chains, either explicitly by optimizing a predetermined model setup (Kim, Realff, & Lee, 2010; You & Wang, 2011) or implicitly by concluding centralized or distributed supply chain as a dominant strategy within a certain range of considered model optimizations (Martinkus et al., 2018). *Table 8* depicts the studies and the considered logistics systems.

Table 8

Logistics systems considered by reviewed supply chain model studies

Logistics system considered	Study
Distributed supply chain (Hub and Spoke; “advanced”)	Kim, Realff, & Lee, 2011; Kostin et al., 2018; Martinkus et al., 2018; Ng & Maravelias, 2017; Zamboni, Shah, & Bezzo, 2009; Zhu & Yao, 2011
Centralized supply chain (“simple”)	Jåstad et al., 2023; Lin et al., 2014; Zhu & Yao, 2011
Centralized vs. Distributed supply chain	Kim, Realff, & Lee, 2010; You & Wang, 2011
Multimodal/Intermodal Transport	Bojic et al., 2018;Akgul et al. , 2011; Morrow, Griffin, & Matthews, 2006; S. de Jong et al., 2017
General (cost) optimization of the logistics system	De Mol et al., 1997; S. de Jong et al., 2017; Zhu & Yao, 2011

Finally, insights from supply chain models and expert interviews indicate a picture, in which centralized and distributed supply chains will constitute the dominating logistics set-ups in the future.

5.4.2 Centralized Supply Chains

Centralized supply chains refer to the approach of performing the pretreatment of the feedstock, at the same location, as the final conversion takes place (Kim et al., 2010). Due to performing all processing steps at on location, OPEX and CAPEX can be decreased, and easier management of the process chain is facilitated (Kim et al., 2010).

Five Supply chain models generally considered centralized supply chains (see Table 7). Two supply chain models compare centralized supply chains with distributed supply chains (Kim et al., 2010; You & Wang, 2011), whereas three supply chain models at least consider them as part of a growing process (Jåstad et al., 2023), or in the context of logistics and supply chain optimization (Lin et al., 2014; Zhu & Yao, 2011). In all cases, the importance of feedstock availability and feedstock proximity to the plant is emphasized and minimization of transportation distances is underlined (Lin et al., 2014). "For a Lignocellulose plant, it makes sense that it should be located near grain-growing regions, so that transport distances can be kept as short as possible and sustainability can be increased", as an expert in lignocellulosic advanced biofuel research confirmed. *Feedstock proximity* is not specified in terms of a generalizable definition of kilometers in the individual modellings, however specialists interviewed mentioned ranges of 50-150km as a range when talking about raw and unpretreated lignocellulosic biomass to conversion plant, depending on the feedstock. "It makes no sense to transport straw when there is more than 50 kilometers radius. With wood, the ratio to the energy required for transport is better […]", as one interviewee claimed. Another respondent added that "it's very hard to reach scale in these types of facilities because typically your collection radius is 100 kilometers […] it's very spread out. So it's hard to collect and hard to transport".

Moreover, it can be concluded that if centralized supply chains are compared to distributed supply chains, at least in the long run, due to economies of scale and mature markets, distributed supply chains are the most economically viable option, however in the small and more immature case, small scale centralized supply chains are a viable option (Jåstad et al., 2023).

Generally applicable conclusions are difficult to draw. For the case of large scale centralized biorefinery, such as modelled by Lin et al. (2014) it can indeed be stated that large centralized lignocellulosic biorefineries must have a focus on feedstock abundance and feedstock proximity to be economically viable. Geographic characteristics and abundance of the grain growing regions in the US partly differ from European characteristics, yet most sustainable biomass availability both in the US and Europe is considerable. Furthermore, the potential for agricultural residues in 2030 is projected to be more than double that of forest residues (Balan, Chiaramonti, & Kumar, 2013), insinuating large scale centralized plants to be more applicable in the US compared to Europe.

Either way, the concept of centralized large scale conversion plant is just suitable with vast amounts of feedstock steadily available and feedstock proximity as being a major factor. Only one plant like that is currently operating on a commercial scale in Europe. The lignocellulosic, large scale conversion plant in Podari, Romania. This plant shows the difficulties with this approach. One expert, who works in the field of lignocellulosic advanced biofuels research and consulting and who has supervised such projects for over 20 years stated that "it is one of the first, and presumably the only foreseeable plant […] it is still trying to reach scale and is not yet operating at full capacity". Finally, the locational factors for centralized supply chains can be summarized as feedstock availability and -proximity as the pivotal aspects.

5.4.3 Distributed supply chains

Distributed supply chains or „hub and spoke networks" as they can also be delineated and as depicted in *Figure 24*, describe supply chains, that are not linear, meaning that an intermediate densification step of the biomass early in the supply chain is used (e.g., palletization or liquefaction). This is done to reduce transport cost, even though it implies an increase in CAPEX or OPEX at the same time (de Jong et al., 2017).

All studied supply chain models considering distributed supply chains are unified by the fact that a more complicated system requires for smart application of pretreatment and storage facilities, plus the least cost transport between the respective facilities (De Mol et al., 1997; Jåstad et al., 2023). In this context, experts emphasized that densification and/or pretreatment of feedstock close to raw material is and will be important to reduce transport cost and transport efficiency. One specialist stressed in that regard that "what you need is to develop these logistics chains with initial pretreatment units locally at the scale of where the agricultural residues become available".

Compared to the centralized and linear supply chains, the considerations of distributed supply chains must include another level, which exceeds state-of-the-art feedstock availability, transportation distance minimization and logistics optimization. Due to the larger complexity and extensiveness of such a supply chain system, the *time* it takes for a distributed system to develop is of crucial significance either. Both according to the supply chain models reviewed and the expert interviews conducted, distributed supply chains constitute the most likely supply chain set up for the future of lignocellulosic advanced biofuel supply chains, under the condition of a mature market in place. This was mentioned explicitly by De Jong et al. (2017), who emphasized that distributed systems are part of the final model outcome to reduce overall cost, yet "neglecting the fact that production systems grow organically and originate from bottom-up action of single actors" (De Jong et al., 2017, p. 1068). Implicitly a mature market is for example insinuated by (Kim et al., 2011), who expected maximum demands for their optimal model outcome and by Martinkus et al. (2018), who assume to have established co-location and repurpose strategies in place. Maximum demand, as well as an establish co-location infrastructure in place, constitute attributes, that can just be assumed in a more mature and saturated market, which is far from the current state-of-play. Subsequently, it was emphasized by experts that the future rollout is not an "all at once" approach, but rather that it will be an iterative process, just like the policy cycle mentioned in 5.1.1. The SAF expert clarified in this regard: "I just cannot make the case that I'm going to build 5 pretreatment facilities and one biorefinery, because that's just too complicated of an investment […] We're not going to build a hub and spoke system ourselves […] in the end this is going to be sort of a bottom-up effort". In this context, various experts underlined that the most likely system to evolve in the future will consist of small- to medium scale distributed supply chain systems and some large centralized biorefineries at strategic locations to foster the advanced biofuel rollout in the EU. One specialist posited in this context that "a few large refineries doesn't add up either. We need many large refineries, but we also need small ones that can make better use of regional biomass".

Simple one-step treatments for simple technologies and close to feedstock is the way to approach the rollout as an expert from the pulp and paper, respectively biochemicals sector stressed. The expert, who is in a leading position at a known company that produces biochemicals partly out of lignocellulosic raw material, enumerated that adding another intermediate step, "naturally extends the efficient transport distance". He concomitantly exemplified that there are just two viable options to approach the feedstock inherent characteristics in the future, which are either (co-)locating in areas where existing feedstock, infrastructures and synergies can be exploited (which is what the expert's company did), or to locate where feedstock is abundant and build the refinery at a scale that compensates for the additional costs implied in the remote location and the construction of the greenfield plant and its connected supply chain.

5.4.4 Transport, Infrastructure & Agglomeration effects

Transportation and infrastructure will play an increasing role in the energy transition as pointed out in the Green Deal (2019). Rethinking policies, for clean energy supply, large-scale infrastructure, transport, multimodal mobility as well as energy storage, retrofitting and upgrading of existing infrastructure have been highlighted (European Commission, 2019). Important insights related to transportation and location-specific factors have already been discussed while distinguishing between central and distributed supply chains. These insights include considerations such as the significance of feedstock proximity for reducing transportation costs. Additionally, it has been emphasized that transportation patterns vary based on the supply chain configuration. Regardless of the specific setup, there is a consistent emphasis on the need to minimize the transport of lignocellulosic material.

Transportation related infrastructure

Building infrastructure from the ground up is bound to significant costs. Therefore, making use of existing infrastructure and facilities is projected to be the dominant strategy by experts interviewed and implicitly included in supply chain modellings. Transportation infrastructure touches upon road, rail, waterways, and the corresponding facilities such as port areas, loading and unloading terminals, however overall Infrastructure also encompasses existing facilities and industrial areas. Depending on the supply chain model and its individual focuses, transportation and infrastructure is either implicitly assumed to exist (Akgul et al., 2011; Kim et al., 2010; Zhu & Yao, 2011) or explicitly utilized for a specified region and its truly existing transportation possibilities, such as Bojic et al. (2018) neglecting rail lines in their model due to bad condition, just focusing on road and inland waterway transport in Serbia. De Jong et al. (2017) find that the ideal mode of transportation is scale-dependent, and that intermodal transport bears the potential to reduce cost on the one hand and to facilitate economies of scale on the other. This in turn emphasizes the importance of existing transportation infrastructure fostering the economic viability of the supply chain. In this regard one expert underlined the leverage that transport mode in combination with pretreatment has on the transportation distance, which in turn emphasizes that existing infrastructure is a crucial location specific factor to consider for plants to be built in the future.

Agglomeration dynamics and exploitation of synergies

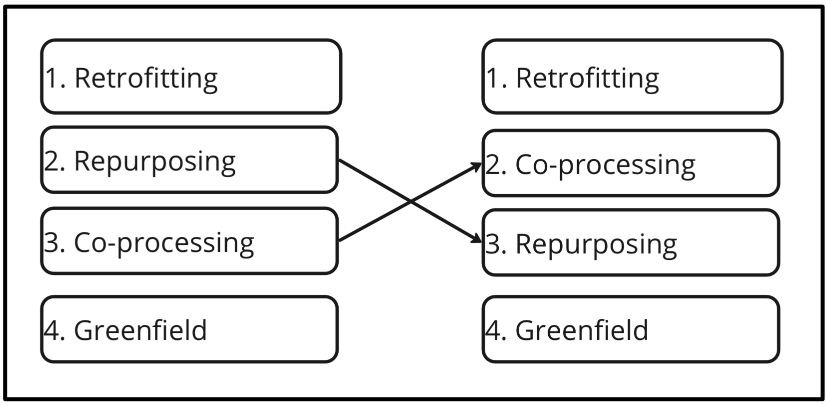
Going beyond transportation related infrastructure, existing storage, pretreatment or conversion facilities, respectively whole industrial areas as a potential leverage have been pointed out as crucial factors to reduce cost, optimize supply chain designs and accelerate the rollout. Implicitly these aspects touch upon *agglomeration dynamics and synergy exploitation* that have been concluded to be crucial in current plant analysis (Chapter 5.3), supply chain modellings (S. de Jong et al., 2017; Martinkus et al., 2018; Zamboni et al., 2009) and expert interviews. One respondent emphasized in this regard that “existing infrastructure, like the connection to rail and ship for example, should be used”. Another respondent expanded that insinuation by emphasizing the need to not just use existing infrastructure, “but also using existing network of plant operators” as a viable way of seizing synergies. The policy expert, who is involved with research on future advanced biofuel systems stated concerning his research, that “one preliminary insight would be that it plays a huge role if you have an industrial transition in that area”. In terms of adequate industries that can be profited of, the chemical and petrochemical industry, as well as the fossil fuel industry at large was named, as these locations would provide convenient prerequisites to drive the transition. One expert exemplified this for chemistry-oriented industrial areas, emphasizing that a mature chemical cluster in place fosters an effortless “shift towards bio based processes”.

Adding to and interrelated with existing infrastructure and agglomeration effects, strategies like *Co-location, Co-processing*, *Retrofitting and Greenfield plants* have been highlighted in the context of the future rollout of advanced biofuels. These strategies, that experts perceive as pivotal for the future rollout of lignocellulosic advanced biofuels, stress the need to capitalize on existing infrastructure and industrial activities in any regard. Whereas Zamboni et al. (2009) specifically highlight the advantages of integrating production and distribution with respective existing infrastructures, Martinkus et al. (2018) are even more explicit and find *Co-locating* and *Retrofitting* strategies for lignocellulosic fuel production as facilitating efficient production and simultaneously emphasizing that attained cost reductions in the early phase of commercialization bears the potential to translate into improved cost-competitive lignocellulosic advanced biofuel refineries. De Jong et al. (2017) explicitly emphasize the cost reduction possibilities that accompany process integration such as *Co-processing* and *Co-location* strategies, thereby underlining those as pivotal location specific factors for a future rollout of such fuels. Jåstad et al. (2023) find that *Greenfield plants* are needed when addressing the exploration of resource-abundant land and the establishment of a biofuel production system from the ground up, as examined for a distinct Norwegian forestry supply chain. This is confirmed by an expert interviewed, who stressed the lacking practicability of *Greenfield plants* in the context of a large-scale rollout: "To set up such a plant, from the initial planning until the fuel is finally produced, quite a few years pass and it consumes huge amounts of investment costs. I don't see big biorefineries being built on a regular basis. That's just too costly and risky".

Comparing the supply chain model deductions with state-of-the-art practices in the field, *Co-processing*, respectively *Co-location* and *Retrofitting* is already being practiced. Chapter 5.3 clearly points out that most of the biorefineries that use lignocellulosic material at least as a part of their input are located in forest rich areas. This is confirmed by the pulp and paper and biochemicals expert who mentioned that the company he works for operates biorefineries that are "completely integrated in those locations, because most of the feedstock accumulates just there naturally […] also it bears the opportunity get crude tall oil from surrounding plants". An advanced biofuel expert from Austria stressed that it is always important to examine, "if synergies with existing plants, facilities or industries can be seized". Generally, *Retrofitting* is a big matter of consideration and provides a lot of opportunities, as a respondent from the fossil fuel industry stated. *Retrofitting* and *Repurposing* have also been described by experts as very promising. Five of the 17 Interviewees, all working in the fossil fuel industry, were asked to rank the four different options of "Retrofitting", "Repurposing", Co-location" and "Greenfield plants" as most likely biorefinery building options with regards to the future rollout, also considering viability and cost factors. Responses were relatively uniform. "Retrofitting" was always ranked first, and "Greenfield plants" were always ranked last. "Co-location" and "Repurposing" were also considered as being very relevant and viable tools and were placed on either second or third position. Nevertheless, the distance to the least preferred option was prevalent in any of the assessed rankings. This is depicted in *Figure 23.*

Figure 23

Ranking of most viable future approaches for building advanced biofuel plants



5.5 Converging Methodological Insights

Approaching the research gap at hand necessitated for diverse research strands to be applied in this thesis. Current plant location analysis allowed to get insights into the state-of-play of location decisions that are shaped by strategic and long terms planning and therefore allow for a knowledge transfer into future decisions. Supply chain modellings touch upon the individual case but are yet future directed and allow for deductions of dominant strategies for cost reduction, supply chain model design optimization and hence location specific factors that facilitate these optimal solutions. Insights from expert interviews provided valuable viewpoints and perceptions from specialists who are actively engaged with the topic daily. These experts offered firsthand perspectives on the factors that drive, hinder, and are needed to facilitate the future adoption of lignocellulosic advanced biofuels. Due to limitations (Chapter 7.1), and due to the abductive nature of the study at hand conclusions can be drawn and results can be stated. Yet, deducing a ranking of the discovered locational factors would be inappropriate. Further insights into this still under-researched field would be needed to determine a certain order of the findings. Nonetheless, does the concise portrayal of respective locational factors provide relevant perceptions of what will be of importance when it comes to expanding the production system of lignocellulosic advanced biofuels. *Table 9* depicts a summary of the insights and observations that could be gained during the diverse research methods. It depicts the findings referring the locational factors in place or projected to be vital for the future rollout of lignocellulosic advanced biofuel production.

Table 9

Overall findings of location specific factors

Current plant analysis	Supply chain model indication	Expert insights
Existing transportation infrastructure ⇨ Road, Rail, Waterway	Make use of existing transportation infrastructure ⇨ Road, Rail, Waterway and Pipeline (just in the far future)	Make use of existing transportation infrastructure ⇨ Road, Rail, Waterway and Pipeline (just in the far future)
Industrial Areas and resulting agglomeration effects ⇨ Adjacent logistic companies ⇨ Chemical industries ⇨ Forestry industry ⇨ Pulp and paper industry ⇨ Other (e.g., windmill builder)	Seizing existing industrial areas and - facilities, especially: ⇨ Forestry ⇨ Agriculture Seize agglomeration effects & Synergies ⇨ Retrofitting ⇨ Co-location ⇨ Co-Processing ⇨ [Greenfield] Adjacency to > Forestry and forest rich areas, Agriculture, Harbours/Port areas	Seizing industrial areas and – facilities, especially: ⇨ Chemistry ⇨ Oil refining industry ⇨ Forestry => Pulp & Paper Seize agglomeration effects & Synergies ⇨ Retrofitting ⇨ Co-location ⇨ Co-Processing ⇨ [Greenfield] Adjacency to > Forestry and forest rich areas, Agriculture, Harbours/Port areas
	Always important: > Feedstock availability & Feedstock proximity > Pretreatment close to feedstock Blending close to market	Always important: > social and political suitability > Feedstock availability & Feedstock proximity > Pretreatment close to feedstock Blending close to market > Access to renewable energy (and hydrogen)

6. Discussion

The research at hand aimed at providing more insights in the locational factors that will influence and shape the production of lignocellulosic advanced biofuel in the EU in the context of a potential future rollout until 2050. Decisive factors that impact the future location decisions of the respective biorefineries were investigated. The results of the analysis confirm the industrial location theory, which underlines transport cost, agglomeration, infrastructure, and policies as crucial aspects for a location decision. Furthermore, and especially focusing on the advanced biofuel industry, findings show that those factors are accompanied by a range of other factors that are important for the future rollout of the respective refineries but also for the industry in general. Specific policy instruments to advanced biofuels, such as quotas and blending sub-targets on EU- and member state level will constitute the foundation. Those will be crucial to provide investors with the needed clarity and planning horizon to facilitate investments in the field. Without the right policy instruments, on European and on member state level, the rollout will not be feasible, because advanced biofuels are still more expensive than fossil fuels and most conventional fuels (IEA, 2020a).

Regarding location specific factors, making use of existing (transportation-) infrastructure, industrial areas and existing pretreatment-, storage- and conversion facilities will be of decisive importance to push the rollout and to reduce production- and supply chain cost as much as possible at specific locations. *Retrofitting*, *Co-processing* and *Co-location*, will be dominant strategies to seize existing industrial areas, however Greenfield plants will support the rollout as well, if economically viable. Feedstock availability, respectively feedstock proximity will be key, as well as other case-specific regional considerations, such as access to renewable energy. The underlying dynamic pushing the industry will be shaped by a step-by-step narrative, iteratively creating a pan European network, guided by a few leading countries that are already at the forefront of current production of advanced biofuels. Moreover, as delineated in chapter 5.4.2 and 5.4.3, the configuration of biomass supply chains will likely be influenced by the choice between *centralized bioenergy production* (involving a large conversion plant) and *decentralized bioenergy production* (involving several distributed small plants) (Mafakheri & Nasiri, 2014). It appears to be an intrusive assumption that seizing these location specific factors holds economic advantages compared to building such systems and facilities from the ground up. Against the backdrop of advanced biofuels still being more expensive than fossil fuels, saving money during the production and distribution process naturally facilitates price reductions of the final fuel, which in turn makes it more attractive for the market and potential investors (IRENA, 2019).

6.1 Results and related publications

Contextualizing the findings with previous research supports understanding the meaning and magnitude of the research at hand. Generally, studies on location specific factors for biofuels is rare. Previous research on location factors has been executed for ethanol-, biodiesel- and “agro-industry”-plants and reinforces the validity of results for the present case of lignocellulosic biofuels (Fortenbery et al., 2013; Haddad et al., 2010; Kenkel & Holcomb, 2006). Respective results of these related publications emphasize the potential significance of current plants for the future of renewable biofuels, the corresponding production facilities and suggest that gaining an understanding on the location criteria concerning biodiesel plants could offer valuable insights into comprehending the next generation of biorefineries. They argue that these plants will likely be developed as integral components of a comprehensive energy policy. Ba, Prins, & Prodhon (2016) point at the strategic and future oriented nature of newly built factories, thereby underlining the significance of findings at hand. In terms of comparability of results, Haddad et al. (2010) present locational factors deduced from 10 different studies on manufacturing industries and so-called agri-businesses. Findings from these related industries advert to the same locational factors that have been found in the research at hand. Decisive locational factors that have been found in those studies were: Policy considerations as predetermining investments, market access, feedstock availability and -proximity, infrastructure, agglomeration, existing facilities, transportation, regional considerations (state and local taxes, local government incentives, labor availability, geography, population density) and importance of production process (technology). These findings are remarkable, especially considering that all these aspects have also been found to be crucial for the rollout of lignocellulosic advanced biofuels and the respective production facilities.

Whereas Haddad et al. (2010) underline the significance of feedstock proximity for the ethanol industry, Fortenbery, Deller & Amiel (2013) found that biodiesel plants tend to cluster together in certain geographical regions. This allows for a potential contextualization with location specific factors for lignocellulosic biorefineries. Even if the products of ethanol and biodiesel in themselves are not comparable to each other due to different inputs and different technologies used, and with regards to the respective studies being conducted for the US, they could yet provide insights into the general rollout of advanced biofuels in the EU. The aforementioned future division of evolving supply chains into centralized- and distributed supply chains and their mixed setup of pretreatment plants partly producing biocrude oil and larger centralized plants converting that biocrude oil into final fuels, insinuates cross-links to biodiesel and ethanol production dynamics. Whereas biodiesel plants utilize oil-based feedstock, current bioethanol plants are dependent on abundant and nearby feedstock. Linking the respective location specific factors of those plants back to the research and the findings at hand, observations indicate validity. Overall, the results confirmed the expectations that similarities between locational factors for the European rollout of (lignocellulosic) advanced biofuels and location specific factors of ethanol and biodiesel production plants in the US, were assumed to be observable, as stated in the introduction.

6.2 Results against the background of industrial location theory and in the context of an alternative theory

Industrial location theory

Findings and answers to the research question are in line with industrial location theories' basic assumptions and complement the theory by pointing out factors, especially relevant for the sector of lignocellulosic advanced biofuels, thereby adding new insights. All three methods, analysis of current plant locations, supply chain modellings and expert interviews, confirmed and underlined the importance of locational factors considered in the industrial location theory. They add on the theory's stated factors by pointing at economic aspects that go beyond just transportation cost. Essentially, results found that reduction of cost does represent a necessity, from feedstock supply cost up until production cost. Moreover, regional considerations, such as access to renewable energy, which was pointed out by experts, have been neglected by the theory. This is especially important for advanced biofuel production to maintain sustainability throughout the production process. Furthermore, findings specify *agglomeration,* by stressing*, Co-location, Co-processing and Retrofitting,* and also aiming for *Economies of Scale* as crucial strategies to consider when investigating suitable production locations (S. de Jong et al., 2017; Martinkus et al., 2018; Zamboni et al., 2009).

Alternative explanation for location decisions

An alternative to the industrial location theory which constituted the baseline for the research at hand is provided by August Lösch's profit maximization theory. Lösch suggested *profit maximization* as the decisive factor for a location, completely disregarding least cost as a factor and assuming demand and revenues to be decisive for firm's locations (Jyoti, n.d.). According to this alternative approach for location decisions, revenues and demand are steering forces for location decisions rather than production and distribution costs (Jyoti, n.d.). Two of the 15 supply chain models studied (*Table 6*) optimized the respective supply chain based on a profit maximization principle, thereby optimizing according to Lösch's ideology (Kim, Realff & Lee, 2010; Kim, Realff & Lee, 2011). The models optimize supply chains according to different demand and revenue scenarios. They conclude that distributed supply chains will be the optimal solution for high demand providing significantly higher profits than a centralized supply chain. In these models, centralized supply chains automatically represent the most viable solution for reduced or volatile demand. This is reasoned based on differing fixed cost for each system, holding that centralized and more simple supply chains incorporate smaller fixed costs than implicit in a complex distributed supply chain (Kim, Realff & Lee, 2010). This emphasizes how profit maximization theory relies heavily on factors like the internal economies of size and scale, as well as the external economies associated with market density and diffusion. These elements play a crucial role in shaping the supply chain network to create a biofuels production system that is both cost-effective and resilient for the overall infrastructure (Kim, Realff & Lee, 2010). Especially against the background of the current situation of lignocellulosic advanced biofuels, profit maximization theory almost self-evidently disproves its applicability and appropriateness for the intended future rollout. Due to the predominant immature status of the field, demand is currently not apparent and yet needs be increased in the future. Furthermore, lignocellulosic advanced biofuels do not have an established market to provide. Lösch's theory is ignoring political decisions, however those have been identified by the research at hand as seminal for the future of the whole industry and constitute the only current facilitator of driving demand. Moreover, in times of global networking, demand must no longer solely be local, as opposed to one of Lösch's assumptions (Jyoti, n.d.). Naturally, some member states have more demand than others, nonetheless will policies significantly impact and increase demand throughout Europe (and worldwide) (Ebadian et al., 2020) . As a result of the fact that demand will then increase everywhere, attention must again be paid to reducing costs, thereby again strengthening the industrial location theory's assumptions, or at least putting more emphasis on cost than on demand. Demand is demonstrably exogenously triggered by policy instruments, quotas and blending targets as argued in chapter 5.1.1. Therefore, also in comparison with Lösch's theory, reducing cost as much as possible along the supply and value chain seems to be the plausible way to approach the rollout of lignocellulosic fuels, especially in its current infancy.

6.3 Locational factors in the context of short- and long-term development

Looking at the state of play of lignocellulosic advanced biofuels and contextualizing it with projections, surrounding conditions and the previously mentioned time component, it must be pointed out that the industry currently resides between past developments of biofuels, future ambitions towards increased concerns of climate policies and being based on the fact that no concrete plan for the future rollout exists yet. Just as the iterative policy cycle (explained in chapter 5.1.1) shapes developments in the advanced biofuel industry, respective research conducted in the field will in turn also be shaped by a similar iterative dynamic, thereby implicitly incorporating the *step-by-step* approach stressed by the experts interviewed. Locational factors that were found in this research, generally describe aspects that are necessary to consider, when evaluating location decisions in the realm of system expansion of advanced biofuels in the future. In this context, it must yet be differentiated between what is possible to implement soon (~2030), based on the immature system in existence, and what is expected to prevail in the far future (~2050), touching upon the mature and developed system that is expected to be in place. Kenkel & Holcomb (2006) differentiate between cost factors for current and future locations. Whereas they stress feedstock acquisition cost as constituting the major factor for current ethanol plants, they emphasize that the long-run cost structure of future locations might also be impacted by co-product prices, utility costs, and transportation economics on both the input and output sides. Certain locational factors may find greater relevance in the long term, while others may be more pertinent in the short term. This implies that experts and supply chain models concur that the future rollout will bring together larger centralized conversion facilities at strategic locations with smaller decentralized plants. These decentralized plants will leverage abundant feedstock, producing advanced biofuels on a smaller scale or producing intermediates by pretreatment, which is then transported to conversion facilities.

This underlying subdivision of supply chain actors in supply- and demand-oriented firms, a differentiation among location decision factors, needs to be considered. The industrial location theory accommodates for changing feedstock characteristics in terms of weight-gaining or weight-losing feedstock. Lignocellulosic materials represent weight-losing feedstock, underlining the need for the first processing steps happening close to feedstock and final processing steps happening close to market access (Jåstad et al., 2023). (Haddad et al., 2010) observed patterns that biofuel producing firms were prone to locate in counties with less population density and close to feedstock abundant areas, vis versa strengthening the argument found in the research at hand that when considering the rollout of lignocellulosic advanced biofuels and the needed point of origin as first and foremost representing feedstock abundance. In this context and considering again what is possible to build in the near (~2030) and in the far future (~2050) it is important to emphasize that not every plant size is equally economically viable. Larger and more complex refineries are more expensive. To operate them profitably, large amounts of input are needed to produce large amounts of output (Lin et al., 2014). Those *economies of scale* facilitate profitability and in turn impact the location decision due to the strategic consideration of upstream supply chain processes, such as needed transportation to supply the respective quantities of raw- or pretreated input material.

6.4 Finding's implications

In practical application, the findings offer valuable insights into the relatively unexplored realm of lignocellulosic advanced biofuels. These insights could serve as a foundational contribution to theory development or solution approaches particularly addressing the intricacies of the respective supply chains, both upstream and downstream. By investigating pathways for future rollout-connected intricacies and the respective solutions, a clearer overall understanding might emerge, bolstering potential implementation. Furthermore, the observation that a combination of centralized and distributed supply chains is likely in the distant future provides valuable input for evaluating these scenarios at a more detailed level, both on the European and on the member state level. This comprehensive approach could, in turn, guide the formulation of more precise policy instruments to support successful implementation. Enhanced clarity could also facilitate interplay among different stakeholders, particularly in sectors like transport. Societal factors are just implicitly touched upon in this research. Regional considerations that are needed for the individual plant location decision touch upon factors such as available workforce or change of environment in case of a greenfield plant being built. Increased industrial action in the area might have positive societal consequences. Moreover, influences on societal aspects can be viewed on the local and the European scale. Locally, increased economic activity in this field could result, next to increased employment rates, in more people informing themselves with the topic which could create awareness and facilitate education in the overall topic of renewable fuels. On the large scale, a European wide rollout of advanced biofuel do incorporates short term and long term effects. In the short term, and due to lignocellulosic fuels potentially impacting transport fuel prices, societal resistance might occur. Implementation of fundamentally new circumstances could mostly be regarded critically by society, especially when it has an ostensibly negative impact (e.g. increased flight or shipping prices). Nevertheless, the long-term consequences, such as mitigated climate change, to which those fuels can contribute in the realms of a future rollout, would naturally have a positive impact on the overall life quality of individuals in every society. Eventually it can be hold that contrary to the projected demand and the significance of lignocellulosic advanced biofuels in general, the findings indicate that a rollout will not happen in the needed time.

6.5 Methods & Limitations

Finally, certain *limitations* must be mentioned that have impacted the research to a certain extent. Regarding the sample size of interviewees, it's essential to acknowledge that its limitation stemmed from a shortage of responses. All potentially relevant actors in the field have been approached, ranging from Non-Governmental Organizations (NGOs) to delegates of the European parliament and supply chain managers of advanced biofuel producers, of which none agreed to participate in interviews for this research. Due to the natural evolvement of replies to interview requests, it turned out that majority of interviewees were from the research and consultancy field of advanced biofuels. This by itself could constitute a bias in the responses given because practical in-field experiences of production are lacking. Even if eventually 5 interviewees with a practical background (Pulp & Paper/Biochemicals, SAF, Fossil Energy/CtL, Transport fuel trade, US biofuel industry) and five more from the fossil fuel industry participated, just one expert was informed by advanced lignocellulosic production, and biochemicals (not advanced biofuels). Various tries to get an interview with a SC manager of a company producing lignocellulosic advanced biofuels were not successful and were mostly denied due to non-disclosure agreements. Therefore, more insights in the actual industry of interest and with regards to practical experiences in lignocellulosic supply chains would have contributed more valuable insights.

At the time this thesis was written, RED_III was in development. Since it is not foreseeable how implementation of the RED_III is going to impact the overall market, results are informed by soon outdated policy circumstances. Another aspect impacting at least the timeliness of the research results refers to the Covid pandemic that shaped the last three years, slowing down the economic activity impacting immature industries, which are uncertain even without a pandemic. Up-to-datedness of studies in the field of (lignocellulosic) advanced biofuels was therefore also impacted.

Generally, the vast uncertainty and immaturity surrounding the field of lignocellulosic advanced biofuels constituted the major underlying limitation. The original intent was to complement current deployment and production capacities, with future supply and demand projections on European and member state level. Combined with experts' insights, this would have allowed the research at hand to draw more detailed conclusions on the magnitude of a required rollout on a member state level. By that, more specific factors for individual countries' locations could have been exemplified, thereby providing a clearer picture on how the future rollout would need to be approached. Also, and aside from the research purpose, this would generally allow policy makers to come up with more detailed strategies. Yet, there are no publicly available, respectively accessible future projections on the member state level. This was confirmed by a member of JRC personally. This, plus the missing data on countries readily available technologies makes it hard for strategy developers and policy makers to eventually translate the assembled information into such legislations. This underlines another fundamental limitation overarching the whole field of research, also picking up the underlying general uncertainties. It could be described as a *"chicken and egg"-problem.* As the results show, detailed and scenario specific policy instruments are needed to facilitate the development of the lignocellulosic advanced biofuels. In turn, detailed insights about projected supply and demand, as well as available technology on member state level would be needed to reveal scenario conditions, under which a rollout of certain technologies would be most feasible. This would in turn provide insights in the needed biorefineries Thereby fostering clarity on the whole supply chain. Again, this would then immensely support the development of scenario specific and targeted policy instruments, such as quotas and blending targets, to push the rollout as efficiently and effectively as possible.

Vague projections on the EU level, such as depicted in *Figure 18* (Chapter 5.2.2), can be used as an argument for needed further research at most, and not for case- and scenario specific strategy development. Next to the very few Future projections showing exact numbers as depicted in chapter 5.2.2, there is a large lack in clarity about the future of lignocellulosic fuels in the future in general. Literature, touching upon future deployment is either just focused on a global scale or lacking a common approach that would facilitate comparability. Some project available biomass or conversion capacity, others project ethanol, biodiesel or just bioethanol quantities, for the most part not delineating if first- or second-generation ethanol. Moreover, projections rarely project exact numbers, but just percentaged shares.

Regarding the research question, it must be emphasized that even if the research at hand allows to deduce locational factors that will most likely be important for the future rollout of lignocellulosic fuels, the results must yet be viewed in the context of the overall prevailing uncertainty. Either way, there is still a large gap between the locational factors explained by future deployment, supported by interviews and SC modellings and the lack of clear context conditions that surround the prevailing overall situation. Context conditions created by current policy only has a sub target on the European level and does therefore not allow to provide clear answers yet.

Even if a thorough integrative analysis is not possible and despite the limitations that had to be dealt with, by approaching the research question from 3 different perspectives, and compensating for the lack of member state details by a manual location analysis of current plants that at least partly produce lignocellulosic intermediates or final products, the results can at least provide a well substantiated indication of location specific factors that will most likely be of importance when considering location decisions of pretreatment or conversion facilities in the supply chain of lignocellulosic advanced biofuels.

7. Conclusion

This study aimed at answering the following research question: *What are the most important locational factors, relevant for the European future rollout of biorefineries focused on producing lignocellulosic advanced biofuels?* To support answering the main question, four sub-research questions were posed, looking at the state of play and future projections of lignocellulosic advanced biofuels, analyzing location decision of biorefineries currently producing lignocellulosic fuels and providing insights into relevant expert opinions and supply chain modelling studies.

7.1 Addressing methods and research questions

The study identified distinct location specific factors likely to be important for the future rollout of lignocellulosic advanced biofuels and their respective biorefineries in the EU. The factors center around case specific opportunities for transport- and production cost reduction and point at feedstock availability, feedstock proximity, as well as making use of existing (transportation-) infrastructure and industrial areas. Location specific strategies to seize existing industrial areas and infrastructure include *Retrofitting*, *Co-location*, *Co-processing* to reduce production cost as much as possible. *Centralized and distributed supply chains* were found to be the most likely design options for future lignocellulosic advanced biofuel supply chains. Centralized and simple supply chains for smaller-scale production plants or pretreatment facilities and decentralized supply chains for larger plant capacities and more complex supply chains.

The immature and undeveloped industry of lignocellulosic advanced biofuels is shaped by vast uncertainties originating from a lack of detailed and scenario specific policy instruments both on the European and on the member state level. Concomitantly, this results in the current non-existence of planning horizons for financial investors, significantly limiting the financial resources needed for both research purposes and the expansion of the already existing technology and production. This is underlined by the clear mismatch between current installed production capacity (0.43 Mt/y), current demand (~1 Mtoe/2020) and projected demand until 2050 (~25.15 Mtoe), implying a required increase of ~2,500%.

To approach the prevailing gap in knowledge and the prevailing uncertainties that create this mismatch, analysis of location factors of current lignocellulosic biorefineries allowed to observe agglomeration effects, access to transportation infrastructure and feedstock availability as being prevalent. 37% of the respective biorefineries have access to road, rail, and waterway transportation. Another 37% show access to at least road and rail transportation, and 89% show agglomeration effects, thereby indicating examples of viable location strategies.

Subsequently, studying different supply chain modellings resulted in similar findings. Depending on the model design and if a general optimization of logistics or a defined geographical area was considered, utilization of existing (transportation-) infrastructure as well as industrial areas, could be observed. Additionally, seizing existing pretreatment-, storage- and/or conversion plants was always considered, if existing. Feedstock availability and -proximity as an underlying necessity was emphasized.

Complementing and confirming the other research method's findings, experts strongly emphasized access to and seizing of existing transportation- and production infrastructure as well as Retrofitting, Co-location, and Co-processing as being crucial. They specifically pointed at forestry, agriculture, chemical industry, as well as the oil refining industry for providing location specific advantages in the future. Moreover and going beyond the other method's findings, access to renewable energy, next to local and regional suitability of social and political circumstances were stressed as important location specific factors.

7.2 Implications & Recommendations

Looking into the future and with regards to the urgency of the topic, there are various *recommendations* for topics that would significantly contribute relevant insights in the overall matter of lignocellulosic advanced biofuels and its future deployment. First and foremost, precise models are needed in different scales, from global up until regional to provide policy makers with some guidance to making clear strategies for future deployment. The "chicken and egg"-problem described in the limitations needs to be solved to facilitate an iterative process for finding solutions and lowering burdens in and of the field. Studies on the technological capabilities and even about the awareness of potential contributions of lignocellulosic fuels on a member state level could support that. The discourse needs to be further supported and more clarity will have to be established. Studies that focus on each member state individually and providing insights in the country specific surrounding circumstances (awareness, access to renewable energy, inspecting potential feedstock rich areas, etc.) could have an enormous impact on the needed dynamic within the entire EU. Furthermore, combining the estimated biomass availability with the technological capacity in a specific locational context would create a basis for a more certain and detailed projections. This would shed light on potentially available quantities of lignocellulosic advanced biofuels, thereby enabling policy and legislations to highlight complexities and needed developments in the field. When more clarity is reached in terms of technological possibilities and realistic feedstock availability, combining those insights with the concept of the Biorefinery complexity Index (BCI), could provide case specific certainty about which kind of pretreatment and/or conversion plant could be suitable for a certain geographic area in a certain member state. Reaching such level of detail in the overall discourse could significantly push the industry and the entire EU. Furthermore, the role of countries and sector specific relevant industries outside the EU must not be neglected in future studies. Since import has been mentioned by literature and experts as playing an important role for the future and the global positioning of the EU in this regard, it would certainly be valuable to shed light on the exact impact, different import scenarios would have on the European market. This would naturally be more effective, if the previously mentioned recommendations on further research would have been conducted already, nevertheless, modelling various situations can prepare already to find a best solution in case of a quickly accelerating development. Eventually, providing more insights on the member state level in the EU would be crucial to break the mutually reinforcing cycle of uncertain dependencies and thus face possible future developments more prepared and knowledgeable. At the same time, global interdependencies must not be neglected.

To conclude, this thesis provides insights in the state-of-the-art knowledge of locational factors relevant for the future rollout of lignocellulosic advanced biorefineries. It points out the urgent need for detailed policy instrument adaptation to facilitate the necessary development and sheds light on the needed clarity on the member state level. Even if lignocellulosic advanced biofuel is still in its infancy, tackling the problems pointed out and being aware of the correlations between supply chain dynamics and locational factors needed, bears the potential to accelerate the current slack in development, thereby contributing to pave the way for a greener Europe until 2050.

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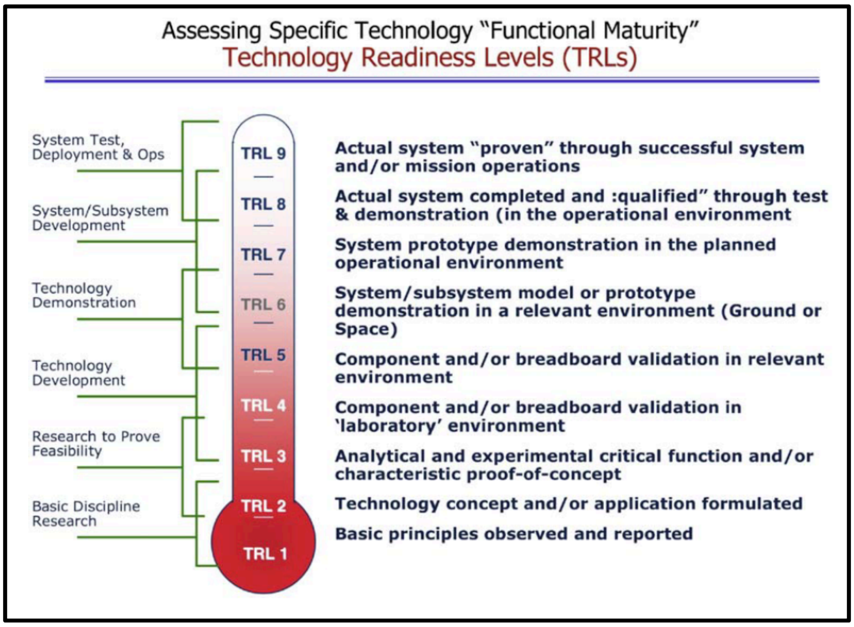
Appendix I

Technological Readiness Level (TRL)

To date, technologies for the commercialization of advanced biofuels are not mature enough, respectively well enough developed to significantly provide support to the Biomass directed energy transition. And as Mankins (2009) posits, the development of new system capabilities is typically dependent on the prior success of advanced technology R&D efforts. According to Mankins (2009), major challenges of any project or technology development are performance, schedule and budget. Inevitably, those aspects are also crucial for the development of biorefineries, designated for advanced biofuels. Therefore, the so-called Technology Readiness Level (TRL), represents a good way of approximating the current technological progress and its flaws. Technology Readiness Level (TRL), which represents a widely accepted standard for ranking the maturity of the different solutions (di Gruttola & Borello, 2021), is a framework widely accepted and applied in many variations and many different industries "to provide a measurement of technology maturity from idea generation (basic principles) to commercialization" (Rybicka et al., 2016, p. 1004). Most importantly and therefore also crucial for the thesis at hand, the TRL can also be adapted "to support understanding of capabilities and resources required to develop technologies at different stages of development" (Rybicka et al., 2016, p. 1004). More specifically the TRL inherits 9 different stages. TRL1, which is the lowest level, respectively earliest stage, describes the situation, in which basic scientific research leads to and results in observation and reporting of principles of a technology. Those results provide the starting point for more applied research and development. Every stage in the TRL framework makes it possible to grasp the development stage of a technology and thereby making it tangible. Every stage makes it possible to get an educated assessment of maturity, also including the typical costs, associated with every stage. The last and final stage in this framework is TRL9. "By definition, all technologies that succeed in being applied in actual systems go eventually to TRL 9" (Mankins, 2009, p. 1221).

Figure 24

Definition of Technology Readiness Level



Source: (Mankins, 2009, p. 1218)

Appendix II

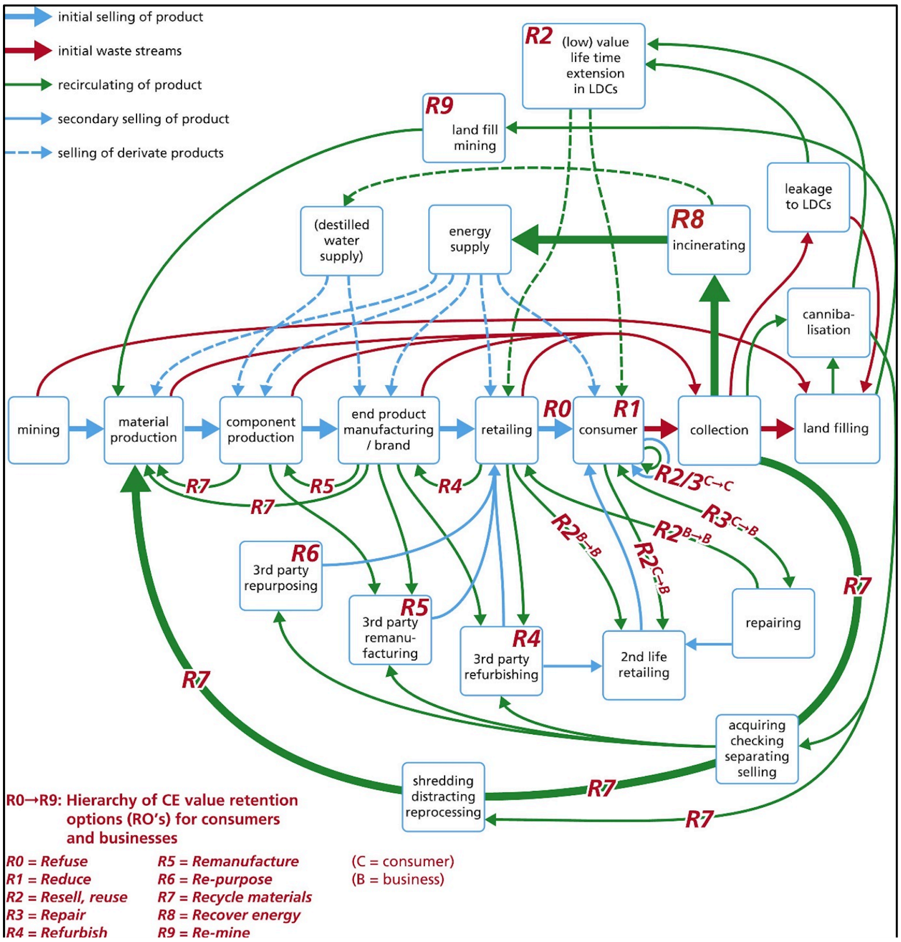
<u>Circular Economy & Bio-based Economy</u>

Circular Economy (CE) is a broad concept with many different inherent definitions. Circularity describes the elimination of waste and pollution, circulating products and materials at their highest values and regenerating nature (Ellen MacArthur Foundation, n.d.). The Ellen MacArthur Foundation describes CE as “a systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution” (Ellen MacArthur Foundation, n.d.). It tackles fundamental problems inherent in the predominant linear system, in which humans “take materials from the Earth, make products from them, and eventually throw them away as waste” (Ellen MacArthur Foundation, n.d.). According to the European Commission (2012, p. 9), bioeconomy can be defined as the “production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy”. Looking at the deployment of a successful bio-based economy on EU level, the development of a highly efficient and cost effective biorefinery system will play a key role. Largely relying on biomass within its future vision, automatically opens the questions of sufficient supply of biomass on EU level. Cultivation of biomass just with the purpose of supplying the bio-based sectors is critically regarded because it conflicts with environmental sustainability, food production and might cause indirect land-use change (ILUC). Therefore, and due to the underused biomass sources, such as wastes and agricultural and forestry residues, utilization of this kind of biomass, which simultaneously constitutes the feedstock for advanced biofuels, is encouraged and developed.

Several studies provide models, educated guesses, assumptions, and predictions of how the bioeconomy and more precisely the required biomass, especially for advanced biofuels, will develop in the future. De Jong et al. (2020) for example state a global bio-based chemical and polymer production of around 90 million tons. Next to the sustainability benefits of circular economy, the Ellen MacArthur foundation estimates the macro-economic potential to 1810 billion or 1,81 trillion euro (Ellen MacArthur Foundation, 2015). To reach that potential, CE and all its inherent strategies and opportunities will have to be utilized and exploited. *Figure 25* shows the complex interdependencies that this will entail.

Figure 25

Mapping Circular Economy Retention Options: The Product Produce and Use Life Cycle



Source: (Reike, Vermeulen, & Witjes, 2018, p. 258)

Appendix III

Future projections: First selection of studies

Table 10

First selection of studies

Study/Publication	Horizon	Fuel considered	Projection
FEV Consulting (2019)	2050	Diesel type fuels	23-35 Bln liters Demand; Not further specified
IEA (2022b)	2050	liquid biofuel [(Bio) Ethanol, (Bio) Diesel, Bio Jet Fuel]	No specific projections for Europe
IRENA (2014)	2030	Biofuel / Advanced biofuel	No specific projections for Europe
European Commission (2021b)	2050	Biofuels and Biogas	No specific projections
European Commission (2017)	2050	Biodiesel, Biokerosin, Ethanol/Biogasoline	Projections on conversion capacity
IEA (2022a)	2027	Biofuel	29 200 Million Liters Per Year (MLPY)
Padella et al. (2020)	2050	Advanced biofuel	Precise projections on demand and supply of advanced biofuels
EPure (2018)	2030	Biofuel / Advanced biofuel	Just relatively precise on advanced ethanol: ~1,6 Mtoe/year (2030) & ~ 3,7 Mtoe/year (2050)
Maniatis et al. (2017)	2030	Biofuel	No specific projections on advanced biofuels
IEA (2021)	2050	Biofuel / Advanced biofuel	The advanced lignocellulosics ~ 10,3 Mtoe, and the advanced HVO ~15.5 Mtoe.

Appendix IV

General interview questions - Master Thesis Advanced Biofuels

Basic set of questions:

1. What is your perception of the current situation of (lignocellulosic) advanced biofuels in your country/Europe?
2. What role does the general development of lignocellulosic ABF play for you at “InstitutionX” and in what regards are you involved in the development?
   - ⇨ From your perspective, what are the main challenges/burdens facing the advanced biofuels industry in Europe?
     Adding on that: what are the most important driving factors on the other hand?
3. Challenges in the field of development of 2nd generation biofuels are addressed through intensive research and development activities
   => which are the most important factors when it comes to developing the future in this field?
   => Which technologies (there certainly won't be one dominant technology) do you think will be the most important in achieving the EU formulated "blending targets"?
4. Before we go into a bit more detail, I would be interested to know how you see the future and opportunities for advanced biofuel in general, or what role you see it playing in different future scenarios and especially in the transportation sector?
5. who are the key stakeholders in the debate that are essential to bring to the table and who will play a seminal role?
6. The debate regarding the future development of "advanced biofuels" is still characterized by many risks and uncertainties.
   - ⇨ What are the biggest risks and uncertainties that you have been able to identify over the years and based on your experience in the research field?
7. What role do site/location-specific factors play in the planning and construction of new biorefineries? What are these site/location-specific factors that can influence the future locations of the refineries?
8. What comes to your mind when you consider the debate about the feasibility and implementation of the "blending targets" by 2030 and especially 2050?
   =>Which factors do you see as crucial?
9. If you look at the situation of advanced biofuels, especially against the background of the projected sharp increase in demand and comparing this to current capacity and capacity under development, a rather large gap becomes apparent. In order to meet the demand, the industry or the entire advanced biofuels system still needs to evolve.
   => How do you see the world of advanced biofuels developing?
   => Where do you see the development of advanced biofuels going? (=> especially the lignocellulose based "advanced biofuels").
10. How do you estimate the speed of technological development of advanced biofuels in NL/Austria/EU? And how do you estimate the situation for the years 2030 and 2050?
11. For example, let's talk about the provision of "feedstock", both in the necessary quantity, quality and at the right price. Accordingly, the question arises as to how this will look in the future.
    => Will the required "feedstock" be produced in the EU? Will most of it be imported? Will there be several "large scale" conversion plants, which can produce multiple "outputs"

and which can be "fed" with different raw materials? Will trade in intermediates increase accordingly, or will there even be many decentralized factories focused only on the production of various intermediates?
Will it be a "multiple input" and "multiple output" concept or rather a dispersed and decentralized concept and why?
=> Based on your experience and expertise, which scenarios do you consider most likely when we look at the development until 2050?

12. Do you see certain "hot spots" in the EU where these required biorefineries will mainly be built? Which location factors do you consider essential (also in the European context)?
13. What do you see as the key challenges and opportunities in the supply and value chain for advanced biofuels, and how can these be addressed to promote sustainable and cost-effective biofuel feedstock production?
14. Can you give me a final picture of the future prevailing system in the EU? (Related to advanced biofuels and the associated and required biorefineries) => how do you imagine the prevailing interdependencies and the system?

Appendix V

Agenda - Workshop at the Technical University of Darmstadt

ETIP Bioenergy European Technology and Innovation Platform — CLARA

Funded by the Horizon 2020 Framework Programme of the European Union under Grant Agreement No. 817841

Enabling the Clean Energy Transition with 2nd Generation Biofuels

2nd CLARA Public Workshop – Agenda

Date: 25th April 2023

Place: TU Darmstadt, Wilhelm-Köhler-Saal (S1|03 283), Hochschulstraße 1, 64289 Darmstadt

Thursday, 25 April		
09:00 – 09:15	Introduction • Welcome • Project Overview	J. Ströhle
09:15 – 10:45	Presentation CLARA • Pilot Testing • Commercial Process Design Concept • Socio- and Techno-Economic Assessment	CLARA Consortium
10:45 – 11:00	*Coffee break*	
11:00 – 12:30	Presentation Other • Jet fuel production from residues and wastes via hydrothermal liquefaction: Results and perspectives from the EU projects HyFlexFuel and CIRCULAIR • Gasification as key enabling technology for advanced biofuels • Topic: R&D and commercial application of HTW Gasification	V. Batteiger (Bauhaus-Luftfahrt) N. Dahmen (ETIP Bioenergy) E. M. Moghaddam (GID)
12:30 – 13:30	*Lunch*	
13:30 – 14:30	Panel Discussion Enabling the Clean Energy Transition with 2nd Generation Biofuels	
14:30 - 16:00	Pilot Plant Visit • 20 min presentation on pilot plant • Pilot plant visit in small groups, depending on the current operation	B. Epple

This project has received funding of the European Union's Horizon 2020-Research and Innovation Framework Programme under grant agreement No. 817841 (Chemical Looping gasification foR sustainAble production of biofuels --- CLARA). The content of this work reflects only the author's view, and the European Commission is not responsible for any use that may be made of the information it contains.

Appendix VI

Further Findings from the expert interviews question

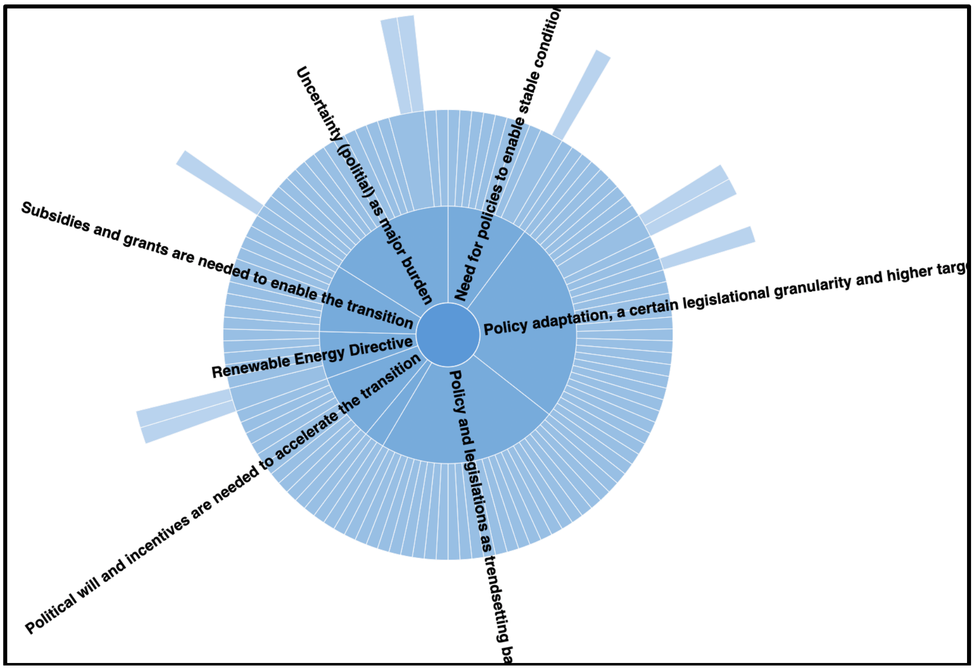
Politics, policies & legislations

Politics, policies, and legislations related topics were prominent answers to the questions asked. Even though those are not directly related to locational aspects and factors for the future rollout of advanced biofuel, experts perceive them as the crucial and fundamental basis. This becomes even more striking, when looking at the subcategories. The subcategories themselves depict the topics that interviewees touched upon when talking about the role of policies and legislations and can be summarized as follows:

- Need for policies to enable stable conditions and long term financial investment
- Policy adaptation, a certain legislational granularity and higher targets are needed
- Policies and legislations as trendsetting basis
- Policy implementation by member state
- Political will and incentives are needed to accelerate the transition
- Renewable Energy Directive
- Subsidies and grants are needed to enable the transition
- Uncertainty (political) as major burden

Figure 26

Sunburst-Diagrams Politics, policies & legislations



Looking at the subcategories, it becomes obvious that experts perceive policies and legislations as at least holding the potential of being a major driver of advanced biofuels. Policies and legislations represent the trendsetting fundament, on which everything is built upon. “Policies determine everything" as the policy expert stated. Consensus prevails when it comes to the needed policy adaptation in the future. Current policies in place are perceived as not being strict and focused enough. An industry expert, who deals with fossil fuel companies and especially crude oil shipping companies regularly, stated explicitly that, "if you ask these companies off the record, they all will say, the government has to have to place much higher goals for us". It was pointed out that just politics and the legislations set in place have the power to move things in the needed direction, and that not creating stable policies uncertainties in the market are facilitated. This will inhibit the needed financial investments in the industry and by that facilitate stagnation. In this regard the need for subsidies and grants was emphasized by almost everyone.

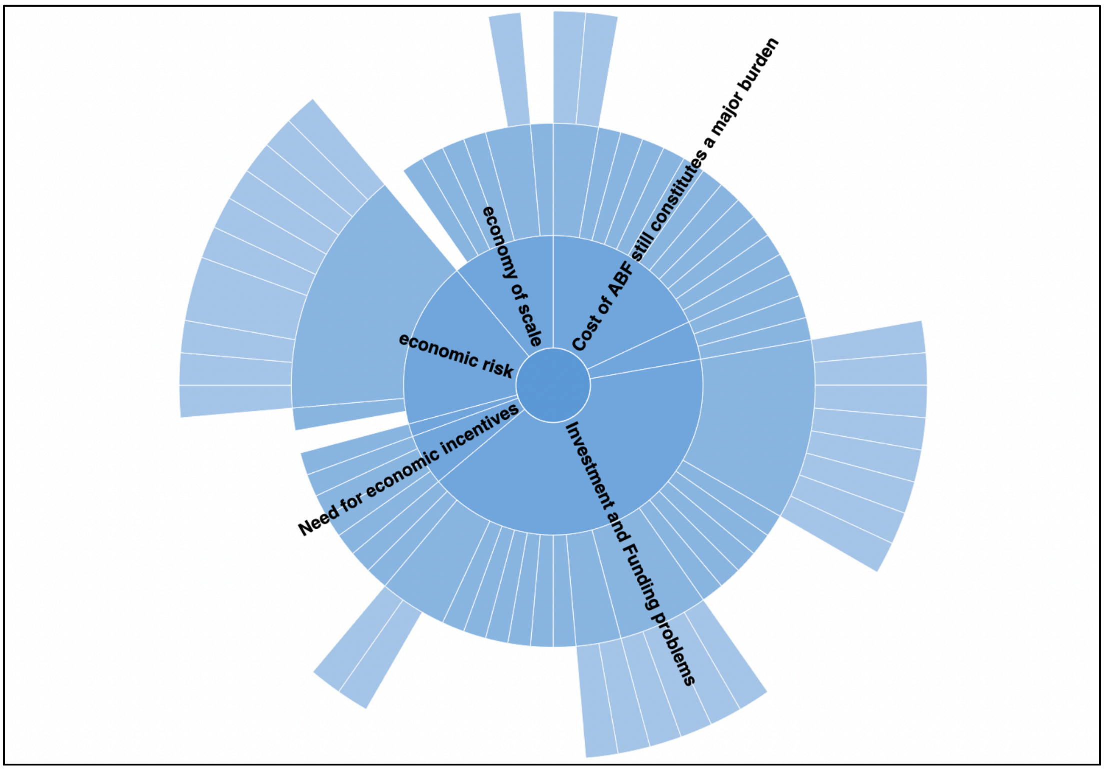
Economic considerations

Concomitantly with the political considerations, the importance of economic aspects was pointed out to be seminal. Even though no questions, directly focused on financial and economic terms were asked, economic considerations yet represented one of the most considered topics by experts, showing its urgency. The following subcategories depict the most prominent topics mentioned by experts when talking about drivers and burdens for lignocellulosic advanced biofuels:

- Cost of advanced biofuels constitutes major burden
- Creating market access for final products
- Economic risk
- Economies of scale
- Investment and funding problems
- Need for economic incentives
- Short term profit orientation hinders investment

Figure 27

Sunburst-Diagram Economic Considerations



Essentially, experts stressed the pressing need for detailed and precise policy instruments so that a long-term planning horizon for financial investors would be created. As Christian Aichernig, Chairman of BEST Energy, pointed out during the panel discussion attended, when asked about the locations by the researcher: “The most important part of this question is where will the money come from? Because that’s the central part of all our considerations […] we still *need massive public funding*”. All this eventually touches upon the fact that experts underline the need for (lignocellulosic) advanced biofuels to reach cost parity or at least need to become significantly cheaper, to be able to compete with fossil fuels. “It’s still too expensive” and “it’s always the cost”, as two experts from the field stressed. In turn, this is just possible, if enough biorefineries will be built to foster the development of the field. What makes this complex is that a market needs to be in place that shows viable business cases to attract investments that would then in turn strengthen research and development. “At one point, the business operation needs to be profitable”, as one expert underlined. Furthermore, there is a “mismatch between the risk of the case and the risk appetite of investors, but also banks“, as the SAF expert emphasized. Finally, experts underlined that the right policies are needed to facilitate investments in the field, without which a rollout will not be possible.

Technology

Interviewees were asked what kind of technology they see as prevailing and being most important for the addressed future rollout. By touching upon the topic of technology, a wide range of technology related topics predominant considerations were mentioned. Technology plays a central role in the overall discussion and research question. Interviewees reinforce by their statements the importance of technology and the direct and indirect implications for location decisions due to the interrelatedness with feedstock matters. The following subcategories make up the overall statements:

- Intermediate production and densification of biomass
- Modular systems as potential solution
- Need for technological development
- Need to be open for technology
- Technological difficulties
- Technologies likely to play a major role
- Technology is already there

In terms of technology, there is a certain consensus among the respondents regarding the further development of the various technologies needed in the future and to the effect that even the level of development of the most prominent technologies is not yet sufficient. Especially in view of the technological difficulties the industry is facing regarding the efficient conversion of feedstock.
It has been mentioned that the existing technology is already there. However, this does not relate to the commercial scale and a potential European wide rollout. “On the lab scale and demonstration scale all the all the technologies are already there”, as one participant, who works in the research field for advanced biofuels, stated. On the larger scale and regarding the European wide rollout, there is consensus that further development of technology is needed to accommodate for the inherent complexities. The future rollout “requires different technologies and technologies suitable for the smaller scale and for the large scale“, as another participant, who has been working in the

research field for advanced biofuels for decades, emphasized. Another person stated: “There is not just one technology, we have to consider all technologies”.
Concerning the need for further technological development, it was pointed out that “technological limitations still exist”. A participant who has been working in the field of biofuels in the US for over 45 years points out that there is “definitely room for improvement in technology”. Furthermore, “technology development will be very central in Europe“, as the policy expert postulated. Finally the main technological difficulties are represented by the necessity that “there needs to be breakthroughs in the technology and also in the quality it produces that it can be fed into existing refineries”. This statement of a respondent who is working in the field of sustainable aviation fuel is supported by an interviewee working for a large fossil energy company, who pointed out, referring to sustainable aviation fuel that “after all, the kerosene produced from biomass must meet exactly the same requirements as it does at the moment. In other words, I must trim the composition of the product so that it has exactly the same properties as kerosene has had up to now”. To that effect, Fischer-Tropsch-Fuels and pyrolysis have been pointed out as being very promising yet having to become more efficient and cheaper.

Lastly, Intermediate production and densification of biomass had been emphasized by a significant number of respondents as constituting a major aspect in the overall debate. Location wise, conversion to intermediates and final products, if feedstock and technology allow that, will be happening close to the raw material. One expert stated: “what you need is to develop these logistics chains with initial pretreatment units locally at the scale of where the agricultural residues are“. Either way, all experts agree upon the fact that densification and/or pretreatment of feedstock close to raw material is important to reduce transport cost and transport efficiency. Either way, “initial processing can be well in the simplest form to make chips, but it can also be to do pyrolysis or do torrefaction as a pretreatment step. It could also be that you say well no, but I produce intermediates like methanol”.

The previous elaborations on the interview findings provided the basis for understanding the context and the most important topics given in the interviews that underline the multi levelness of complexity that is dealt with when approaching topics like the future rollout of advanced biofuels especially with regards to location specific factors.
Location specific topics have just been addressed implicitly so far. The following categories that have been deduced from the interviews cover this topic more explicitly. The categories and how experts perceive their interrelatedness for the future rollout of advanced biofuels will be stated.

Regional considerations

Regional considerations were brought up by interviewees in the context of what they perceive as important for the future European rollout of advanced biofuel. The resulting categories are as follows:

- Predominant regional conditions
- Local conditions play a major role

Both categories represent the need to utilize local and regional conditions. As a baseline, regional and local conditions are represented by aspects such as feedstock, renewable energy available, hydrogen access, policy and legislations in place, relevant stakeholder in the region, availability of skilled personnel and existing infrastructure.

To put it in a nutshell, by pointing out the need for adequate regional and local conditions, experts emphasized the non-existence of a generizable pattern to put on a location search.

Supply chain logistics & Feedstock Matters

Supply chain logistics also constitutes just a minor topic, at least considering the frequency it was mentioned in the interviews.

- Logistics as a key aspect

When looking at the future, supply chain logistics hardly played a major role for experts. Nevertheless it was pointed out that distribution of feedstock, supply chain efficiency and general logistics topics should not be neglected.
With regards to *Feedstock Matters* for the future rollout of advanced biofuels, interviewees were asked questions about the necessary quantity and quality of feedstock required, but also where this feedstock will come from (see interview scheme, *Appendix IV*). After analyzing the interviews, feedstock matters represented the third most mentioned overall topic, deduced from the expert interview's answers. The summarized subcategories can be summarized as follows:

- Certification of feedstock
- Competition for feedstock will be a predominant matter
- Feedstock and output
- Feedstock availability – a crucial factor
- Feedstock cost as major factor
- Feedstock intricacies
- Feedstock limitations
- Feedstock proximity is important

Answers given by the participants were far reaching and addressed a wide range of feedstock-related issues that were simultaneously providing insights on location specific aspects. "Feedstock availability" and "Feedstock proximity" as overarching sub-categories have been mentioned the most, followed by "Competition for feedstock" and "Feedstock intricacies".
Either way, answers including feedstock availability and competition for feedstock center on the same concern, which is getting hold of enough feedstock in the future to produce enough ABF for the European market, whereas the competition view, represents the underlying problem of international competition and increasing global sustainability targets fostering the demand for biobased products and in this turn also advanced biofuels.

„If any industries start to think about using biomass, they really have to think about where they're going to secure the long-term supply of feedstock […] in the end, there can be a lot of competition for the raw material. I think that is one of the biggest issues", as an expert from the US biofuel industry stated. In this context, a specialist from Austria emphasized that "commodity competition will certainly intensify and then of course there is always the question of economics, which sector of the economy will then pay more for the commodities".

The statements concerning feedstock availability underlined the potential scarcity of biomass in the future. “Most important is biomass availability“ as a specialist working in the field of SAF underlined.

In this regard, an expert, working in the bunkering sector has noted that lipid based organic feedstock, such as UCO and HEFA, which right now still represents by far the largest share in currently produced biofuels, will be impacted by the increase in competition for feedstock. “Used cooking oils […] comes from Asia and they will very likely need it to produce these fuels themselves in the future”. That is supported by another respondent (Austrian expert in advanced biofuels research) who stated that:

“not only Europe would like to use these alternative fuels, but also countries like the USA or Brazil, where a lot is already being used. But there are also these emerging markets like India, China, which will then also go in this direction”. That is why especially lignocellulosic feedstock represents an opportunity to fill that upcoming void.

“Feedstock proximity” and “Feedstock intricacies” also represent dominant interview answers but are more focused on the biophysical characteristics of lignocellulosic biomass and complexities in the supply chain that arise because of those. The resulting intricacies result from difficulties in processing it towards intermediate and final products.
“Cellulosic biomass is just a very challenging feedstock […] it's very spread out. So it's hard to collect hard to transport and then it's also quite heterogeneous in in terms of chemistry and composition and and contaminants“, as the SAF specialist underlined. Additionally, the feasibility of cellulosic feedstock collection has been questioned by several participants:

“At the moment there are vast sources, but they are not being utilized or only to a very limited extent. And that's of course because of logistics, it's not easy to collect these agricultural residues and make them available for let's say production at large scale”
“Another risk is if you need to collect your biomass from hundreds of suppliers. Basically farms. For example, in in straw right. How are you going to contract that?“, as another respondent added in this regard.

Feedstock proximity in turn, describes the participants statements directed to the need for minimizing transport of the unprocessed raw material raw. This was also mentioned in terms of the international competition for biomass, intermediates and final products which was forecasted. Lignocellulosic transport distance of 100 km radius at most around the raw material location has been mentioned by multiple specialists. “It is very hard to reach scale in these types of facilities because typically your collection radius is 100 kilometers”. In this context another expert stated: "For a lignocellulose plant, it makes sense, of course, that is near grain growing

regions, so that one can keep the transport distances here as short as possible and thus increase the sustainability".

The underlying credo that a participant pointed out is that it is "very important to get the feedstock from the point of generation or production to the fuel production site as efficiently as possible". According to experts, this implies focusing on Europe as much as possible throughout the whole supply- and value chain: „We cannot just simply rely on resources from the US or from Brazil or some from somewhere else […] we also really have to exploit our own resources in Europe“.

Altogether, answers suggest that location specific factors have to accommodate a vast range of complex and feedstock and technology inherent intricacies, that have to be considered in the bigger picture. Answer imply a conflict between economic and technological feasibility.

Synergies, infrastructure and industry

When asked about locations and site-specific factors that interviewees regard as crucial for the future rollout, every respondent emphasized the need to reduce cost as much as possible and therefore make use of existing industrial areas, infrastructure and that creating and seizing synergies will be of major importance in terms of future rollout of advanced biofuels in the European Union. The following sub-categories were deduced from the respondent's answers:

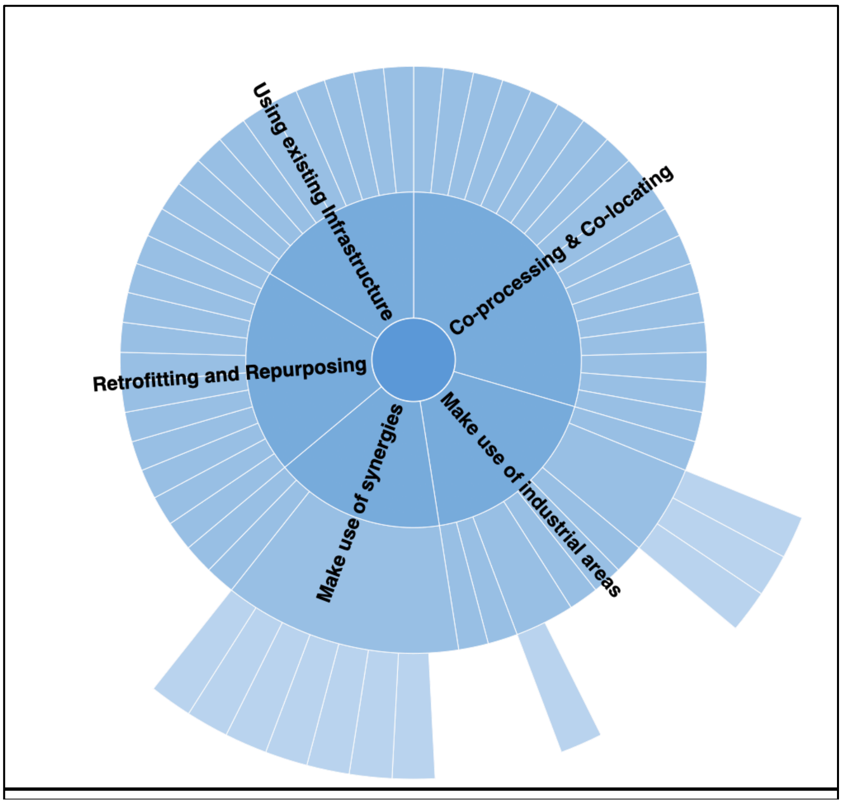
- Co-processing & co-locating
- Make use of industrial areas
- Make use of synergies
- Retrofitting & Repurposing
- Using existing infrastructure

The individual answers that are represented by the original codes are relative evenly distributed among the individual sub-categories. Participant's replies suggested consensus that some kind of capitalization on existing conditions represents the dominant strategy.

The diagram below depicts the even distribution of answers given in the individual sub-categories:

Figure 28

Sunburst-Diagram Synergies, Infrastructure and Industry



The answers given also suggest that interviewees agree on the general need to make use of the particular regional and local conditions but that against the background of the yet very uncertain future of this field, precise details about the rollout cannot be given.

The mentioned need to capitalize on existing infrastructure and industrial areas and make use of potential synergies potentially evolving based on those conditions constituted the baseline in all interviews. Answers and mentioned topics are partly overlapping. When stating the need to make use of synergies, specialists implicitly pointed out the need for existing infrastructures and/or industrial areas: “When thinking about building a plant, you should always examine if you can create synergies with existing plants or make use of existing industries”, as an expert from Austria stated. The policy expert underlined: „Industrial clusters, that's also a huge benefit in terms of position“. In terms of adequate industries that can be profited of, the chemical and petrochemical industry, as well as the fossil fuel industry at large was named. At these locations, it would be „possible to use the existing pipelines or the existing infrastructure of normal oil […]”. In the course of mentioning the need for capitalizing on the existing infrastructures and industries, the terms “co-processing”, “co-locating”, “retrofitting” and “repurposing” were brought up.

“Existing refinery are flexible and you do not need to build new ones” as a specialist for Carbon to Liquid (CtL) and gasification processes underlined. Multiple aspects are important in this regard. From permitting processes to viable technologies. "It's always easier to tear down an old plant on an existing site and build something new, because the site already has existing permits to use it as an industrialsite." As the same interviewee emphasized. In terms of technology and processing, co-processing was mentioned as effective by an expert in lignocellulosic feedstock research: “For the oil-based pathways, the proximity to the fossil refineries makes sense”. Another Interviewee who has been working in the field of advanced biofuel research for over 40 years stated: “[…] especially when you talk about the thermal conversions or the gasification of biomass or pyrolysis oil, it's easy to combine that with the traditional fossil refinery […] technology is there, and you can use it in these existing facilities. They can then produce biofuel out of it. […] Gasification has never been an easy technology but it's possible and but it works best when it has quite some scale”

Outlook 2030-2050

Lastly, this category “Outlook 2030-2050” is based on the answers the participants gave to the question how they would imagine the future of advanced biofuels systems to look like and what driver, burdens, crucial uncertainties and perceived hot spot areas for the respective biorefineries are. The subcategories below depict that:

- 2030
- Driver for European biorefinery development
- Greenfield plants will just be a viable solution in the rarest case
- Import as part of possible future scenario
- Integrated biorefineries as potential solution
- International competition
- Mix of small plants close to feedstock and large plants at strategic locations will be the likely way to go
- Most important sectors
- Presumed hot spot areas
- Pulp and paper industry
- Step-by-step approach

A diverse range of answers, and hence sub-categories could be extracted from the interviews.
Essentially, agreement existed among the respondents that advanced biofuel would take a crucial role. An expert in the field of SAF stated: “we do see in our growth strategy that there will be a large role for lignocellulosic biomass“. But also, in general: "For these areas that are difficult to electrify, we simply need liquid energy sources with a high energy density. I think this is slowly seeping through that this is really necessary, that we need this”.
When asked for the origin of the feedstock in the future, respectively to describe how the supply chain of (lignocellulosic) advanced biofuel would look like, the categories “import as part of possible future scenario” and “international competition” emerged. "International competition” as already being prevalent and as growing and becoming predominant even in the market of advanced biofuels was pointed out. “Fuel trade of any kind “is a global business, and it will stay that way”, as one participant stated. Reaching back to the category of policies and regulations and their role, another interviewee emphasized that „if the European or the Dutch Government comes with much more regulations, these companies will go to other countries where there are less regulations“. The interviewee added: “The companies involved in the field are big companies that are also always looking for bigger opportunities and it looks like the bigger opportunities are overseas […] in Europe it's very expensive nowadays for these energy intensive companies”.
Another reason for international competition is the forecasted need for imports in this regard, that experts pointed out: “It will by no means be possible to fill that demand only by European sources”. Another respondent postulated: “"we have to import, that is my conviction for now”.

"There is no other way, if I want to work reasonably cost effectively and economically, I buy something on the international world market in addition", as a German advanced biofuels specialist posits. Reaching back to the Economic considerations, the importance of it becomes obvious.

By asking the participants, how they imagine the future to look like, three more subcategories could be deduced that all center on the details of biorefineries in relation to their location and supply chain conditions. Greenfield plants were pointed out as just being a viable solution in the rarest case. “To set up such a plant, i.e. from the initial planning until the fuel actually comes out of it, quite a few years pass and it eats up huge amounts of investment costs. “I don't see. In my opinion, somebody go out and build a big biorefinery. That's just too costly and risky”.

Integrated biorefineries however were regarded as a viable and potential aspect in the future. “Ethanol plants will also move towards integrated by refinery plants”, as an interviewee stated.
Another participant mentioned that “in terms of sustainability and circular economy and so thinking from that side, of course the biorefinery with many inputs and many outputs is the nicer concept". Nevertheless it was also pointed out that biorefineries that were interated would be more complex and therefore more expensive, which is contradicting.

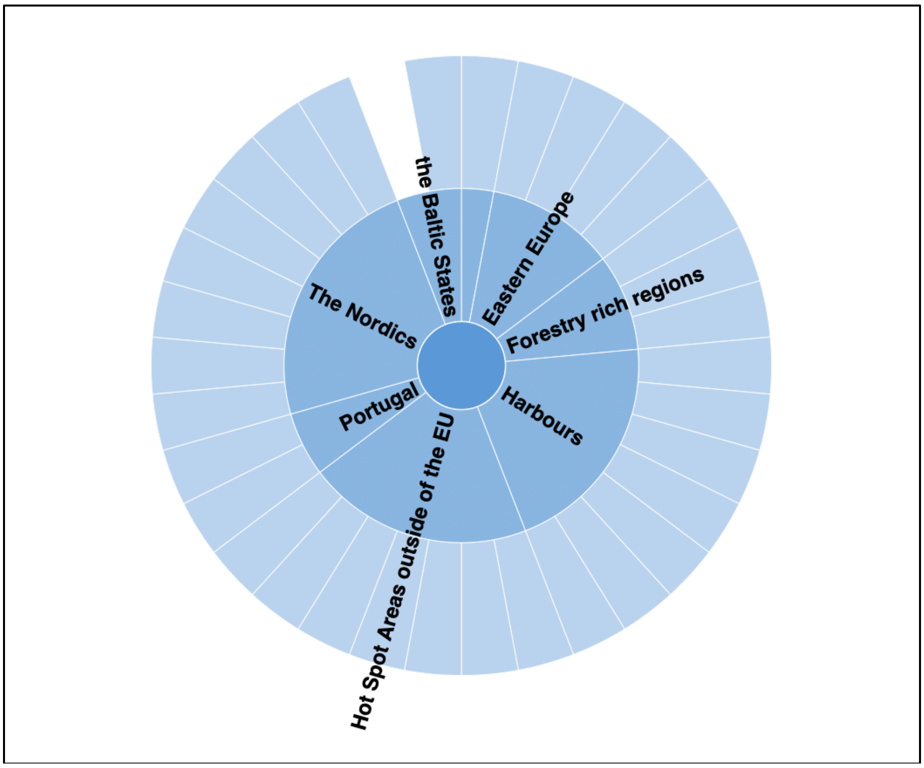
Finally it could be deduced from the interviews, that almost all experts see a system for advanced biofuels in the future, which is represented by a mix of smaller biorefineries or pre-treatment plants close to the feedstock and larger plants, respectively biorefineries at strategic locations, meaning international market access and blending facilities. “Hub and spoke systems are sort of appealing, because from an energy system perspective, that's the most efficient way of sort of reaching scale. Yet, I don't think it's possible to sort of get investments into that. But what I can see is that we build 1 pretreatment facility which already has one of the basically an existing refinery. And I think that would work. And then I can sort of build another one feeding into the same refinery, building another one and maybe then. In a in a fourth step, I build my own biorefinery and start feeding it into it”. This “step-by-step” approach was picked up by other participants as well who emphasized that the will never be perfect conditions for a European wide rollout and that a perfect ABF system “can never sort of emerge sort of all at once”. Reaching back to the category “No-one-fits-all-solution”, one expert stated that “there are also certain technologies that qualify and that become economic already at relatively small scale. So in in in practice that that can lead to really a a mix of of different options".

"We do need many large ones, but certainly also small ones that can make better use of regional biomass, and I think that is also a point that is very much in evidence", as a german specialist for ABF underlined. The Austrian specialist added that "there will have to be regional and national biorefineries, i.e., a headquarters and also a few headquarters with higher production capacities distributed over Europe at a strategically favorable location".

Lastly, participants were also asked to state the *hot spot areas* that they perceive as very likely for participating and being important in terms of the future rollout of advanced biofuels. The weighted results are shown in the following figure X:

Figure 29

Sunburst-Diagram – Presumed Hot Spot areas



The dominant sub-categories are "The Nordics", "Harbours" and "Hot spot areas outside of the EU". The Nordics were mentioned by most of the interview participants due to their vast amount of woody raw materials and their forestry industry. In this regard was the pulp and paper industry mentioned explicitly to provide suitable conditions for co-locating and co-processing in the future. "Producing and collecting woody biomass at a very large scale and bringing it to a central point. Instead of producing pulp and paper, you could produce advanced biofuels, and that's a relatively easy transition form", as an expert stated. In the future, "rerouting of biomass streams from one sector to another […] one of these sectors is the pulp and paper sector where much less paper is going to be needed in the future"

Especially Sweden and Finland were mentioned when the role of the Scandinavian countries was addressed by the respondents: "They have a lot of experience when it comes to sawmills and so on, that could be easily integrated with bio refining initiatives". Also, it was stated by an expert that

“Sweden and in Finland they have a very sophisticated system and they know how to treat feedstock in a good way”. About where in Scandinavia this would going to be happening: “In the Scandinavian countries this will then work in port proximity. Harbors were a prominent answer to the question of future hot spot areas for biorefineries, apart from the Scandinavian context, as well. International harbours like the one in Rotterdam provides the previously mentioned industry proximity, existing infrastructures and international market access.

“Hot spots outside of the EU” especially refer to Latin-America, USA, Asia, Africa and India that have been mentioned in this context and that could play a role in the future. This would also go along with the experts’ projections for the roll of imports in the future rollout of advanced biofuels.

<u>No one-fits-all-solution</u>

“No one-fits-all-solution” constitutes an individual category due to a significant number of interviewees emphasizing the complexities and intricacies that arise while addressing diverse potential solution pathways. Searching for a financially efficient, technologically effective and widely applicable solution represents an ideal scenario. Nevertheless, experts constitute that this will not be possible. As the following subcategories show, the need of individual solutions is unavoidable:

- Different situations require different approaches
- Location choice depends on technology, feedstock and process
- No silver bullet
- Using and seizing everything we have

Experts conceive those upcoming approaches as touching upon the general defossilisation but also the decarbonization of transport. “We don't believe that there is a silver bullet to replace all the energy in all the sectors“, as one interviewee emphasizes. Another expert stated that “There is not this one optimal scenario” for biorefineries. “There are a number of factors that go into it, and I don't think you can give a general answer to that, because it has to be considered individually in each application”.

<u>Reality check</u>

The category “Reality check” summarizes the experts statements that underline the state of play and how it is perceived by them. Different aspects that are relevant in the field of transport and renewable energy were mentioned with all aspects being unified by an underlying skepticism informed by the interviewees looking at the current dynamics in the field realistically.

- Bureaucracy as major burden
- Low hanging fruits and lock-in-effects as burden for transition
- Realistic technological feasibility of fuels
- Skepticism of feasibility
- Slow progress in reality
- Smaller companies as innovation drivers

Bureaucracy is one reason for the slow progress observable in the field of advanced biofuels expansion. Bureaucracy specifically describes the interviewee’s critique of the current system hindering or significantly delaying processes like licensing, permitting, and certification.

This is in turn facilitated by the system in place reinforcing lock-in-effects by “picking the low hanging fruits”, as stated by multiple participants. More precisely, interviewees refer to that by criticizing the current system in terms of enabling industrial actors to exploit the opportunities the system still provides and hence fostering stagnation and hindering transition. UCO and HEFA from Annex IX-B for example constitutes such an example. The system to process those is advanced at commercial, which in turn incentivizes firms to keep using it, because it is cheaper for them. This in turn make experts doubt the realistic feasibility of reaching the overall goals. “If we want to go to 60% greenhouse gas reduction. And we only have 20% biofuels. There's a big mismatch“, as an expert, who has been working in the advanced biofuels research for over 40 years, states.

Social considerations

Although social considerations play a rather subordinate role, they must nevertheless be mentioned as a separate category, since they deal with rather normative issues. Such issues tend to be neglected in the otherwise very technological and pragmatic debate on advanced biofuels.

- Global justice
- Involving the people
- Less consumption as general fundamental basis of the future
- Need for topic related education
- Social impact
- Socioeconomic factors

Those subcategories summarize what has been mentioned in regard of social topics. Dominant within those considerations is the statement that either way, people will have to consume less in order to facilitate the transition towards a more sustainable future. An important aspect will be to include people in the process. By involving the people in general, understand their needs and concerns, gaps in relevant knowledge to overcome potential social resistance can be overcome and finally social acceptance can be improved. This is important for the energy transition overall, but also for biorefineries being built, especially in less industrial areas.

Sustainability concerns

Just like social considerations, sustainability concerns were not mentioned by all interviewees. Nevertheless, the interviewees that did, emphasized its importance.

- Ecological considerations
- Overall sustainability has to be met

Ecological considerations mainly center around feedstock, its cultivation harvest and transport processes. Leaving a certain amount of straw on the field for soil health, but also “water quality, energy demands and spatial planning” is and should be of big importance as the policy expert stated. Next to that, interviewees point out sustainability has to prevail throughout the whole supply- and value chain. “Everybody who puts renewable energy on the market has to prove the sustainability of the product”, as one respondent suggested. A concern arose when thinking about the vast amount of needed biomass in the future and how this collection and cultivation is executed sustainably: “How do we organize sustainable raw material availability?”.

Important stakeholder

Experts were asked, who, in their opinion, the most important stakeholders in the whole debate about the future rollout of advanced biofuels are. The following

- Chemical industry
- Governments
- Agriculture
- Forestry
- Politicians
- Financial sector and investors
- Fossil industry
- Transport vehicle production industry
- Customer
- Project and technology developer
- Biofuel producer

Even though these answers do not have any direct implications for location decisions or factors, they do provide insights in terms of potential points of leverage. The vast range of projected important stakeholder does in turn underline the uncertainty and unclarity of the future development.