Sustainable Transportation in a future 100 % Renewable Danish Energy System

Master Thesis – Energy Technology

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Abstract

The global society is facing a huge challenge concerning global warming if the target of the renowned Paris Agreement, to keep the increase in the global average temperature well below 2 ℃ compared to pre-industrial levels, is to be met. The transportation sector consumes over one fourth of the total energy consumed globally and the CO_2 emissions from the transportation sector are increasing due to a growing energy demand and no obvious solution to replace fossil fuels in the sector. The project investigates if it is possible to design a 100 % sustainable transport system within the boundaries of a 100 % renewable energy system for five different degrees of electrification of the transport sector across three sets of electricity prices in Europe based on a general development of the energy systems. The electrification scenarios are to illustrate different potential developments of electric transportation. The project has created a model of the future Danish energy system to investigate the 15 scenarios where the main inputs are based on literature studies of the subjects. The main inputs are the available residual biogenic biomass, the mechanical demands, potential fuels and engine efficiencies for the different transport modes, the heat and electricity demands for the surrounding energy system and the technology data for both the fuel producing units and for the surrounding energy system.

Based on the assumptions of the project and the inputs to the model it is possible to meet all demands of the energy system, even in an isolated system with limited biomass resources. It is found that the socio economic costs of the system greatly decrease with an increasing degree of electrification, regardless of the development in the European energy systems. This underlines the value of EVs and the demand for research and development within the field. For the remaining transport demand that must be satisfied by fuels other than electricity, the project finds that it is essential to satisfy the demand for jet fuel for aviation first since the only technology assumed able to produce 100 % approved jet fuel is the Fischer-Tropsch process. Gasoline, which can be utilised to satisfy other transportation demands than aviation, is produced as a by-product in the process. Furthermore, the project finds that the carbon bottleneck can be broken by implementing emerging direct air capture technologies which penetrates the market if sufficient hours with low electricity prices are present. Electricity as a fuel for transportation is found to outcompete both the synthetic fuels in all scenarios and fossil alternatives. However, the pure production costs without externalities for the latter are lower than for the renewable synthetic fuels which call for political actions if the 100 % renewable energy system is to become reality. By utilising only the global biomass potential and operating the system without interconnectors it is found that the system can be scaled to a potential European solution though it results in increased socio economic costs.

Preface – Acknowledgements

This master thesis is conducted by Maria Broe and Thomas Dalgas Rasmussen at the Faculty of Engineering, University of Southern Denmark, in the period from February 1st to June 1st 2018.

The supervisors at the University of Southern Denmark were Lars Yde, Abid Rabbani, Kasper Dalgas Rasmussen, Anders Winther Mortensen and Henrik Wenzel. We would like to thank all of them for many great discussions and inputs to the project. It would not have been possible to conduct the work at this level without their guidance and support.

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List of Abbreviations and Acronyms

AEC	Alkaline electrolysis cell
AES	Average energy savings
AFQRJOS	Aviation Fuel Quality Requirements for Jointly Operated Systems
ATJ	Alcohol to jet
BID3	Better Investment Decision
CHP	Combined heat and power
CNG	Compressed natural gas
DAC	Direct air capture
DEA	Danish Energy Agency
DG	Distributed generation
DME	Dimethyl ether
EC	Electrolysis cell
ENTSOE	European Network of Transmission System Operators for Electricity
ENTSO-G	European Network of Transmission System Operators for Gas
EV	Electric vehicle
FC	Fuel cell
FP	Frozen Policy
FT	Fischer-Tropsch
GCA	Global climate action
HEFA	Hydrotreated esters and fatty acids
IC	Interconnector
ICE	Internal combustion engine
JIG	Joint Inspection Group
LES	Large energy savings
LNG	Liquefied natural gas
MCEC	Molten carbonate electrolysis cell
MES	Moderate energy savings
PEC	Photo-electro-chemical
PEM	Proton exchange membrane
PHEV	Plug-in hybrid electric vehicle
pkm	Passenger km
PV	Photovoltaic
RWGS	Reverse water gas shift
SAK	Synthetic aromatic kerosene
Sifre	Simulation of Flexible and Renewable Energy sources
SIP	Synthesis iso-paraffins
SOEC	Solid oxide electrolysis cell
SPK	Synthetic paraffinic kerosene
ST	Sustainable transition
tkm	Tonne km
TYNDP	Ten Year Network Development Plan
V2G	Vehicle to grid
W2W	Well to wheel
WGS	Water gas shift

1 Introduction

CO_2 emissions from the transportation sector are increasing and there is no single solution to the problem considering implementation of renewable energy or other tools to decrease emissions [1], [2]. The problem consists of a growing energy demand for transportation and no obvious solution to replace fossil fuels in the sector. Due to rising fossil fuel prices, depletion of fossil resources, anthropogenic climate change and growing transport demand there is an increased focus on the design of future renewable energy systems and sustainable fuels for transportation [1]. The energy demand for transportation in Denmark has increased by almost 50 % in the last 30 years while the energy demand for electricity and heat has decreased. The transport sector has therefore become the most energy consuming sector in Denmark [3]. On a global scale, 64 % of anthropogenic CO_2 emissions arose from power generation and transport in 2009, and in 2014 the transport sector alone required 27.9 % of the total energy produced globally [4], [5]. Furthermore, CO_2 emissions from transport are estimated by IEA to increase between 16 % and 79 % from 2010 to 2050 [5]. The large increase arises from an expected doubling of international air traffic and a 50 % increase in transportation of goods by road [6]. The renowned objective of the Paris Agreement, to keep the increase in the global average temperature well below 2 °C compared to pre-industrial levels and pursuing effort to limit it to 1.5 °C, is threatened by the present development in the transport sector [7]. This paper focuses on a 100 % renewable energy system including transport. It considers many diverse issues that arise when trying to overcome the challenge of designing a socio economically optimal sustainable transport system, e.g. the scarcity of biomass and synergies of conversion technologies across energy sectors. The main goal of the project is to minimize overall costs for a 100 % renewable transport sector depending on different framework conditions and to analyse the future possibilities to meet the transportation demand sustainably.

The transport sector is particularly complex because of the various demands, modes, technologies and fuels. Some technologies and fuels covering the same demand consist of different infrastructure due to varying production pathways (well to wheel, W2W), e.g. electric vehicles (EVs) and fuel cell (FC) cars for person transport on road. Agreement exist that electrification of transportation is a sound solution and that the transport sector should be electrified to the largest extent possible [8]. Electrification can significantly improve the fuel efficiency and act as a flexible consumer for intermittent renewable electricity production, hence it can decrease the total fuel consumption of the integrated energy system [8]. Biomass is also an interesting energy source for transportation since it can be converted to energy dense fuels to cover demands not suited for electrification [9]. However, due to the direct link between biomass and food production, deforestation and land-use, and due to the need for bioenergy for controllable production capacity in the heat, power and industrial sectors, the use of biomass must be limited due to scarcity of the resource [8]–[10]. The future of transportation will be affected by technology improvements of batteries for all types of demands for transportation. This project works with several scenarios with different degrees of electrification to cover the uncertainty of this development. It also works with varying framework conditions for the trajectory of the European energy systems that affects the boundary conditions of the Danish transport sector in the form of electricity prices [11]. Taking future development of transport fuels and technologies and the trajectory of the energy sector in to account, this project aims to design a sustainable and 100 % renewable transport sector for Denmark. Furthermore, the transportation demands and domestic biomass potentials are compared to European and global averages to investigate if the Danish system can be scaled to deliver a sustainable solution on a global scale.

1.1 Reading Guide

The report is initiated with the section *Problem Statement* where the purpose of the project is described along with the most essential frameworks included in the project. This is followed by an overall description of the methodology applied in the section *Methodology*.

Hereafter a more thorough description of the framework conditions is given. First the European boundaries used for the simulations in the project are described in the section *European Framework Conditions* including an explanation of how they are used in the project. Second the framework in the form of demands and resources available for the system are discussed and determined in the section *Demands & Constraints for the Energy System*. The demands covered are for the entire energy system while focusing on the transport demands. Demands and available biomass resources for Denmark are compared to the European and global equivalents. Third and last the electrification scenarios used as a boundary for the simulations are described in the section *Transport Electrification Scenarios* including a description of the fuels implemented to cover the residual transport demand.

Following the description of the framework conditions the section *Fuel Production Pathways* describes the technologies implemented in the system for production of fuels for transportation. This is done based on a literature search regarding relevant fuels and technologies. The implementation of these technologies in the Sifre modelling tool is described in the section *Modelling*. The section also includes an overall description of the generic method if Sifre and ADAPT.

The results from the simulations are presented in the section *Simulation Results*. First the results are compared on an overall level across all simulations followed by a more detailed analysis of selected scenarios. In the section *Sensitivity Analyses* the effect of some of the framework conditions are analysed. This is done for the parameters which are expected to have the largest influence on the results including biomass resources and transport demand.

The report is concluded with a discussion of the most uncertain parameters which have not been analysed in the sensitivity analyses in the *Discussion* and a summary of the main conclusions found through the project in the *Conclusion*.

More detailed information regarding several elements in the project can be found in the *Appendices*. References to the relevant appendices are made throughout the report. Furthermore, two excel files are attached including the main results from both the base simulations and the simulations performed for the sensitivity analyses.

2 Problem Statement

It is expected that the Danish energy system will transition to 100 % renewable energy towards 2050. A keystone in this transition is the transportation sector, which is assumed to be the most challenging sector to transform from fossil fuels to renewables. Based on limited biomass resources, a large electrification is expected. However, it is deemed unlikely that some forms of transportation such as aviation and freight transport can be satisfied solely by electricity. Therefore, technologies to convert carbon resources to energy dense liquid fuels are necessary.

The project investigates and models different pathways to produce liquid bio- or electro fuels. The pathways are designed to be operated in the future energy system with intermittent power production. The pathways are based on known technologies and expected development towards 2050. The technologies in the pathways integrate the sectors of electricity, gas, heat and transportation. The project implements several conversion technologies from biomass or other carbon resources and/or electricity to fuels for transportation in the model. A model is constructed to optimise the capacity and use of the pathways.

The aim of the project is to identify the optimal configuration of a 100 % renewable transport sector and energy system, and to find the cost for transportation fuels under different boundary conditions and assumptions regarding the electrification of the transportation sector. Furthermore, the project investigates how the pathways in the renewable transport sector influence the entire energy system. The European transition will have a large impact on the boundary conditions, e.g. the electricity price, and the degree of electrification of the transportation sector will have an effect on both the demand to be satisfied by liquid fuels and electricity. Thus, these aspects will impact the optimal pathway. The project investigates the optimal allocation of conversion technologies and renewables for the different scenarios by optimising the system in the constructed model.

2.1 Further Description

The pathways can utilise both biogas, solid biomass with thermal gasification and CO_2 from direct air capture as carbon sources. The project will analyse the conditions under which thermal gasification is preferred over direct air capture.

The analyses will be made under varying future boundary conditions regarding the development of the European energy systems. The boundary conditions will be based on the TYNDP18 framework conditions from ENTSO-E and ENTSOG in 2040, Distributed Generation, Sustainable Transition and Global Climate Action. Again, the transportation sector is in focus, since it is the keystone in sustaining the green transition. The five following scenarios regarding the degree of electrification will be studied further.

Full: Full electrification of the transportation sector (also aviation and shipping)
Ambitious: Full electrification except flights over 2000 km and ships travelling more than 90 minutes
Moderate: Full electrification except flights over 1000 km, ships travelling more than 45 minutes and heavy duty vehicle ranges over 800 km
Slight: Full electrification of trains, light duty vehicle ranges below 150 km, heavy duty vehicle ranges below 250 km, 5 % of shipping and national flights
Conservative: Only transit busses, light duty vehicle ranges below 20 km and the share of rail that is already in the process of being electrified is electrified

The above electrification scenarios will be studied under the varying boundary conditions from TYNDP18 to examine the optimal distribution of the different type of conversion technologies and plants in the system based on socio economics. The tools Sifre, ADAPT and BID will be used for the analyses.

2.2 Problem Scope & Delimitation

The project will focus on the transportation sector, hereby assuming a development of the electricity and heat sectors for the future energy system. The synergies for the different conversion technologies to fuels are in the scope of the project. The heat and electricity sectors are included in the modelling.

The cost of infrastructure for reinforcing the electricity and gas grid, for charging/filling stations, CAPEX and OPEX for different types of vehicles are not in the scope of the project. The project will investigate the cost for producing fuels and evaluate compared to engine efficiencies.

3 Methodology

This section describes the methodology applied in the project. Focus is on the main assumptions that have been made and boundary conditions identified. The statements made in this section are further elaborated throughout the report.

The approach of the project is a holistic analysis for different scenarios regarding the degree of electrification in the future sustainable transport sector and 100 % renewable energy system. The energy system is modelled on an aggregated level representing the entire Danish energy system with few units, which is a simplified approach. However, due to the complexity of the system and the holistic focus of this project it is deemed reasonable, even though there is a risk of both investing in and operating the system unrealistically optimal. The future Danish transport demand, that must be satisfied, is a fixed quantity based on recent literature on the subject [12]. The mechanical demand is defined for aviation, shipping, train, heavy (trucks/busses) and light duty vehicles (vans, cars etc.) [13], [14]. Consensus exists on the superiority of EVs through numerous research studies that work with the technology, e.g. battery characteristics and range on a single charge [15], the impact on optimal investments and operation in the power system [16], fuel cost in the form of a charging price [17], operations of EVs as a flexible load [18], etc. It is a well-researched area. Electrolysers and FC cars are also elucidated in several research studies. Hence, technology data from recent literature can be utilised [14], [19], [20]. Fewer studies exist on synthetic fuels for transportation, though it has been the subject for a lot of recent research. Both technical and economic studies of the processes, feasibility studies based on system analyses and more specific studies on aviation are available [6], [9], [21]–[28]. However, few system analyses exist that include the demand for jet fuel for aviation, which is a significant omission. Based on a literature study of the field, the technology data for conversion units and engines are determined.

The energy inputs and by-products, by type and quantity, are standardised pr. output fuel for each technology to make the energy streams comparable and mixable. Methane in the form of liquefied natural gas (LNG) and compressed natural gas (CNG) and methanol are chosen as the preferred liquid fuels, though not for jet fuel. A similar approach can be found in [3]. Methanol is a drop-in fuel replacing gasoline for internal combustion engines (ICEs), where only few modifications are necessary for optimising the fuel economy [29]. Dimethyl ether (DME) has the same characteristics as a drop-in fuel replacing diesel. There are losses in the conversion from methanol to DME, but a diesel engine is more efficient than a gasoline engine [3]. Hence, the well-to-wheel (W2W) efficiencies for the two fuels are alike. Methanol is chosen for the simplicity of having fewer possible output fuels. For LNG and CNG as a fuel in the future Danish transport sector additional investment in infrastructure is necessary. The cost of additional infrastructure is not in the scope of this paper, e.g. fuel stations, reinforcement of the gas/electricity transmission and distribution grid. The demand for aviation is the only type of transport demand that cannot be met by CNG, LNG or methanol. Bio/electro jet fuel for aviation consists of synthetic paraffinic kerosene (SPK) [6]. The only technology expected to be able to produce jet fuel for aviation for a 100 % blend while still meeting sustainability criteria is the ASTM certified Fischer-Tropsch (FT) pathway [30]. Due to large uncertainties regarding development of other processes capable of producing jet fuel in large scale, the FT process is chosen as the only pathway to jet fuel in the model, as it is deemed unlikely that a new technology reaches a commercial level within the short period required for it to contribute to fulfilling the goals of the Paris Agreement.

An exogenous factor other than the transport demand is available biomass resources. The available biomass resource is currently a hot topic due to the focus on global warming and the search for alternatives to fossil fuels in many sectors. Biomass has so far been the easy substitute for coal at Danish power plants, though it is considered a temporary solution. Ultimately, it places a constraint on the available biomass for fuel production due to the expectations of a growing global demand [10]. The constraint in the model in this paper is the national residue potential with the global potential added as a sensitivity study. The biomass included in the potentials is residues and biogenic biomass. Energy crops are excluded to secure the sustainability of the system. The definition of sustainability regarding environmental science is "*the quality of not being harmful to the environment or depleting natural resources, and thereby supporting long-term ecological balance*" [31]. Hence, a balance that can be continued indefinitely and therefore does not deplete resources or create pollution.

The overall energy system analysis is performed via simulations of models for the future European and Danish energy systems. The European system is modelled in the unit commitment tool Better Investment Decision (BID3) [32]. The total demand, installed capacities of renewables, etc., are determined by the framework conditions for 2040 developed by ENTSO-E and ENTSOG in the Ten Year Network Development Plan for 2018 (TYNDP18) [11]. The TYNDP18 scenarios are only modelled until 2040. It is the closest to 2050, where a 100 % renewable energy system is expected to be a reality, and is therefore used. The output electricity prices from BID3 are utilised as boundary conditions for the Danish energy system that is modelled in the unit commitment tool Simulation of Flexible and Renewable Energy sources (Sifre) [33]. The model of the Danish energy sector is based on the consumption model from the Danish Energy Agency (DEA). The Sifre investment module, ADAPT, is applied to find the optimal capacities to meet the demands. The demands and the possible pathways to cover them, e.g. constraints on electrification, are altered in the Sifre model for the different electrification scenarios. The analysis is based on hourly simulation of the Danish energy system with the objective of minimising the total costs while meeting demands. Units can be fixed and also set as a variable that the model can invest in. Hence, capacities are an output of the model. The focus of the paper is to compare the outputs for the electrification scenarios, both for a system level and for energy pathways for different transport fuels.

All in all, demands, boundary electricity prices, fuel prices, degree of electrification, technology data and biomass availability are exogenous factors that work as inputs to Sifre and ADAPT that model and optimise the configuration and operation of the system.

4 European Framework Conditions

The Danish energy system, and especially the power system, is well-connected to neighbouring countries. It is therefore highly influenced by these countries and the rest of Europe. Trading of electricity across the borders to Norway, Sweden and Germany has a large impact on the electricity price in Denmark. Due to these strong interconnections, Denmark was price taker in the electricity spot market in at least one of the above mentioned countries in 90 % of the hours in 2015 [34]. The interconnector capacity is expected to increase further in the future with the coming cables to Germany through Kriegers Flak at the end of 2018, to the Netherlands in 2019 [35] and to Great Britain in 2022 [36]. It is thus important to include the European context when analysing the Danish energy system. In this project it is handled by including a price boundary in the simulations, consisting of the electricity prices in the countries that the Danish energy system is expected to be connected to in the future. These countries include Sweden, Norway, Germany, the Netherlands and Great Britain. The prices are based on the TYNDP18 scenarios set up for the development of the European energy system by ENTSO-E and ENTSOG. The scenarios describe three different pathways towards 2040. The main purpose of the scenarios is to assess the adequacy of both the power and gas infrastructure in the future. Most of the scenarios are constructed in both 2030 and 2040 [11]. Since this project deals with a 100 % renewable energy system, which is not expected to be achieved by 2040, neither of the simulations are an ideal representation of an expected European framework. However, since this is the most accurate data available, and due to the uncertainty, which lies in projections in general, the scenarios for 2040 are used in the simulations. In an attempt to account for this inaccuracy and uncertainty, all three scenarios are included as framework conditions in the simulations. In the following subsection the three scenarios are described and a brief explanation of how these scenarios are transformed to a set of electricity prices is given.

4.1 Framework Scenarios

The three TYNDP18 scenarios used as framework for the simulations are called Sustainable Transition (ST), Distributed Generation (DG) and Global Climate Action (GCA). The three scenarios are designed to be in line with the European 2050 climate targets, including an 80% reduction in greenhouse gas emissions in 2050 compared to 1990 levels [11], [37]. Overall descriptions of the three scenarios are given below.

- **Sustainable Transition (ST):** The main storyline in ST is a rapid and economical CO_2 reduction by replacing coal by gas in the power sector. The scenario is highly influenced by a low natural gas price resulting in a high demand for gas in all sectors and a lower degree of electrification of heat and transport. In this scenario climate goals are achieved through both international trading schemes and national regulation and subsidies. The ST scenario would require a large acceleration in the efforts to decrease CO_2 emission after 2040 to reach the European climate targets in 2050 [11].

- **Distributed Generation (DG):** In the DG scenario the prosumers are at the centre. Small scale generation technologies and battery costs have been rapidly declining, resulting in a large distribution of residential PV panels with batteries. The low battery costs also result in a high degree of electrification in the transport sector. The climate goals are achieved through a strong European trading scheme [11].

- **Global Climate Action (GCA):** The GCA scenario is based on a global climate effort resulting in larger renewable units located where the best wind and sun resources are found across Europe. This is also the scenario with the largest penetration of renewable gasses. The light transport sectors are electrified to a large extent, where heavy transport relies more on liquefied natural gas (LNG). The climate goals are achieved through a global trading scheme resulting in the highest CO_2 price and largest CO_2 reduction of the three scenarios [11].

The three scenarios are characterised by different fuel prices, demands and installed capacities. According to [11] it results in the generation mixes for each scenario presented in Figure 1. The two scenarios for 2025 are two varieties of a best estimate scenario and the EUCO2030 scenario is an external scenario from the European Commission which models the achievement of the 2030 climate goals of the European Council [11]. This scenario was included in the TYNDP18 work instead of a GCA30 scenario as these two scenarios were found to be similar [11]. The general trend is an increase in the total electricity demand over time. This increase is more significant in DG and GCA due to a higher degree of electrification. In all three scenarios the use of fossil fuels decreases as the integration of renewables increases. The tendency of increasing share of renewables in the electricity supply is most apparent in DG and GCA. The resulting shares of renewables in the electricity supply in 2040 are 62 %, 71 % and 77 % for ST40, DG40 and GCA40 respectively [11]. For the gas supply there is the same overall tendency with the highest share of renewables in GCA [11].

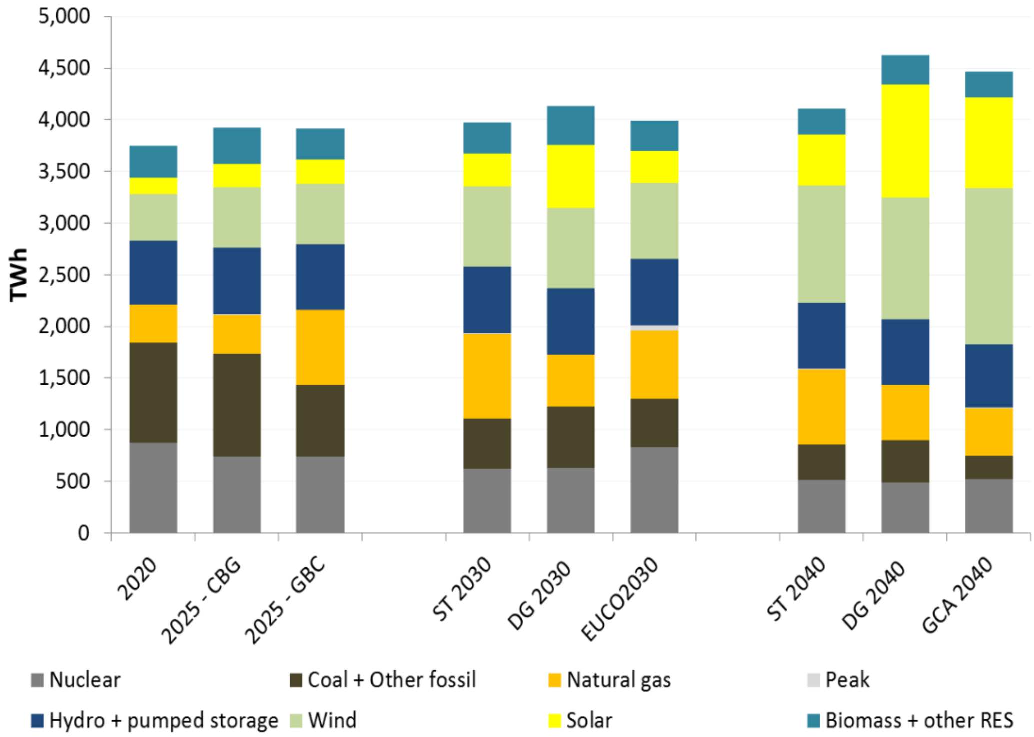


Figure 1 – Electricity generation mix in the TYNDP18 scenarios [11].

As explained above, the European development is included in the simulations as a price boundary for Denmark. Therefore, the above described scenarios need to be transformed to such a price boundary consisting of hourly prices in the countries Denmark is connected to. This is done using the electricity marked model BID3. BID3 is an optimisation model that simulates the power market resulting in, among other things, hourly prices for the price areas included in the model [38]. In this project, BID3 is used to simulate the European power market. Based on detailed input from European TSOs to the TYNDP work, Europe is simulated for ST40, DG40 and GCA40. These simulations result in hourly power prices in all price areas, and can thus be used to construct the price boundary of Denmark in each of the scenarios. The fundamental principles of the BID3 simulation tool are described in the box below.

BID3 simulation tool – fundamental principles

BID is a unit commitment model, an optimisation tool that optimises the merit order dispatch of producers and the flows on interconnectors by minimizing the total cost of supply to minimise the socio economic costs of the system. The cost of supply consists of productions costs of thermal plants, the opportunity cost of water (water value) and the cost of losses on interconnectors. The main constraints of the optimisation are meeting the demand in each hour, capacity of interconnectors and plants, renewable profiles and conservation of water in pumped storages [38].

The price on the wholesale power market is found as the intersection between supply and demand and it becomes the marginal production cost of the most expensive production unit needed to be able to meet the demand. The variable cost of production for plants are built up by efficiency, part load efficiencies, fuel cost, transportation cost for fuel, O&M costs, start-up costs, operating costs, availabilities, and etc. The model does not cover grid investments nor tariffs or taxes on electricity consumption [38].

Norway and Sweden are divided in several price areas. The ones included in this project are SE3, SE4 and southern Norway since these are the areas Denmark is connected to. The resulting price duration curves for ST40 are depicted in Figure 2 along with an average for all the price areas included. The average curve of the neighbouring countries smoothens out the price changes in each area, eliminating the largest price spikes and zero price hours. It does, however, show the general tendency of the prices.

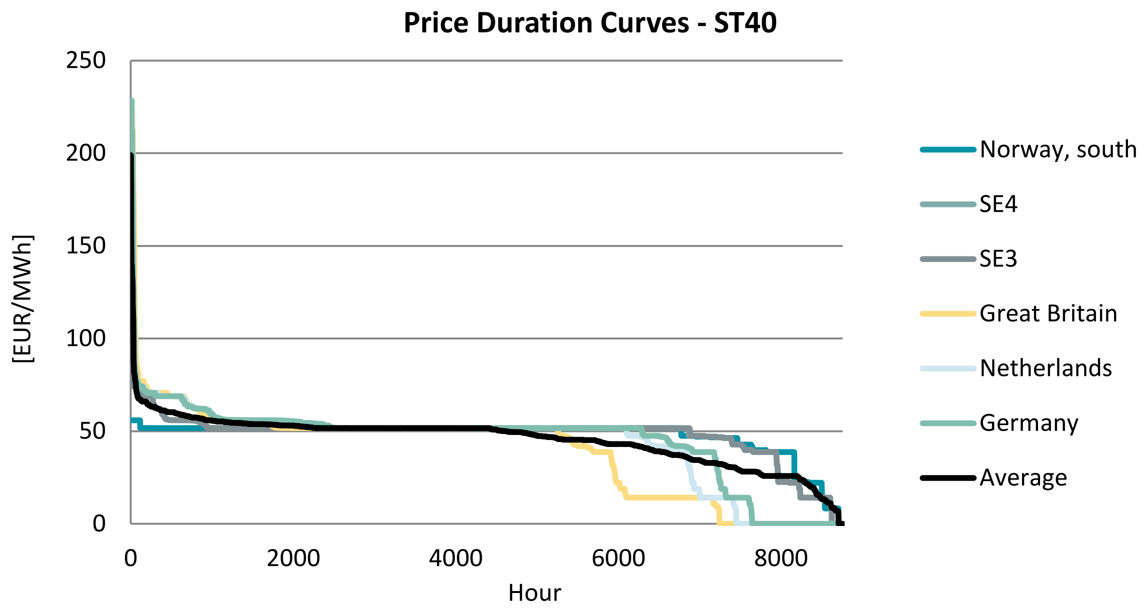


Figure 2 – Price duration curves for ST40. The average curve is the duration curve of the hourly averages in the boundary countries.

The duration curves of the average prices in the boundary price areas for the three scenarios are depicted in Figure 3. Even though the average curves are smoother than the actual duration curve of each price area, they still indicate differences between the scenarios. The duration curve of the prices in DK1 for 2017 is included as a reference to how the duration curves are expected to change from today to 2040. Generally, there are larger price variations in the 2040 scenarios than in the reference for 2017. The curve for ST40 is most similar to 2017 with the smallest variations, where GCA40 implies the largest price variations. In general, DG40 has the highest prices. A limitation to the modelled prices is apparent from the figure, where negative prices arose in 2017 but do not occure in the modelled prices.

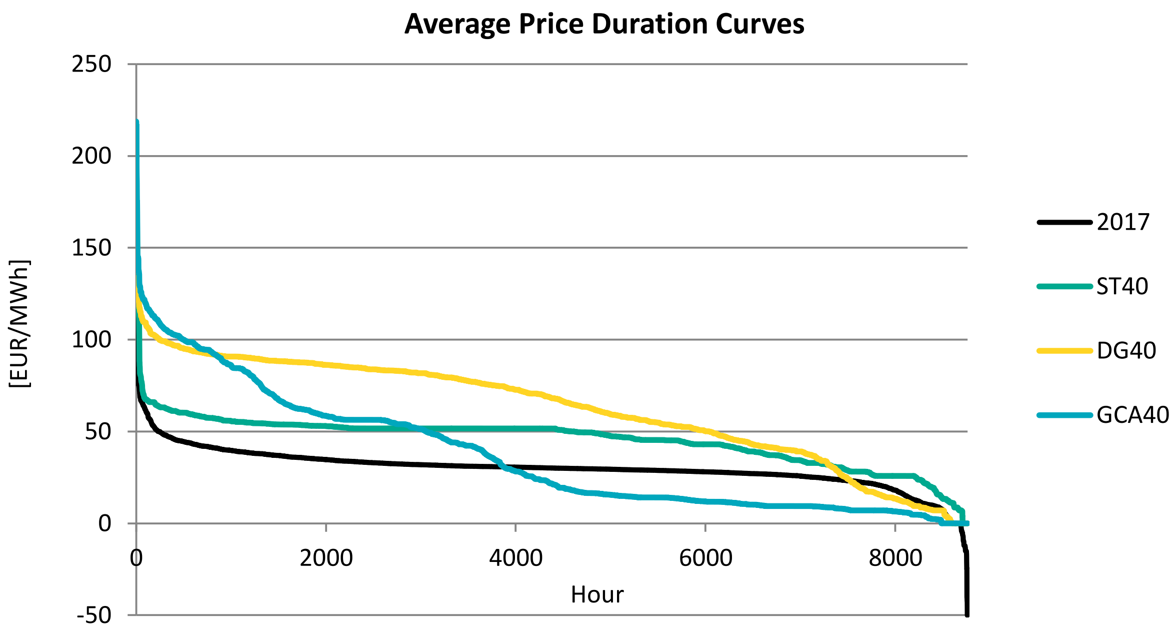


Figure 3 – Average price duration curves for the three TYNDP18 scenarios and 2017 in DK1 for reference.

Both the average prices and the price variations are relevant, especially when investigating the potential of power to fuels (PtX), which has the possibility to operate flexibly according to the electricity price. The average price in the price boundary along with the standard deviation of the average prices in each scenario are presented in Table 1. As also illustrated in the duration curves DG40 has by far the highest average price, and GCA40 has the largest price variations represented here by the standard deviation.

[EUR/MWh]	2017	ST40	DG40	GCA40
Average	30.1	45.5	62.1	37.0
Standard deviation	10.7	14.0	28.4	32.9

Table 1 – Average prices and standard deviation of average boundary prices in the three TYNDP18 scenarios and for DK1 in 2017 for reference.

The above described prices in each of the boundary areas of Denmark in all three scenarios are included in the modelling of the Danish energy system in this project. Specifically, the prices of the neighbouring countries are uploaded as a fixed quantity in Sifre. Hence, the price areas can trade electricity on an hourly basis with the interconnector capacities as the only constraint. Since the neighbouring price areas are not modelled, the prices in these areas will not change as a consequence of trading with Denmark as they would in reality. Thus, it is expected that the entire capacity of the interconnectors will be utilised in most, if not all, hours. To account for this, sensitivity analyses are included with reduced capacities on the interconnectors.

5 Demands & Constraints for the Energy System

To be able to model the Danish energy system in 2050, the future demands and constraints must be estimated. The demands are an input parameter to Sifre. It is important to state that the demands are projected values with large uncertainties connected to them. The demands are divided into different groups for the different sectors and may be further divided, e.g. for transportation for the different transportation services. The demands are based on the projection from the Danish Energy Agency (DEA) [39]. The projection is calculated from a model (EMMA) developed by the DEA to, on an aggregated level, describe the connections between economy, energy and environment [40]. The actual consumption and the projected demands are of course linked, but due to different efficiencies and fuels for possible conversion technologies to cover the same demands, e.g. heat pumps or gas boilers for district heating, the consumption varies depending on the energy pathway from fuel to demand. Hence, this project works with demands as input parameters for the models. The models optimise the consumption via the given possible energy pathways to minimise the costs. The technologies available to cover the same demands are assumed to be substituting goods, meaning that e.g. ICE and EV cars provide the same value.

The demands covered are electricity, district heating, process heat, individual heating and transportation (including both national and international aviation and national shipping) [39]. Again, demand not to be confused with consumption. District heating, process heat, individual heating and transportation can all use electricity as a fuel. The demand group electricity covers the classical electricity demand from industry and households [12]. The demands and the division into different groups are based on the Danish Energy Statistics from 2011 [41]. The energy services are equal for all the electrification scenarios included in this project, meaning that the demands are equal. From the results of the hourly simulations in Sifre the yearly fuel consumption is to be determined. The exogenous constraint in the form of available biomass is estimated from a literature study on the subject as described later in this section.

In this section the present demands are presented and briefly discussed followed by projected demands for the future Danish energy system. Furthermore, the Danish demands for transport are compared to the European average to see if the Danish energy system can be representative of Europe. Hereafter, the Danish biomass potential is estimated and compared to the global potential to investigate if the resulting sustainable energy system of the project can be scaled to deliver a potential European solution on how the entire energy system can be converted to be sustainable.

5.1 The Future Danish Energy Demand

The total Danish energy consumption in the period from 1990 to 2016 is shown in Figure 4. It can be seen that consumption for transport accounts for a little more than 25 %. Furthermore, it is the only sector where the consumption has increased in the period. There have been slight reductions in consumption by residential households, industry and the energy sector. As seen from the figure the total consumption has been rather constant in the whole period. It is approximately 800 PJ with small variations through the years.

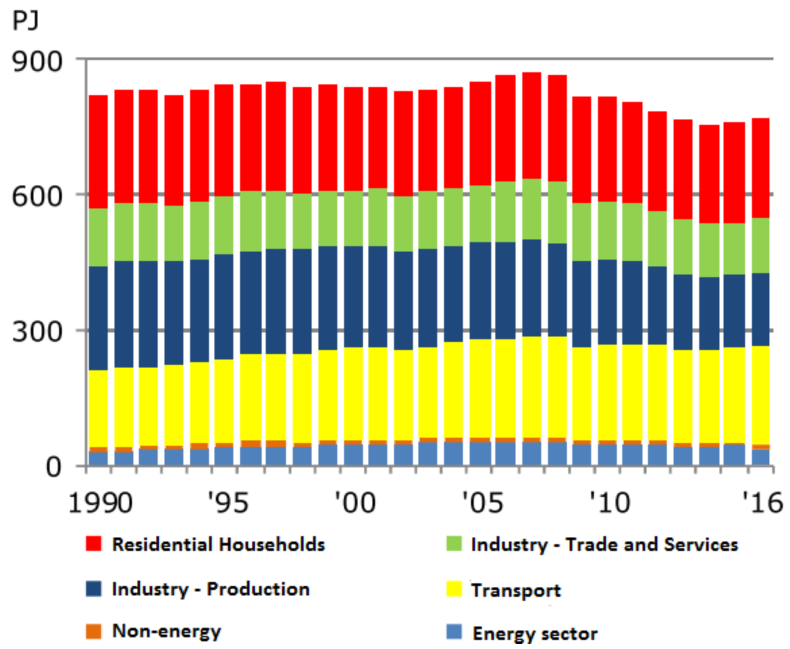


Figure 4 – The total Danish energy consumption divided into areas of use from 1990 to 2016 [41].

The DEA has made four scenarios projecting the energy demand in 2050 based on different levels of energy savings. The four scenarios are Frozen Policy (FP), moderate energy savings (MES), large energy savings (LES) and average energy savings (AES) [42]. An overview of the projected demands for 2050 can be seen in Figure 5. Compared to the Danish Energy Statistics, the demands are grouped a little differently in the consumption model by the DEA [12].

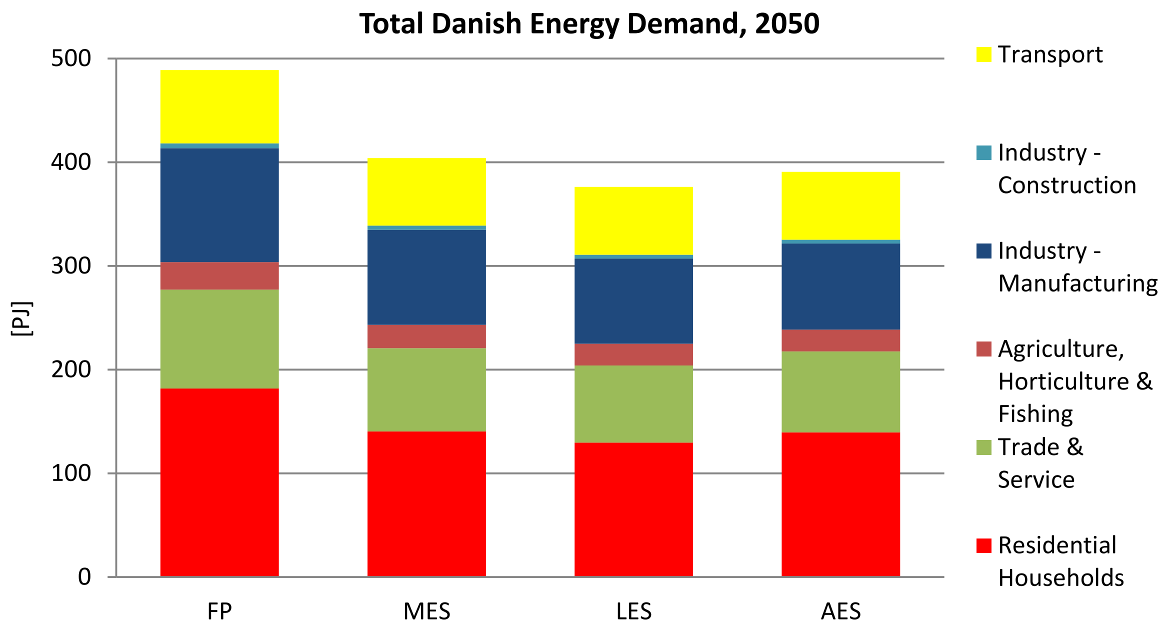


Figure 5 – Projected total Danish energy demand in 2050 grouped by sectors for the DEA scenarios (FP = frozen policy, MES = moderate energy savings, LES = large energy savings & AES = average energy savings). It is mechanical energy demand for transport, not fuel consumption [12].

It is important to stress that the transport demand depicted in Figure 5 is the mechanical demand, not to be confused with the fuel consumption that will be larger due to conversion losses in engines. It is the same for Figure 6. Here, the demand groups are divided into types of energy services - electricity, district heating, process heat, individual heating and transportation.

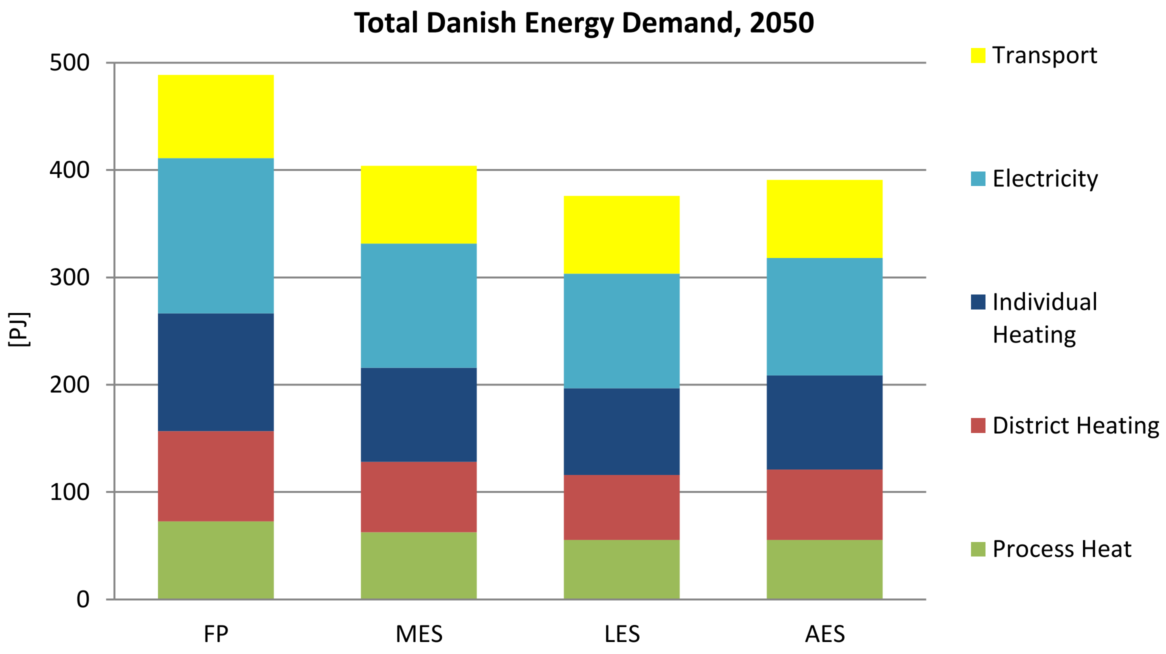


Figure 6 – Projected total Danish energy demand in 2050 grouped by energy services for the DEA scenarios (FP = frozen policy, MES = moderate energy savings, LES = large energy savings & AES = average energy savings). It is mechanical energy demand for transport, not fuel consumption [12].

Comparing Figure 4, Figure 5 and Figure 6 it is apparent that the total energy consumption is decreasing from present levels to 2050. The four DEA scenarios do not reach 800 PJ. Though, if a total fleet efficiency of the transport sector of 25 % is assumed the MES, LES and AES scenarios reach a total consumption around 600 PJ. It is still far from present levels due to energy savings and efficiency improvements for the whole system [39]. This project has chosen the AES scenario for further analysis. The transport demand is equal in the three latter scenarios and the variations for the demand for the other energy services are small. Besides, the focus of the project is the transport sector. The different demand groups will therefore not be further presented or evaluated in the project except transport. However, data is available for the AES scenario in *Appendix A – Energy System Demand 2050*.

5.2 Transportation Demand

The historical energy consumption for transportation in Denmark divided into transport services is shown in Figure 7. In 2016, the consumption for road transport was approximately 75 % of the total consumption. Aviation stands for another 20 %, and the remaining 5 % are split between rail, sea and other means of transport, e.g. in the army. As stated in the *Introduction*, the transport demand and therefore the consumption has been increasing, as evident from the figure.

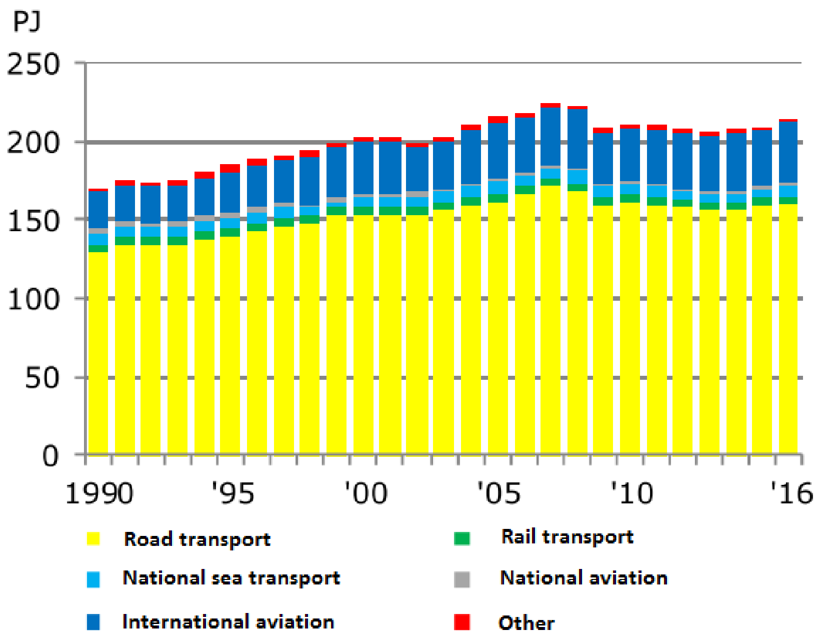


Figure 7 – The Danish energy consumption for transportation divided into transport services from 1990 to 2016 [41].

As mentioned indirectly, the given transport demand does not include international freight transport by sea. Neither does the projection by the DEA, but it will be included in a sensitivity analysis. Furthermore, it does not include machines not on the road or Danish vehicles fuelled abroad. However, the DEA model for consumption includes foreign vehicles fuelled in Denmark [12]. In outline, the model includes transportation on road, national and international transport by rail, national and international aviation, national transport by sea and the energy demand for transportation for the Danish army [43]. The model is a spread sheet-model based on the latest statistical data for a whole year[12] . The model was last updated with data for 2016.

Efficiency Improvements [MJ_{mech}/km]	[%/year]		Total [%]
	2020-2035	**2035-2050**	**2050**
Light road	0.25 %	0.17 %	**6.35 %**
Van	0.05 %	0.03 %	**1.13 %**
Truck	0.05 %	0.03 %	**1.13 %**
Bus	0.05 %	0.03 %	**1.13 %**
Motorbikes	0.05 %	0.03 %	**1.13 %**
Rail – passenger	0.05 %	0.03 %	**1.13 %**
Rail – freight	0 %	0 %	**0 %**
Shipping	0 %	0 %	**0 %**
Aviation	0.60 %	0.50 %	**17.16 %**
Army – aviation	0 %	0 %	**0 %**
Army - road	0 %	0 %	**0 %**

Table 2 – Expected efficiency improvements for transport services from 2020-2050 [42].

The projections for future demand are based on the expected development in demand for different transport services and the expected development for efficiency (including new emerging vehicles). Here, efficiency does not refer to engine efficiency but the efficiency in converting mechanical energy to a distance travelled. Thus this efficiency improvement is a measure of e.g. improved aerodynamics and utilisation of vehicles. The expected yearly developments are shown in Table 2 and Table 3 for efficiency improvements and demand growth respectively.

Demand Growth [km]		**[%/year]**			**Total [%]**
	2020-25	2025-30	2030-35	2035-50	**2050**
Light road	1.42 %	1.15 %	1.09 %	0.96 %	**33.05 %**
Van	1.61 %	1.44 %	1.28 %	1.38 %	**50.85 %**
Truck	0.98 %	1.12 %	0.94 %	1.35 %	**49.52 %**
Bus	0.36 %	0.29 %	0.27 %	0.24 %	**7.43 %**
Motorbikes	1.78 %	1.44 %	1.36 %	1.20 %	**42.83 %**
Rail – passenger	0.89 %	0.72 %	0.68 %	0.60 %	**19.58 %**
Rail – freight	0.39 %	0.45 %	0.38 %	0.54 %	**17.53 %**
Shipping	0.10 %	0.11 %	0.09 %	0.13 %	**4.13 %**
Aviation	1.78 %	1.44 %	1.36 %	1.20 %	**42.83 %**
Army – aviation	0 %	0 %	0 %	0 %	**0 %**
Army - road	0 %	0 %	0 %	0 %	**0 %**

Table 3 – Expected demand growth for transport services in Denmark from 2020-2050 [42].

The assumed yearly developments lead to an increase in demand for transportation in 2050 compared to 2020, which is the reference year of the projections. It is shown in Figure 8 that the mechanical energy demand is expected to increase by 26.5 % in the period based on the assumptions regarding yearly demand growth and efficiency improvements. The mechanical energy demand divided by engine efficiencies equals the total fuel consumption. The average vehicle fleet engine efficiency in 2010 was 24.97 %. The mechanical energy demand for 2010 of 52.64 PJ became a total fuel consumption of 210.78 PJ, as seen in Figure 7. The average efficiency is expected to increase in the future, not only due to the yearly developments but because of the penetration of electric engines with higher efficiencies than existing ICEs [44], [45]. The penetration of electric vehicles not only decreases the total fuel consumption but also the total energy demand to produce the fuel because of varying efficiencies for the different energy pathways to e.g. electricity, liquid and gaseous fuels [13].

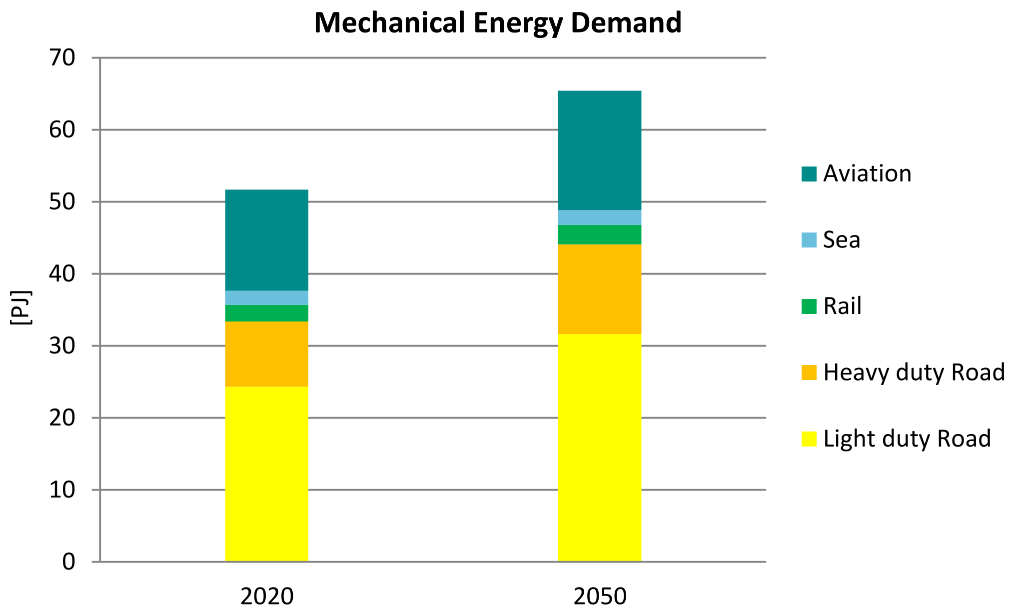


Figure 8 – The total energy demand in mechanical energy for transport in 2010 and 2050 for the five main categories of transport services [42].

The projection of the transportation demand by the DEA includes more details than the main categories of transport services. E.g. it includes 33 different types of road transport to give a realistic estimate of the total fleet efficiency of vehicles on road [43]. For simplicity the many categories are grouped in the five main groups in Figure 8 in this project. The project works with different scenarios regarding electrification of transportation for the five aggregated categories. Based on future expectations on technology development and market penetration the project will determine the spread of the different vehicle technologies for the scenarios. This is done in section *Transport Electrification Scenarios.*

5.3 Consumption in Denmark Compared to Europe

To investigate if it is possible to scale the results of the project to a European scale, the average transport activity pr. capita is compared for Denmark and Europe as a whole. Due to the availability of data the transport activity is measured in the sum of person km (pkm) and ton km (tkm), the latter for freight. The data for Denmark is from the CEESA study [13]. The data for Europe is from the European commission [46]. As seen from Figure 9 the transport demand pr. capita is very similar for the two areas. The total demand varies 5 %, and the individual transport demands are also similar. Aviation varies the most being a little more than twice as large for Denmark as for Europe. For sea transport it is the opposite, it is twice as large for Europe as for Denmark. Though, it is still a small fraction of the total demand.

The comparability for transport demand pr. capita for Europe and Denmark is large. Due to large uncertainties when projecting demands and the fact that the data was found from independent projects, it is almost impressive to find data that alike. If scaling the Danish demand to European scale, the demand for aviation will affect the final energy system a lot due to the difficulty of making sustainable jet fuel. Though, the energy system designed by this project is definitely scalable to a European scale in a broad context. Another constraint that ought to be compared is the sustainable amount of biomass residues pr. capita that can be utilised for energy and transportation. This is done in the next section, *Sustainable Biomass Potential*.

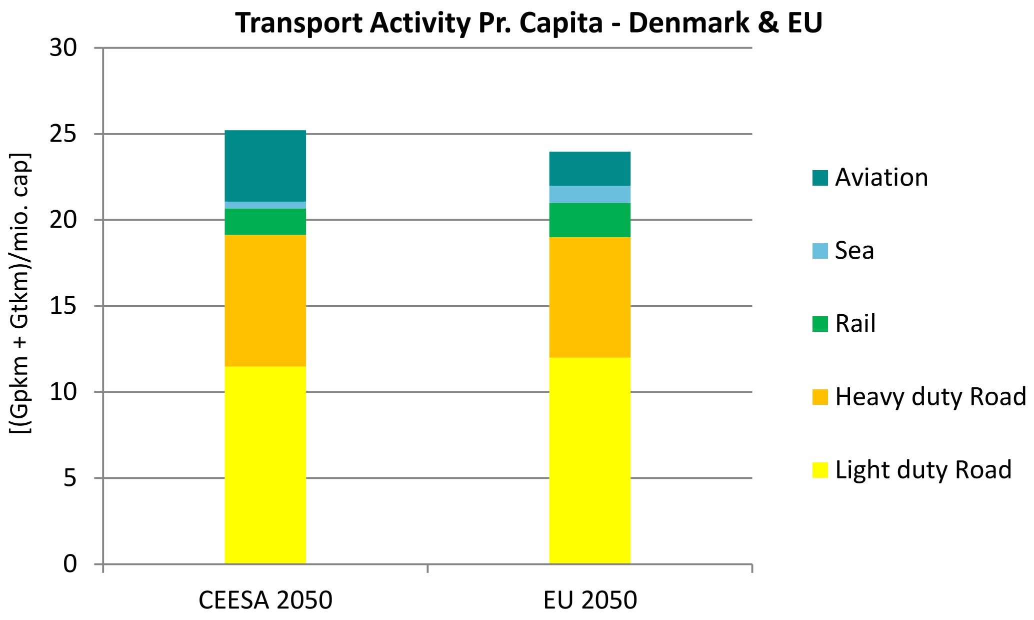


Figure 9 – Projected average transport activity pr. capita in pkm and tkm for Denmark and EU in 2050.

5.4 Sustainable Biomass Potential

Biomass is going to be a scarce resource in the future energy system. Biomass has so far been the easy substitute for coal at Danish power plants for combined heat and power production, though it is considered a temporary solution. In the future energy system, biomass can be utilised for production of liquid fuels and as a fuel for controllable electricity production to stabilise the frequency of the grid. The optimal split between the two must be analysed depending on the demands of the system and the given inputs, as done in this project. Other sectors currently relying on fossil fuels will also potentially shift to biomass as the fuel/input, e.g. the chemical industry [10]. However, due to the direct link between biomass and food production, deforestation and land-use, the biomass used for energy and transportation must be limited to the residual and biogenic biomass [8]–[10]. It will most likely become a severe bottleneck in a fossil free society [10].

Taking a national point of view for Denmark many studies and projects have tried to estimate the domestic biomass potential available for the energy system. EA Energy Analyses have found and compared 14 studies on the matter [47]. The studies analysing the current potential have an average value of 148 PJ/year, while studies of the future potential have an average value of 214 PJ/year for the domestic biomass potential. The main differences are for energy crops and straw due to restructuring of crops. The studies assume that the carbon balance is equal regardless of how the biomass is used in the system. It does not consider if the residues from e.g. anaerobic digestion of wet biomass is delivered back to the agriculture to maintain the carbon, protein and phosphorus balance of the fields [47]. To avoid a yearly decrease of organic matter in the fields as well as competing with food production, the energy crops potential is excluded in this project. The estimated values for the future biomass potential from the different studies can be seen on Figure 10. On the figure, the “Average” column depicts the average for the studies to the left of the column which are studies included in the literature search by EA energy analyses. The average for e.g. straw only reflects the studies that include a non-zero value for straw. The three most right columns are other relevant studies included in the comparison.

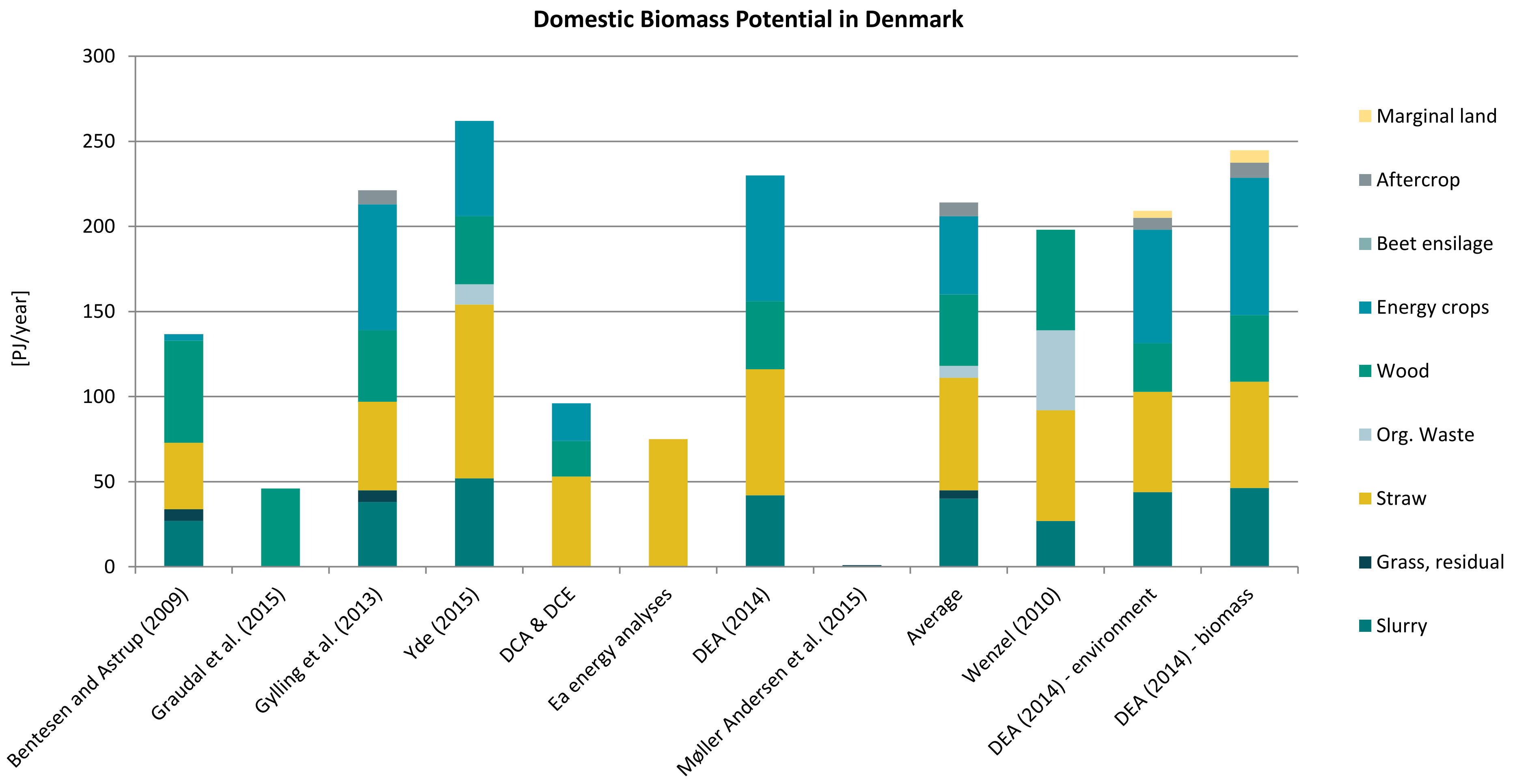


Figure 10 – Estimates for the biomass potential for energy use in Denmark split into different biomass categories based on the lower heating value of the organic dry matter. The "Average" column depicts the average for the studies to the left of the column which are studies included in the literature search by EA energy analyses. The average for e.g. straw reflects only the studies that include a non-zero value for straw. The large variations in the studies are because of different assumptions and focus areas, e.g the study from Ea energy analyses which only focuses on the potential for straw. The three columns to the most right are other relevant studies [10], [39], [47]–[49].

The constraint on biomass utilised in the simulations in Sifre for this project are based on the analysis from Wenzel [10] equal to 198 PJ/year of biomass potential split into 59 PJ of wood, 47 PJ of organic waste, 65 PJ of straw and 27 PJ of slurry, as shown in Figure 10. It is due to the consideration of excluding energy crops and the fact that the total potential is close to the average from the literature study from EA and the additional analyses from the DEA.

Taking a global point of view, as for Denmark, many have tried to estimate the biomass potential for energy purposes. The studies take different sources of biomass into account, from the biophysical maximum to what is estimated economically feasible to residues only [10]. Hence, the results vary a lot, from 75 to 500 EJ/year. The study from EA Energy Analyses also discusses the global biomass potential. The interval from the study is from 100 to 300 EJ/year which is among others based on an IPPC report on bioenergy [47], [50]. The IEA also released their estimates based on a recent literature study on the subject. Their interval ranges from 51 to 287 PJ based on six studies from IRENA (2016), Greenpeace (2015), Shell (2011), WEC (2016), S. Searle and C. Malins (2014) and V. Daioglou (2016) [51].

The estimated biomass potential is unavoidably uncertain. Factors both inside and outside of the bioenergy sphere can influence the availability, e.g. the balance between increases in agricultural productivity and efficiency and global food demand, re-establishing degraded lands back into production, reduction of food waste, co-production of food and energy and generally maximising the efficiency of utilised bioenergy resources with respect to fossil carbon saved [51]. Regardless of the future potential, the current supply of biomass to the energy sector equal to 63 EJ must increase if a global fossil free society is the target [51]. For comparison the global fossil fuel consumption today is around 400 EJ [10]. Hence, if no disruptive changes emerge the biomass supply will become a bottleneck. Again, the potential biomass is dependent on what is included, e.g. waste, agricultural and forestry residues, other forestry materials, energy crops, algae, etc., and on the constraints applied on biomass supply [51]. The more recent papers, that include considerations on the impacts of direct land-use changes (ILUC), have reduced the differences regarding underlying assumptions and there seems to be consensus that up to 100 EJ can be delivered without serious difficulties before 2050. The gap up to 300 EJ/year is more uncertain and depends on many assumptions. A global biomass potential of 150 EJ/year, equivalent to 15 GJ/person for a global population of 10 billion in 2050, is used as an input for the sensitivity analysis in this project [52]. Compared to the domestic biomass potential of 198 PJ and a population of 6 million in Denmark in 2050, equal to a Danish biomass potential of 33 GJ/person, the biomass potential is more than halved. The consideration regarding the global potential pr. person is to be able to argue that the Danish system can be expanded/scaled in a sustainable manner to include the entire globe.

6 Transport Electrification Scenarios

There is a general consensus that electrification is an efficient and cheap way to replace the use of fossil fuels in many sectors, including transportation [13], [53]–[55]. This is, among other things, due to the high efficiency of electric engines, and the possibility of producing renewable electricity from known technologies such as PV panels and wind turbines [56]. Furthermore, the energy pathway that results in electricity as a fuel implies fewer losses and by-products in the production phase of the fuel [13]. It is therefore assumed that electrification would be the preferable pathway for the transport demand. Electrification of transport can happen in two ways – direct or indirect. There are limits to the degree at which both pathways can be utilised. Direct electrification depends on infrastructure supplying a cable available to the end user at all times. An increased flexibility of electrification can be obtained by indirect electrification, where a battery is used as an intermediate storage. There are, however, also some limitations to the degree of possible indirect electrification, especially for heavy transport such as trucks, ships and airplanes [53]. These limitations arise due to the required range and energy to meet the transport needs in relation to both the cost and energy density of batteries. Battery technologies have gone through significant developments during the last decades as illustrated for lithium-ion batteries in Figure 11. The energy density has increased while the cost has decreased. This development has to at large extent been driven by increased demand from small portable electronics such as laptops and cell phones and the increased attention to electrification of transportation and electricity storage opportunities [57].

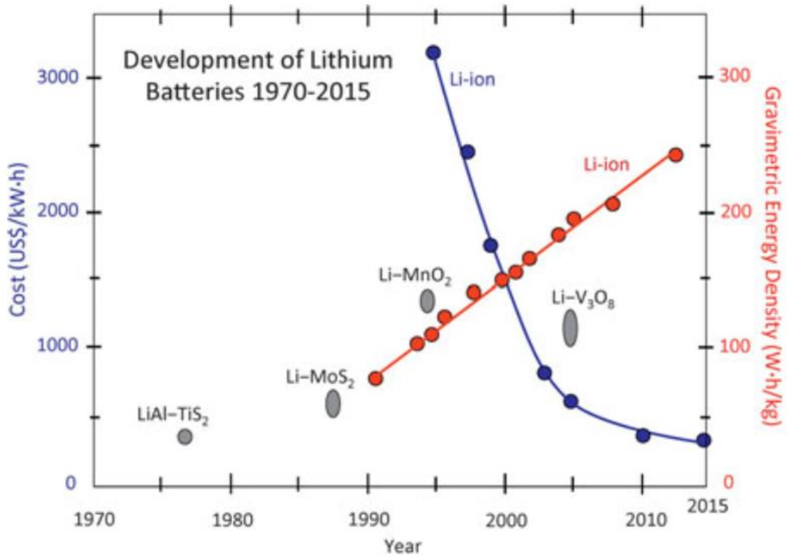


Figure 11 – Development of cost and energy density of lithium batteries [57].

Significant effort continues to be put in research and development of different battery technologies regarding cost, energy density, capacity, charging rate, etc. [58]. Presently, only 0.7 % of the energy used for transportation in Denmark is electricity and thus large changes are required for electricity to satisfy a significant part of the transport demand [41]. Due to the above factors, it is challenging to attempt to predict to what extent the Danish transportation sector will be electrified in the long run. To account for this uncertainty, different scenarios for the electrification of the transportation sector are set up and analysed in the energy system model. The degree of electrification is thus an exogenous factor of the modelling and will result in a residual need for other means of satisfying the projected transport demand. To set up the electrification scenario, research is done on the state of the art within electrification of the different transport modes along with expectations of future possibilities. The transport modes covered correspond to the categories presented in *Transportation Demand*. In the first subsection the electrification scenarios are outlined. Hereafter, the fuels implemented in the model to satisfy the residual demands are described. Lastly the vehicle efficiencies for the different fuel types used in the modelling are presented and used to estimate the total fuel demand in each scenario.

6.1 Scenarios

Based on the research described in *Appendix B – Electrification of Transport Modes* related to electrification of different transport modes, five scenarios are set up for the electrification of the entire transportation sector. As mentioned, this is done in an attempt to account for uncertainties regarding technological development of batteries and adoption of the technology in different sectors, including the development of alternative propellants. The scenarios are described by a share of the mechanical transport demand for each of the five transport modes that is covered by electricity. All the electrification shares in the scenarios are based on the current use of the different transport modes and do therefore not account for the fact that this might change in the future. E.g. that the distribution between distances travelled for light duty road might change.

The first electrification scenario, “Full”, is the most ambitious scenario when it comes to electrification. Hence, the entire transport sector is electrified. This scenario is included more as an extreme case for comparison and not as much as a realistic expectation.

In the second electrification scenario, “Ambitious”, 100 % of rail, light road and heavy road transport are still electrified, while only a share of sea transport and aviation is electrified. Electrification of ferry routes between 45 and 90 minutes would correspond to 20-40 % of the energy demand for ferries in Denmark. The upper part of this interval, 40 %, is used for the electrification of sea transport in this scenario. For aviation all national flights and the international flights with distances up to 2000 km are electrified. This level of electrification corresponds to 46 % of the person km travelled by plane in 2016 [59], [60]. Even though the average energy consumption pr. person km is lower for the longer distances it is assumed reasonable to use the same percentage for the share of the mechanical transport demand that is electrified.

In the third electrification scenario, “Moderate”, the ambitions for the electrification of heavy road transport are lower. Here, national truck transport, international truck transport with distances below 800 km, corresponding to Tesla’s Semi Truck, and all bus transport is electrified. Using the same approximation as above, that the share of person km and ton km can be translated to share of mechanical energy demand this corresponds to 93 % of the energy demand for heavy road transport [61]–[63]. For aviation, all national flights and international flights with distances up to 1000 km are electrified. This is based on an expectation of additional improvements in the technology in the long run compared to e.g. Wright Electric, who expects to have a commercial plane flying routes up to almost 500 km by 2027. This level of electrification corresponds to 29 % of the Danish person km travelled by plane in 2016 [59], [60]. For sea transport, the lower interval of the estimate from the Danish Energy Association of 20 % is used.

In the fourth scenario, “Slight”, the degree of electrification is reduced in most of the transport modes. For aviation, only the national transport is electrified, corresponding to 1 % of the person km travelled [59], [60]. The electrification of sea transport is reduced to 5 % in this scenario. For heavy road transport, trucks travelling distances below 250 km and transit busses are electrified, corresponding to 48 % of the demand for heavy road transport [64]–[66]. For light road transport, trips below 150 km are electrified. Looking at passenger transport by car this corresponds to 87 % of the trips taken [67]. Neglecting the distribution of trips travelled by vans and the fact that more energy is used pr. trip for the longer distances, this share could be used for the degree of electrification. However, to account for the fact, that some users would like their car to occasionally travel longer distances the percentage is reduced to 80 %.

In the fifth and least ambitious electrification scenario, “Conservative”, no electrification is implemented in aviation and sea transport. For heavy road transport, only the transit busses are electrified, corresponding to 8 % of energy demand [64]–[66]. In the light road transport mode only very short distances below 20 km are electrified, corresponding to 30 % of the trips travelled by car [67]. Again, this is used as the share of the mechanical energy that is electrified. For rail transport, the remaining 358 km of the rail network, which are not in the progress of being electrified, are not electrified. This corresponds to 10 % of the rail network. Even though, the majority of the trains probably run on the electrified part of the rail network this percentage is used as the share of the energy demand for rail that is electrified.

An overview of the five electrification scenarios is presented in Table 4. The scenarios represent different possible outcomes for the electrification of transport.

Scenario	Rail	Light road	Heavy road	Sea	Aviation	Total
Full	100 %	100 %	100 %	100 %	100 %	100 %
Ambitious	100 %	100 %	100 %	40 %	46 %	84 %
Moderate	100 %	100 %	93 %	20 %	29 %	78 %
Slight	100 %	80 %	48 %	5 %	1 %	52 %
Conservative	90 %	30 %	8 %	0 %	0 %	19 %

Table 4 - Electrification scenarios – share of mechanical energy that is electrified for each transport mode in each scenario.

Based on the energy demands projected in the section *Transportation Demand*, these electrification scenarios can be used to determine the mechanical energy demand that should be covered by electricity and the residual demand to be covered by other propellants in each scenario. The electrified mechanical energy demand for each scenario is presented in Figure 12. The residual demand for each scenario corresponds to the difference between the total electrified demand and the line representing the total mechanical energy, which is the same in all scenarios.

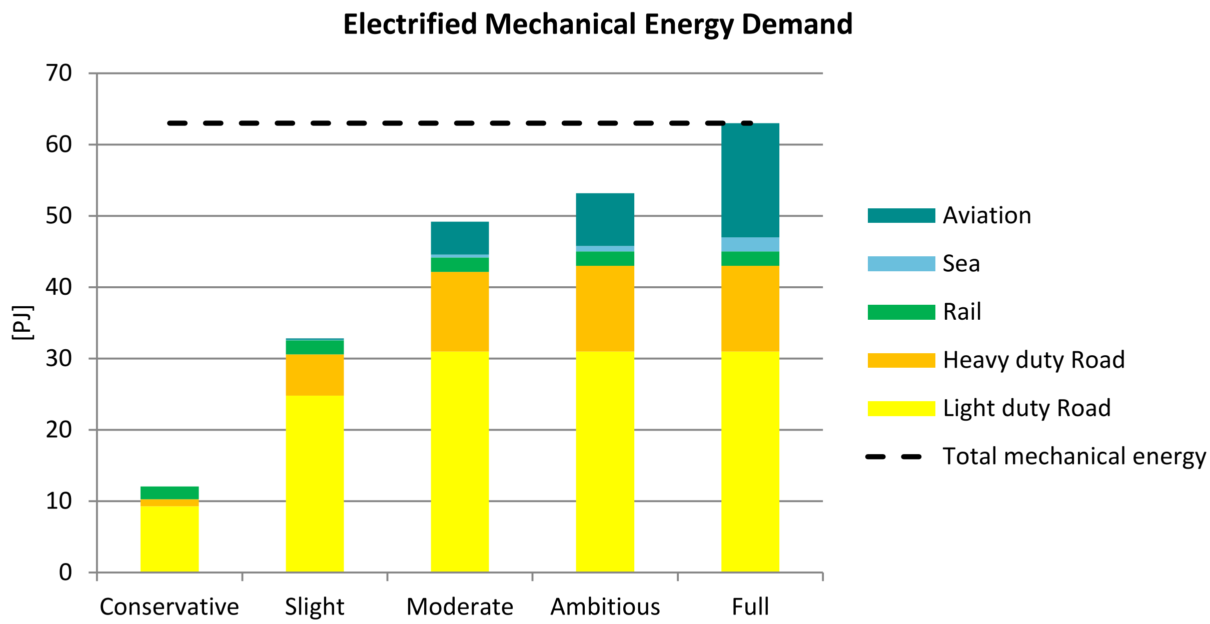


Figure 12 - Overview of electrified mechanical energy demand in each electrification scenario.

It is obvious, that the electrification scenarios will have a large impact on the modelling since the residual demand to be covered by other propellants vary greatly from scenario to scenario. The conversion technologies to liquid and gaseous fuels are more reliant on synergies with the heat sector. Furthermore, carbon inputs are needed for these fuel pathways and again the engine efficiencies vary a lot.

6.2 Residual Transport Demands for Liquid & Gaseous Fuels

In each of the electrification scenarios the residual transport demand, which is not electrified, must be covered by a fuel with a higher energy density since this is often the limitation to the degree of electrification. For most of the transport modes, there are numerous fuel options. However, for aviation there are no immediate alternatives to the kerosene-based jet fuels used today [68]. The best option to replace the fossil fuels in aviation is therefore to produce synthetic kerosene, using either biomass or CO_2 from the atmospheric air as a carbon source [69], [70]. The process of producing synthetic kerosene results in a number of by-products, of which some can be used to satisfy demands in other transport modes. This element is further elaborated in *Fuel Production Pathways*.

For the other transport modes there are several fuel options including sustainably produced liquefied natural gas (LNG), compressed natural gas (CNG), hydrogen, diesel, gasoline, methanol, ethanol and DME [71]–[73]. In this project, methanol, LNG and CNG have been chosen as the only fuel options, apart from electricity and the by-products from the production of jet fuel. It is necessary to define the final fuel, in order to identify possible pathways to this fuel and the conversion losses and investments related to these pathways. Methanol has the lowest carbon to hydrogen ratio of any liquid fuel and therefore it is well-suited for utilising the limited carbon resources through upgrading with hydrogen [13]. This is the reason why methanol is chosen over e.g. ethanol. The benefits of using methanol are among others that it can be used directly in an ICE as a replacement of gasoline with few modifications and that the existing fuelling infrastructure can be utilised [13]. Furthermore, methanol can be used in all transport modes except aviation. DME could be another fuel option. From a well to wheel perspective, the efficiency of methanol and DME are very similar [13]. Since the main focus of this project is the use of biomass and CO_2 from direct air capture to satisfy the demand for transport fuels, it is less significant whether DME or methanol is chosen. LNG and CNG are chosen as the other fuel options. This is done to allow for a more direct use of the biogas resources with fewer conversion steps than if you have to convert it to methanol. Both CNG and LNG are included since they are well suited for different transport modes. LNG is, due to the high energy density, suited for heavy road and sea transport. The shipping industry has already adopted the use of LNG [71]. In 2015 the first Danish ferry to run on LNG was commissioned. It operates the route between Jutland and Samsø and by 2020 the largest containership in the world will be running on LNG [74], [75]. LNG is however poorly suited for light road transport due to high losses from evaporation, hence CNG is included as an option for both light road and busses [76]. Due to the low energy density of both biogas and methane, they are less suited for direct use in the heavy transport modes which require the largest amount of alternative fuels. Hydrogen is not included as a direct fuel option due to the high cost associated with hydrogen vehicles, compression, transport and storage [77]. The costs associated with establishing infrastructure for hydrogen is likely to counterbalance the lower costs associated to hydrogen production compared to other fuel types [78]. Furthermore, even after using an energy input equivalent to minimum 13 % of its energy content to compress it, hydrogen still has a low energy density compared to other fuels [77], [79]. Hydrogen would thus be best suited for light transport and are therefore in direct competition with electric vehicles which are assumed to outmatch every alternative [80], [81]. Instead of using it directly as a fuel, hydrogen is used to boost the carbon resources and thereby achieve a better utilisation of them. The different pathways available to produce kerosene, methanol, LNG and CNG are described in brief in *Fuel Production Pathways* and in more detail in *Appendix D – Technology Data*.

6.2.1 Vehicle Efficiencies

Depending on whether you use electricity, jet fuel, methanol, LNG or CNG to satisfy a mechanical transport demand, the mean of transport will have different efficiencies. To account for this, the expected long-run (2050) efficiencies are included in the modelling. The assumed efficiencies are presented in Table 5. Most of the efficiencies are based on the model, Alternativ Drivmiddel - model, from the Danish Energy Agency. Assumptions and other sources are described in *Appendix C – Engine Efficiencies*.

	Light road	Heavy road	Air	Sea	Rail
Electricity	82 %	63 %	58 %	68 %	77 %
Methanol	23 %	24 %		31 %	28 %
LNG		24 %		30 %	
CNG	23 %	16 %			
Jet fuel			19 %		

Table 5 - Applied transport mode efficiencies for the different fuels. The difference for light and heavy road for CNG is due to the utilisation of CNG in busses with bad fuel economy.

Hybrid vehicles are not directly included in the modelling. However, since the modelling is based on an aggregated demand for electricity and alternative fuels for transport, this can represent a combination of EVs, ICE vehicles and hybrid vehicles. Fuel cell (FC) vehicles running on methanol could also be included since they have a better efficiency than methanol ICEs. However, to be conservative, FCs are omitted from the model.

Based on the efficiencies presented in Table 5 and described in *Appendix C – Engine Efficiencies* the mechanical transport demand can be converted to a fuel demand. For most of the transport modes, different fuel options exist to cover the demand that is not electrified. In the modelling, Sifre is used to determine which of the fuels are used. The efficiencies of the different engine types are included in the modelling. Thus, the exact fuel demand will depend on the fuels used to satisfy the demands. An approximation of the fuel demand in each of the electrification scenarios is illustrated in Figure 13. The efficiencies used to calculate the demand for other fuels than jet fuel and electricity are an average of the different possibilities for each transport mode. The figure clearly illustrates the value of electrification when it comes to overall efficiency of the system.

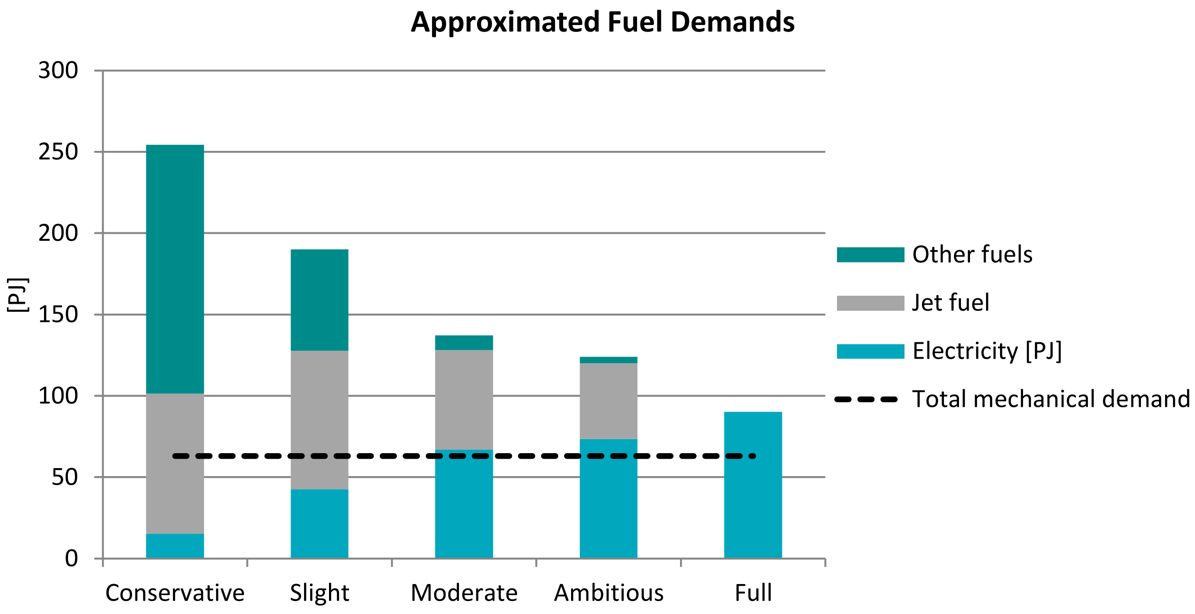


Figure 13 - Approximated fuel demands in the five electrification scenarios.

7 Fuel Production Pathways

In *Residual Transport Demands for Liquid & Gaseous Fuels* methanol, LNG, CNG and jet fuel were chosen as the fuels to include in the modelling to satisfy the transport demand which is not covered by electricity in each electrification scenario. To fulfil the condition of a 100 % sustainable transport sector, these fuels must be produced using only sustainable biomass and renewable electricity as inputs. In the current energy system, electricity is not necessarily a renewable input but in a future 100 % renewable energy system it will be. In this section different pathways to produce the fuels are described in overall terms and the most promising pathways are chosen for further investigation. Several pathways to produce the fuels are included in the modelling and Sifre and ADAPT will be used to optimise how the different pathways are utilised and combined. After the description of the pathways, the integration of the pathways in the surrounding energy system is described.

Numerous pathways exist to produce each of the fuels. This is also the case for jet fuel. However, for safety reasons jet fuel has rigid standards and specifications that must be met. This includes not only the specifications of the fuel but also the production process must be certified [70]. The Aviation Fuel Quality Requirements for Jointly Operated Systems (AFQRJOS) defines the fuel quality requirements for supply into fuelling systems operated to Joint Inspection Group (JIG) standards, which is the case for Danish fuelling systems [82]–[84]. The AFQRJOS embodies the specifications of both the British Ministry of Defence Standard (Def Stan) and the ASTM. The approval process for a new pathway can be quite long and complicated [85]. Therefore, it has been chosen to focus on the pathways that are already approved by the Def Stan and the ASTM. There are currently four pathways approved to produce synthetic jet fuel [86], [87]. The four pathways are briefly described here.

- **Synthesises iso-paraffins (SIP) pathway.** This pathway is based on sugar or starchy feedstock which is pre-treated through hydrolysis to extract sugar molecules [86]. The sugar molecules are directly fermented to hydrocarbons which are hydrogenated. The pathway produces a single hydrocarbon and not a mixture of hydrocarbons as the other processes. Since kerosene used for jet fuel is a mixture of different hydrocarbon chains, this pathway is only approved for a 10 % blend by ASTM and Def Stan [87], [88].
- **Alcohol to jet (ATJ) pathway.** This pathway is based on the same feedstock as the SIP pathway and the feedstock is also pre-treated through hydrolysis to extract the sugar molecules. However, in this pathway the sugar molecules are fermented to produce alcohols which are dehydrated and oligomerised, resulting in a mix of hydrocarbons of different lengths. The double bonds and oxygen are removed through hydrogenation and lastly the different end-products are separated in a distillation step. The end-products are diesel, light ends[1] and kerosene [86], [87]. The ATJ pathway can be sub-divided in two pathways: the synthetic paraffinic kerosene (SPK) and the synthetic aromatic kerosene (SAK) pathway. The SPK fuel contains only alkanes and no aromatics, where the SAK produces aromatic hydrocarbons. Jet fuel must contain aromatics, and therefore the SPK is only ap-

[1] Light ends: The products in crude oil with lower boiling points [194].

proved to a 30 % blend, and only by ASTM [87], [89]. The SAK pathway is not approved according to the two specifications yet [87].

- **Hydrotreated esters and fatty acids (HEFA) pathway.** The feedstock used in this pathway is oil rich feedstock such as oil crops and waste oils. After removing impurities from the feedstock, the vegetable oils are hydrogenated to create hydrocarbons which are hydrocracked to produce hydrocarbons of the desired length. Lastly the end-products are separated in a distillation step. The end-products are the same as for the ATJ pathway: diesel, light ends and kerosene. This pathway is approved by Def Stand and ASTM to a 50 % blend with conventional jet fuel [86], [87], [90].
- **Fischer-Tropsch (FT) pathway.** The key element of the FT pathway is syngas. The syngas can be produced in a number of ways which will be elaborated later. The syngas is processed through FT synthesis where pure syngas under controlled pressure and temperature is fed over a catalyst, resulting in hydrocarbon molecules in the form of a FT wax. The FT wax is hydrocracked and distilled to get a range of end-products. The composition of the end product can be changed by adjusting the operating pressure and temperature in the FT synthesis. The end-products are diesel, gasoline and kerosene [86], [87]. As for the ATJ pathway, the FT pathway can be divided in two pathways; the Fischer-Tropsch Synthetic Paraffinic Kerosene (FT SPK), which only produces alkanes and a similar process which produces aromatic hydrocarbons (FT SPK/A). Both FT pathways have been approved for a 50 % blend [90]. The FT SPK/A is currently the only pathway that produces fuel, which could be used in a 100 % blend due to the presence of aromatics [87].

To limit the number of pathways included in the modelling, it has been chosen only to include the FT SPK/A pathway, which at present is the only option for a 100 % blend. Due to the time horizon of the Paris Agreement it is deemed less likely that new technologies will emerge in time. Furthermore, this is the pathway with the fewest limitations to the amount of feedstock available since syngas can be produced in several ways and even with no biomass input. The FT pathway is assumed to produce gasoline as a by-product as further elaborated in *Appendix D – Technology Data*. It is assumed that the gasoline can be used in the other transport modes in the same way as methanol and with the same efficiencies.

Syngas consist of CO and H_2. Thus, to produce syngas a carbon source is needed. A possible carbon source is solid biomass e.g. wood. Through thermal gasification the solid biomass can be converted to syngas [27], [86]. Before entering the gasification plant the wood must however be dried to the right moisture content. Furthermore, an oxygen supply is needed to achieve the optimal production of syngas, to avoid inert N_2 and to provide heat through combustion to the endothermic reactions [91]. This oxygen can be supplied either from the electrolysis processes, which are described later, or from an air separation unit which uses electricity to separate oxygen from atmospheric air [91]. Continuous operation of the thermal gasification unit is desired, hence a continuous oxygen stream is needed. This could be solved by investing in a storage unit for the oxygen supplied by the electrolysers. The gasification is illustrated in Figure 14 along with the other pathways implemented in the modelling.

Another carbon source for the syngas could be biogas. Biogas can be produced from manure, straw and organic waste through anaerobic digestion. Biogas is a mixture of primarily CO_2 and CH_4 [47], [92]. The biogas can either be upgraded directly or separated in CH_4 and CO_2 streams. There are two types of upgrading, biological and catalytic. This project only concerns the catalytic type due to the readiness of the technology

[93]. Here, hydrogen reacts with the CO_2 content in the biogas and forms methane and water. The process is called methanation or hydrogenation [3]. Alternatively, the biogas can be separated in a CO_2 stream and a CH_4 stream in the CO_2 stripping unit. The methane from the biogas can be converted to syngas through steam methane reforming [94]. The CO_2 must be dissociated to produce CO for the syngas. This can be achieved through several pathways. The CO_2 can be co-electrolysed with water in a high temperature electrolysis cell (EC) to produce syngas. There are two types of high temperature ECs, molten carbonate electrolysis cells (MCECs) and solid oxide electrolysis cells (SOECs). The disadvantage associated with the use of MCECs is that a mole of CO_2 is transported across the cell for every mole of fuel produced, resulting in a mixed stream of CO_2 and O_2 being released at the anode. Here additional energy must be spent on separating the two streams so that the CO_2 can be used again for the cathode reaction [95]. Therefore, SOECs are used in the modelling. The CO_2 could in theory also be electrolysed without water resulting in just CO and no hydrogen [95]. However, to upgrade the CO to syngas and later on to fuels, hydrogen would be needed anyway and therefore this possibility is not included. Another way to dissociate the CO_2 is through the reverse water gas shift (RWGS) process, where it reacts with hydrogen to produce CO and water [28]. As illustrated in Figure 14 this CO stream from RWGS is mixed with hydrogen to obtain syngas.

There are also processes, which are primarily driven by heat that can split CO_2. In a thermolysis unit CO_2 is dissociated at very high temperatures to obtain CO and O_2. Full dissociation of CO_2 is only obtained at temperatures above 3000 °C. The process is still in the research and development phase and especially the separation of CO and O_2 in the product stream at very high temperatures has proven to be challenging. Furthermore, the high temperature poses high demands for the materials resulting in high costs [95], [96]. Due to these challenges it has been chosen to omit this process from the modelling. Lastly, the CO_2 can be dissociated through thermochemical cycles. In a series of thermally driven chemical reactions CO_2 is dissociated to produce CO and O_2. The different reaction steps produce different product gasses which eliminates the challenge of separating them after the processes. Furthermore, the temperature required is significantly lower than for thermolysis. Depending on the number of steps in the process, the temperature varies between 1000 °C and 2000 °C. However, the process still faces several challenges regarding both large losses in the multiple steps and the materials which must still endure high temperatures and rapid temperature changes [95], [96]. It has therefore been chosen to omit this process from the modelling as well. Thus, the two pathways for the dissociation of CO_2 included are co-electrolysis and the RWGS process.

The CO_2 for the co-electrolysis and RWGS can also be supplied without any biomass input by capturing the CO_2 from air. Direct air capture (DAC) of CO_2 is emerging rapidly [97], [98]. CO_2 capture can be performed from industrial process streams, from post-combustion streams in a power plant or directly from atmospheric air [99]. The capture of CO_2 from a concentrated source would offhand be the cheapest alternative [22], [100]. However, in the future renewable Danish energy system, the number of post combustion streams are expected to be limited. Furthermore, the streams that are actually available are expected to be available for a limited number of hours since they arise from peak power production, and therefore they would probably not justify the investment in a carbon capture unit. The available process streams, as e.g. from cement production, are challenging to quantify and project and therefore they are also omitted from the modelling. Thus, direct air capture (DAC) is the only source of carbon capture included, also avoiding constraints on scalability and freedom of operation for the carbon capture process. Two methods are implemented in the Sifre model; scrubbing and calcination, and temperature swing adsorption (TSA) [101]. The methods are further described in *Appendix D – Technology Data*.

Based on the different carbon sources and CO_2 dissociation techniques, several pathways for the production of syngas are obtained. Besides producing jet fuel through the FT process, the syngas can also be used to produce methanol. This is achieved in the methanol synthesis. Another way to produce methanol is through a fermentation pathway. In this pathway, straw is converted to ethanol in a fermenter. The ethanol is then hydrogenated and a chemical synthesis is performed to obtain methanol. However, the fermentation pathway is both more complex and more expensive than the alternative pathways [47], [72]. Therefore, the fermentation pathway is excluded from the modelling.

As mentioned, the possibility of using LNG and CNG for transport is included as well. Liquefaction of methane is obtained by cooling methane to -162 °C. At this temperature, methane is liquid and is approximately 1/600 of the volume of the same amount of gaseous methane at atmospheric pressure and ambient temperatures [102]. Alternatively the methane can be compressed to around 300 bars resulting in CNG with an energy to volume ratio of 35 % of that of LNG [103].

Hydrogen is an essential input in many of the processes involved in fuel production. Several processes exist to produce hydrogen using renewable inputs as opposed to natural gas reforming which is the primary source of hydrogen today [104]. Many of them are based on the dissociation of water. The dissociation can be driven by different energy inputs, e.g. heat or electricity [96]. Examples of heat driven dissociation processes are thermolysis and thermochemical cycles as for the dissociation of CO_2 [95]. However, these processes face the same problems when dissociating water, as when dissociation CO_2, and are therefore omitted from the modelling. Electrical energy can drive the dissociation via electrolysis. Overall, ECs can be classified as either low-temperature or high-temperature electrolysis. The dominating type of cell in commercial use today is alkaline electrolysis cells (AECs). AECs are low-temperature ECs with an operating temperature of 70-100 °C. Another low-temperature EC operating at a similar temperature range is proton exchange membrane (PEM) cells [96]. However, PEM cells rely on expensive materials, and the higher current densities do not seem to compensate sufficiently for the increased cost. Furthermore, the rarity of the material needed limits the ability of PEM cells to meet large scale production [95]. Therefore, AECs are assumed to be the preferred low-temperature ECs. As mentioned, there are two types of high-temperature ECs: MCECs and SOECs. They typically operate at temperatures above 600 °C [95]. For the same reason as in the case of co-electrolysis, SOECs are chosen over MCECs for the electrolysis of water. Compared to AECs, SOECs have faster reaction rates due to the high temperature resulting in a reduced need for expensive catalyst materials. This results in both the lowest capital cost and lowest operating cost. Heat management is however more complicated in SOECs which could lead to larger energy losses. In general, SOECs are less mature than AECs and require further development and testing [3], [95], [96]. Still, due to both the time horizon of the simulations performed in this report and the expectations to SOECs, they are chosen as the electrolysis unit for hydrogen production.

Another possible energy source to drive the dissociation of water is light. This is the case for photo-electrochemical (PEC) dissociation. In PECs light absorbing semiconductors are combined with electro-catalysts to split water with the energy from photons. In reality, this should correspond to a traditional EC powered by a PV panel, which would imply higher efficiencies since there are no losses associated to the transport of electricity resulting in lower prices. However, this does not seem to be the case since the requirements for the photoelectrode exclude the use of the most inexpensive PV materials [95]. PEC is therefore not included in the modelling.

As mentioned, SOECs are driven by heat and electrical energy and the operating costs are therefore highly sensitive to electricity prices. To allow for another possibility for dissociating water and produce hydrogen in case of high electricity prices the water gas shift (WGS) reaction is included. Here, the CO from syngas can be used to reduce H_2O to H_2 [96].

An overview of the fuels and technologies excluded from the modelling and the primary arguments for the delimitations is presented in Table 6.

Delimitations	Argument
Fuels	
Ethanol	Higher carbon content and thus need than methanol
Hydrogen	Infrastructure considerations and low energy density
DME	Well-to-wheel efficiency comparable to methanol
Pathways and conversion technologies	
Fermentation	Complex pathway for methanol production and more expensive
Thermolysis	Still in R&D phase and high demands for the materials resulting in high cost
Thermochemical cycles	High losses and enduring materials
Proton exchange membrane cells	Expensive and rare materials
Alkaline EC	Lower reaction rates, lower efficiency and higher cost compared to SOEC
Molten carbonate EC	Less developed than SOEC and mixed CO_2 and O_2 stream at the anode
PEC	Expensive materials
Synthesises iso-paraffins	Produces a single hydrocarbon resulting in low blending potential
Alcohol to jet	Pathway including aromatics not approved
Hydrotreated esters and fatty acids	Depends on the limited amount of vegetable oils and animal fats as feedstock
Other	
Fuel cell vehicles	To be conservative on fuel demand

Table 6 - Overview of excluded fuels and technologies.

The fuel production pathways included in the modelling is presented in Figure 14. To simplify the figure, the connections from the units producing hydrogen to the processes that consume hydrogen have been omitted. Instead hydrogen is presented as an input in the relevant processes. The production of this hydrogen is included in the modelling in the electrolysis unit or WGS unit. Furthermore, the oxygen supply for the gasification can be from either the air separation unit as indicated in the figure, or the oxygen streams from the electrolysis units can be utilised. Electricity and heat streams going both in to and out of the processes are not included in the overview. There are several synergies regarding excess heat and heat demand in the different processes which are utilised in the system as further elaborated in the following section.

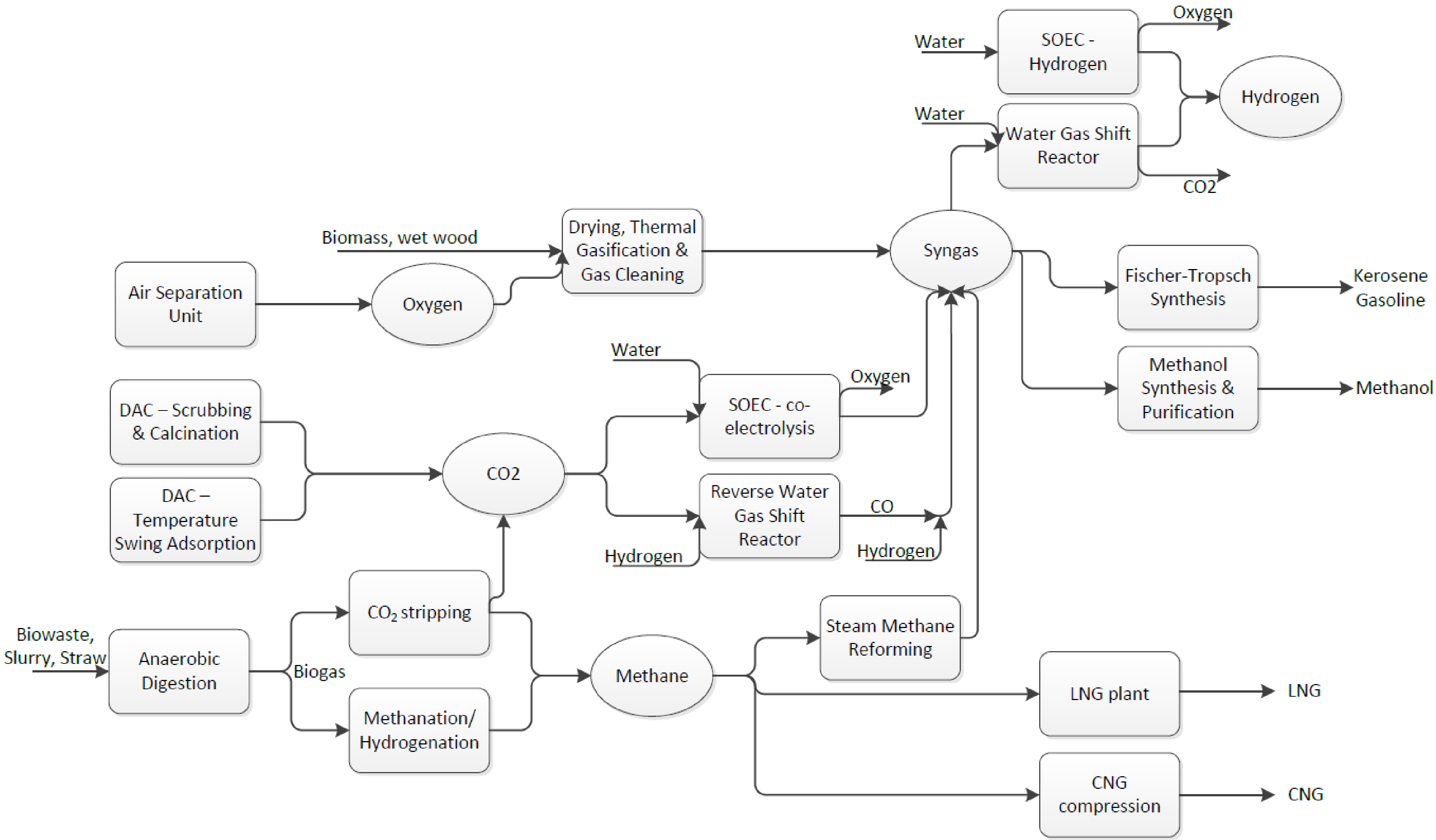


Figure 14 - Overview of the fuel production pathways included in the modelling. Electricity and heat streams are not included in the figure. A more detailed version including all streams and connections to the heat and power system can be found in Appendix G – Sifre Modelling of Fuel Production Pathways.

7.1 System Integration

To achieve the most efficient renewable energy system, it is essential to be aware of synergies between different sectors and technologies in the system. The transport sector should not be analysed and optimised from an isolated perspective but as an integrated part of the entire energy system. Therefore, this section briefly describes the synergies that can be achieved from the technologies included in the transport sector in this project. Hence, focussing on the technologies presented in *Fuel Production Pathways* and in *Appendix D – Technology Data.* Hereafter, the technologies included in the remaining sectors in the modelling of the entire energy system are presented.

There are several synergies between the fuel production pathways and the heating sector. Almost every process in the pathways has an input and/or output of heat. There are several options to use waste heat streams from one process as input for another process, e.g. the high temperature process heat (HTPH) from the gasification process can be utilised as input for the reverse water gas shift. This will require the two processes to be located at the same site. Heat recovery is prioritised internally for each technology at first. The details regarding heat streams flowing in to and out of a process can be found in *Appendix D – Technology Data*. Besides using the heat in the fuel production pathways, it can also be used to satisfy demands outside the transport sector. HTPH can e.g. be used in a steam turbine to produce district heating (DH) and power. Furthermore, the heat can be used to satisfy DH and process heat demands. The different temperature levels are further described in the section *Modelling of Fuel Production Pathways and the Surrounding Energy System*.

It is also important to include connections to agriculture. Some of the biomass resources e.g. slurry are traditionally used as fertiliser in agriculture. To maintain a proper level of nutrients in the soil, residual products from both the anaerobic digestion and gasification are assumed to be returned to the agriculture and used as fertiliser [105]. It is not within the scope of this project to address this further.

In the future renewable energy system, dominated by fluctuating renewable energy from wind turbines and PV panels, there will be a need for flexibility to balance the power system. This flexibility can be achieved from both flexibility in the consumption and from controllable production units. Both of these aspects can be integrated with the technologies in the fuel production pathways. Several of the processes in the pathways have significant electricity consumption, especially the electrolysis and DAC units. This consumption is flexible in the sense that it can operate according to the strain on the grid by shutting down if the grid is overloaded and turning on when there is an excess production, e.g. from wind. In reality this flexibility would be obtained through price signals since an oversupply of renewable power would lead to lower prices and vice versa. Furthermore, the units could act in markets for ancillary services, supplying reserve capacity, regulating power etc. The flexibility naturally involves a trade-off between reduced operating cost and investment in excess capacity if the same demand is to be satisfied. Controllable production units for balancing can be integrated by utilising some of the fuels produced in the fuel production pathways. Both biogas, methane, syngas, hydrogen and HTPH can be used for combined heat and power (CHP) production. Both types of flexibility mentioned here could be increased by including different storage options in the system and thereby being able to disconnect the operation of different units of larger time periods. The anaerobic digestion of biomass should run continuously. Thus if the output biogas (CO_2 and CH_4) should be upgraded to either methanol and/or jet fuel, the hydrogen supply should be continuous as well. If no storage is implemented then the electrolysers are forced to operate continuously. This can be avoided by implementing a storage unit either for biogas, methane, syngas or hydrogen. In general, the flexibility that can be obtained from flexible power consumption in e.g. electrolysis units can be optimised by including storage options. The storage options included are oxygen, biogas, methane, syngas, hydrogen, CO_2, HTPH, DH and batteries for electricity. The investment costs for the different storage options can be found in *Appendix F – Sifre Input Data*.

To utilise the synergies mentioned in this section and to satisfy demands for both electricity and heating in the system, additional investment options are included in addition to the technologies presented in the fuel production pathways. These include the storage options presented, PV panels, heat pumps, wind turbines, solar heating systems, steam turbines, CHP plants and boilers – fuelled by either electricity, gas or wood chips. The data used for the modelling of these units including efficiency, OPEX and CAPEX can be found *Appendix F – Sifre Input Data*. Sifre is used to optimise the investments in these units, cf. *Generic Method of Sifre and ADAPT*.

8 Modelling

This section includes a description of the generic method of the two main tools used in the project: Sifre and ADAPT. Furthermore it is described how the tools are applied in the project and how the pathways described in section *Fuel Production Pathways* are modelled. The section is concluded with an insight in the dynamics of the modelling tools to verify that the dynamics in the system are as expected.

8.1 Generic Method of Sifre and ADAPT

To simulate and optimise the Danish energy system, the tools Sifre and ADAPT are applied. The tools are developed and used by the Danish TSO, Energinet [106], [107]. In this section the tools and how they are used in the project are described.

The tool Simulation of Flexible and Renewable Energy sources (Sifre) is a market simulation tool based on the unit commitment problem with the goal of simulating the spot market behaviour of an energy system. As the name indicates, the tool focuses on the ability to simulate energy systems with an increased amount of renewable energy and increased flexibility in the system [106]. This is in line with both the current Danish energy system and especially the expected future Danish energy system. Furthermore, since the tool is developed with the Danish energy system in focus, the tool supports a high detail level in the simulation of combined heat and power including start-up cost, ramping, outages, fuel mixes etc. [106]. At Energinet, Sifre is especially used to simulate the Danish energy system both now and in the future, but the tool is not hardcoded to any specific energy system as stated:

> *"Hydro power, including pump storages, is currently not supported in Sifre, but other than that the generic design of Sifre facilitates modelling of power markets, district heating, gas, transportation, etc. either as several closed systems or in a single integrated energy system."*[106].

The objective of the optimisation in Sifre is to minimise the costs which corresponds to maximising the social welfare. However, it is possible to include both subsidies and tariffs in the modelling as well and thereby Sifre can also be used to perform simulations for more business economy minded situations. More details on the Sifre tool can be found in the box at the end of this section.

In this project, Sifre is used to simulate the operation of the Danish energy system under different input conditions. The inputs to the model include demands, demand profiles, production capacities, wind profiles, efficiencies, fuel costs, interconnector capacities etc. A demand and a market are naturally linked as e.g. the demand for electricity in Denmark and the electricity spot market. Depending on the purpose of the modelling you can either set the price at a market or you can connect both demand and supply to a market and Sifre can solve for the resulting market clearing price. This allows for different types of markets: external and internal markets. External markets are defined by a fixed price where the price in an internal market is simulated by Sifre [106]. Examples of external markets in this project are the European price boundary and the straw market which are both defined by fixed prices. It is assumed that these prices are not affected by the operation of the energy system. An example of an internal market could be the methanol market. For this market a number of suppliers (e.g. methanol synthesis) and demands (e.g. heavy road transport) are defined. Sifre simulates the system so the demand is satisfied in the cheapest way possible and will supply the user with the hourly market clearing price as an output. Thus, based on the modelling in Sifre, it can be determined how the different demands, e.g. the transport demands, are satisfied and at what price. Furthermore, the Sifre results can be used to determine the total costs of the system allowing for the direct comparison of different system configurations.

The Adaptive Planning Tool (ADAPT) is used as a part of Sifre to determine the optimal investments in different elements of the energy system. This can be both conversion units and interconnector lines [108]. Based on inputs regarding CAPEX and OPEX for the different units, ADAPT can be used to optimize the capacity of different types of units. The user can determine the number of units to be optimised by ADAPT. As Sifre, ADAPT optimises the system to satisfy the demands in the cheapest and most efficient way [107]. By integrating the investment decisions in ADAPT with the system simulation in Sifre, it is possible to account for the fact that the two elements affect each other. E.g. the investments in electrolysis capacity will influence the electricity prices which again affect the socio economic business case for the investment in electrolysis capacity.

In this project ADAPT is used to optimise the capacity of all production and storage units except for the methane storage, which is assumed to be available at the same size as today, and the capacity of onshore wind turbines which is fixed at 9 GW. This is a conservative estimate based on an analysis, which estimates the socio economic potential for onshore wind to be 12 GW [109].

Sifre – Modelling and Optimisation
Overall, there are four building blocks which can be used when building an energy system in Sifre [106]:

- **Areas** that represent a type of energy and possibly a geographical area, e.g. electricity in Denmark. Both supply and demand are connected to an area.
- **Conversion units** that convert energy from one type to another, e.g. biomass to heat in a boiler. There is no limit to the number of input fuels that can be connected to a conversion unit but a conversion unit can only produce two different outputs. A conversion unit must be implemented to connect two areas which consist of different energy types.
- **Storages** that are connected to an area of the same energy type.
- **Interconnection lines** that can be used to connect two areas which consist of the same energy type

The Sifre algorithm consists of three layers to account for the different time horizons in the planning and operation of an energy system. The first layer simulates seasonal storages and investments with a one year time horizon. This is done in hourly time steps and with complete knowledge of the entire year (deterministic). Thus, ADAPT is used in the first layer. To achieve reasonable simulation time the problem is LP-relaxed, implying that the production units can be partly turned on. The decisions of the first layer are transferred to the second layer which decides the timing for maintenance of conversion units. This is done for a full year but with low detail and accounts for the fact that, in real life, maintenance schedules are typically coordinated between production units to prevent power shortages. The decisions made in the second layer is transferred to the third layer which simulates the spot market including production, interconnector flows etc. on an hourly time resolution. Layer three simulates nine days at a time but only the results for the first seven days are used. This is done to prevent the system from shutting down at day seven. Furthermore, the time frame of nine days compared to e.g. an entire year makes the model less deterministic and thus a more realistic simulation of operation [106], [195]. The optimisation in the third layer is not LP-relaxed and does not have full insight as the first layer. Therefore, the investment decisions made in the first layer may seem counterintuitive when looking at the results of the third layer. Still, the results are deemed applicable and it is in fact considered a benefit for the accuracy of the modelling that the third layer is less deterministic to reflect reality.

8.2 Modelling of Fuel Production Pathways and the Surrounding Energy System

All the pathways described in *Fuel Production Pathways* and the additional technologies mentioned in *System Integration* are modelled in Sifre. Furthermore, ADAPT is used to optimise the investments made in each of the technologies. This section describes some general aspects of the modelling.

To perform this least cost optimisation detailed modelling of the different technologies and financial data are needed. The technologies are described in more detail, including all in- and output streams, in *Appendix D – Technology Data*. An overview of the inputs, outputs, efficiencies, OPEXs and CAPEXs derived and identified in *Appendix D – Technology Data* can be found in Table 7. The energy streams of the processes presented in the table are based on the LHV. When optimising the investments the CAPEX is amortised over the lifetime of each of the technologies with a discount rate of 4 %. Both CAPEX and OPEX are stated pr. capacity of primary output since this is the unit used in Sifre and ADAPT. In *Appendix F – Sifre Input Data* the primary output of each process is shown as the first output in the backpressure units, e.g. the primary output from the FT process is the fuel mix consisting of both gasoline and jet fuel.

Several of the processes in the pathways either produce or consume syngas. However, the processes that produce syngas result in different compositions of the syngas and the synthesis processes consuming syngas require different compositions for optimal operation. For modelling purposes the syngas is set at a fixed composition. Instead of just mixing the syngas streams with different compositions in a syngas area, this ensures accurate modelling and that the synthesis processes operate optimally. The composition of the syngas in the model is defined as the syngas composition resulting from the gasification process. This corresponds to a hydrogen to CO ratio of 1.27:1 [91]. The composition of the syngas output from the co-electrolysis is 2:1 [25]. Thus, to achieve the same syngas composition as from the thermal gasification, a separate hydrogen stream is included in the modelling as also indicated in Table 7. This hydrogen can be utilised in other processes in the system e.g. fuel synthesis. In reality you would not separate the two streams, but for the modelling it is necessary to have the same syngas composition in all processes. The hydrogen to CO ratio resulting from the steam reforming is 3:1 [110]. Thus, as for the co-electrolysis, a separate hydrogen stream is presented in Table 7 to obtain a 1.27:1 ratio in the syngas stream. Again, this hydrogen stream can be utilised in other processes in the system. This could e.g. be in the methanol synthesis which operates with highest efficiency at a hydrogen to CO ratio of 2.05:1 [111]. Therefore, a separate hydrogen stream is included in the modelling as an input to the methanol synthesis. A separate hydrogen stream is also used as an input for the FT synthesis since the modelling of this is based on a ratio of 2:1 [77]. As Sifre does not work with mass flows or temperatures of heat streams but only energy flows, three different heat areas have been defined [91].

- District heating (DH) area for heat streams at 50-110 °C
- Low temperature process heat (LTPH) area for heat streams at 110-300 °C
- High temperature process heat (HTPH) area for heat streams at 300-1000 °C

The general idea of the heat areas is to be able to distinguish between temperature intervals. The different conversion technologies have different operating temperatures and therefore different demands for temperature levels of the input heat streams, resulting in different temperatures of the recoverable heat in the output streams. This can also be seen from the different input and output streams presented in Table 7. Connection lines between the different heat areas are included in the modelling allowing for e.g. LTPH to flow to the DH area and supply a demand in this area. It is naturally not possible for the energy to flow to a higher temperature level.

Another challenge resulting from Sifre operating with energy flows is the modelling of the oxygen and CO_2 streams since these substances have a LHV of zero. To model these flows an arbitrary LHV of 1 MJ/kg is set for both oxygen and CO_2. This results in seemingly large cost for the air separation unit as seen in Table 7. However, since the unit is dimensioned according to the same arbitrary LHV it will not influence the results. The arbitrary LHV of CO_2 is also the reason why the CO_2 stripping unit has an efficiency above 100 %. A detailed version of how the pathways illustrated in Figure 14 are modelled in Sifre can be found in *Appendix G – Sifre Modelling of Fuel Production Pathways*.

The amount of fuel to be produced through the fuel production pathways varies from one electrification scenario to another. The scenarios also involve different amounts of electrified transport which are included in the modelling as well. The electrified parts of each transport mode are modelled as electric vehicles in Sifre. Based on a profile, Sifre ensures that the energy stored in the batteries in the vehicles will be sufficient to cover the transport demand in the coming hours based on a consumption profile which represents the use of the vehicles and not the charging of them. The capacities of the batteries vary depending on the demand in each scenario. Common to all the scenarios is that the battery capacity is reduced by 30 % in an attempt to represent expected real-life charging patterns, where the batteries are rarely emptied to less than that and most likely are charged every day. Also, the model operates the batteries as one large unit. It is a simplistic approach but it will increase the flexibility of the charging. The standard profile for electric vehicles is used as the profile for all transport modes. It is expected that e.g. electrified aviation and sea transport will have other demand profiles but due to lack of better alternatives, the profile for electric vehicles are used. If the electrified transport represents a combination of all-electric vessels and plug-in hybrids, the profile is also likely to be different since hybrid vehicles will be able to operate for longer periods without charging. This detail is however also omitted from the modelling and assumed to be of minor importance. Vehicle to grid (V2G) is only included for light duty road EVs and it is assumed that only 20 % of the EVs in this mode can be used for V2G. Only light duty vehicles are included since they are assumed to be plugged in for the majority of the time as opposed to the other transport modes. Only 20 % is included to give an, assumed to be, conservative estimate of the penetration of the V2G technology.

The demands for liquid fuels for transport are represented as an amount of mechanical energy to be covered in each transport mode. The demands are through units representing engine efficiencies connected to the different fuel options, allowing Sifre to optimise which fuels are used in each of the transport modes. The mechanical energy demand is included at a constant profile implying that the demand is divided equally over the year. Since this is not a true representation of the demand for liquid fuels and the liquid fuels are relatively easy to store, storage tanks are included for all the liquid fuels, allowing for a more flexible operation of the production units in the system. The only technology able to produce jet fuel for aviation is the FT synthesis which as mentioned also produces gasoline as a by-product. It is a very important system integration aspect. Hence, the by-product from the jet fuel production must be integrated in the system before considering the production of other carbonaceous fuels. E.g. for the “Moderate” electrification scenario where the amount of gasoline produced in the FT synthesis is more than the demand for other carbonaceous fuels than jet fuel, meaning that neither CNG, LNG or methanol should be produced in this scenario regardless of the costs.

	Total efficiency [Outputs/Inputs]	**Inputs [%-energy of total input]**	**Outputs [%-energy of total input]**	**CAPEX [M€/MW]**	**OPEX [€/MW/y]**
Drying, thermal gasification & gas cleaning	86.4 %	Wet wood (82.58) Electricity (3.10) Oxygen (2.14) LTPH (12.17)	Syngas (68.74) HTPH (17.69)	0.647	25,885
Anaerobic digestion	48.0 %	Slurry/Straw (96.0) DH (2.99) Electricity (1.02)	Biogas (48.0)	0.372	26,009
CO_2 stripping	101.9 %	Biogas (96.90) Electricity (3.10)	Methane (95.93) LTPH (3.10) CO_2 (2.84)	0.246	6,711
Methanation	94.0 %	Biogas (58.13) Hydrogen (38.02) Electricity (3.85)	Methane (89.56) LTPH (4.48)	0.120	2,400
Steam methane reforming	95.0 %	Methane (75.53) HTPH (24.47)	Syngas (55.6) Hydrogen (39.4)	0.283	5,654
DAC - scrubbing & calcination	33.7 %	Electricity (24.21) HTPH (75.79)	CO_2 (9.96) LTPH (23.76)	0.826	16,527
DAC - temperature swing adsorption	38.9 %	Electricity (12.5) DH (61.25) LTPH (26.25)	CO_2 (13.89) DH (25.0)	0.638	15,944
SOEC - hydrogen	87.1 %	Electricity (89.55) LTPH (10.45)	Hydrogen (81.7) Oxygen (5.4)	0.591	14,754
SOEC - co-electrolysis	83.2 %	Electricity (85.54) LTPH (9.98) CO_2 (4.48)	Syngas (60.07) Hydrogen (17.96) Oxygen (5.15)	0.565	14,093
Methanol synthesis & purification	97.6 %	Syngas (67.03) Hydrogen (30.18) Electricity (2.79)	Methanol (76.67) HTPH (1.90) LTPH (11.76) DH (7.29)	0.177	5,317
Water gas shift reactor	93.4 %	Syngas (82.37) HTPH (17.63)	Hydrogen (60.38) LTPH (21.99) CO_2 (11.04)	0.073	3,518
Reverse water gas shift reactor	78.95 %	Hydrogen (67.37) HTPH (20.35) CO_2 (12.28)	CO (78.95)	0.064	3,086
Fischer-Tropsch synthesis & hydrocracking	94.9 %	Syngas (67.58) Hydrogen (30.42) Electricity (2.0)	Jet Fuel (49.97) Gasoline (32.07) LTPH (12.96)	0.505	9,857
LNG plant	90 %	Methane (95.69) Electricity (4.31)	LNG (90)	0.265	5,306
CNG compression	97.5 %	Methane (97.5) Electricity (2.5)	CNG (97.5)	0.152	3,046
Air separation unit	65.4 %	Electricity (100)	Oxygen (65.4)	2.147	64,447

Table 7 – Technology data for the technologies included in the modelling of the fuel production pathways. Detailed descriptions and references can be found in Appendix D – Technology Data. The efficiencies represent the efficiencies implemented in the Sifre model and thus the arbitrary LHV of oxygen and CO_2 are included.

Besides the modelling of the fuel production pathways, the Sifre model also includes the modelling of the surrounding energy system. As mentioned the data regarding other technologies, including electricity and heat production units can be found in *Appendix F – Sifre Input Data*. The surrounding energy system also includes the electricity and heat demands. The demands are described in *Demands & Constraints for the Energy System* and are modelled using standard profiles from Sifre. The profiles are used to distribute the aggregated yearly demand over the course of the year, and vary depending on the type of demand. E.g. the profile for process heat is different from the profile for district heating. In the future energy system it is expected that part of the classic electricity consumption will be able to act flexible according to the electricity price. The flexibility of the classic consumption implemented in the model is limited to a small share of the industry corresponding to 2.5 % of the total classic consumption. Other examples of profiles are wind and solar profiles, which are essential for the production from wind turbines and PV panels. The profiles used in Sifre are from the same year as the ones used in the BID simulations of the price boundary. This is essential to account for potential concurrency in weather conditions in Denmark and neighbouring countries.

Sifre allows for the inclusion of outages and maintenance of all the production units in the system, both the ones included in the fuel pathways and in the surrounding energy system. When modelling e.g. the current Danish energy system this is an essential feature. In this project each type of unit in the system is represented by one large aggregated unit, where in reality it is expected that there will be several smaller units in the system. If outages and maintenance were included in the modelling the entire capacity of a technology would be unavailable for a duration which is assumed to be unrealistic. It is deemed as a smaller flaw to exclude maintenance than if the entire capacity of a technology is unavailable for two weeks due to maintenance. Therefore the system is modelled without maintenance and outages.

As presented in *Sustainable Biomass Potential*, the amount of sustainable biomass available for the energy system is a constraint for the model. The inflow of a fuel to the system in Sifre can only be defined as an energy flow pr. hour. Therefore, the available biomass is converted to an equivalent constant hourly flow. To allow for some degree of flexibility in the use of the biomass resources, buffer tanks are included allowing the system to store the biomass resources for a limited duration of time. It is assumed that straw, slurry and organic waste can be stored for up to a week and wood chips for up to a month. Thus, the capacity of the buffer tanks for each of the biomass resources are set to the maximum possible inflow during the allowed storage time.

The modelling in Sifre attempts to exactly meet all demands in all hours. This implies that the model attempts to eliminate all over- and under production. An economic penalty of 500 and 3000 EUR/MWh is set for over- and under production respectively. It is equal to the current price caps of the electricity spot market operated by Nord Pool Spot. The approach of the model is a consequence of the tool being based on the unit-commitment problem. However, in this system there are some by-products in processes which are not necessarily problematic to have over production for. To eliminate this error, sinks are included in the modelling. A sink is a fictive market where the excess production can be sold at price of zero and where it is not possible to import from. This is included for oxygen which is a by-product in the electrolysis units. The oxygen is used as an input for the thermal gasification and also has a storage option, but if this is not optimal the model can sell it to the fictive market at zero profit. The same is the case for gasoline which is a product of the FT process. If more gasoline is produced than needed, due to the demand for jet fuel, the excess gasoline can be exported to the sink. In reality you would naturally be able to get some profit for the gasoline. However, to avoid an external price of gasoline from influencing the optimisation in the model, the price is set to zero. Since many of the processes involve an excess heat production, a heat sink is included as well in case the demands cannot utilise the entire heat production. Lastly a CO_2 sink is included, if it is optimal to strip the CO_2 from the biogas and/or to produce hydrogen from syngas in the water gas shift unit without utilising the CO_2-stream.

8.3 Model Dynamics

Having incorporated the necessary model technicalities described above and having all the input data set, the model is run to obtain results for the 15 simulations. The five electrification scenarios, “Full”, “Ambitious”, “Moderate”, “Slight” and “Conservative”, are all run for each of the three European framework conditions, ST, DG and GCA. The results presented in the report are based on yearly sums and average costs. However, to give a brief insight in the dynamical operation and dependencies of the model some random samples on hourly resolution are shown for some of the processes. This is done to validate that units operate the way it is expected and respond to changes in e.g. the electricity price.

Figure 15 shows the electricity price, consumption and production for a randomly chosen week with large variations on an hourly basis based on results from DG “Slight”. The difference between the consumption and production is exactly equal to the sum of trade on the interconnectors to neighbouring countries. Hence, Denmark is exporting approximately 7 to 12 GW from hour 25 to 40 in the chosen week, and in the following 5 hours there is almost no international trading of electricity. As evident from the figure, the electricity price and the production from renewables are inversely proportional. When the production from renewables is low the electricity price is high and vice versa. The residual electricity producing units are only gas turbines in this scenario. It is hardly visible in the figure. Not to forget, 20 % of the EVs in the light duty vehicle class have the possibility to give back to the grid, V2G. It is included in the net consumption. Hence, the flexibility is provided by consumption units and interconnection lines. The latter will potentially give too much flexibility compared to reality since the price of the neighbouring price area is a fixed quantity in the model. The same climate year is used for the simulation in BID to obtain the prices in the neighbouring areas as for the simulations in Sifre meaning that the production from renewables of the price areas are closely correlated. Therefore, when the price is low in Denmark it is most likely low in the surrounding areas as well and vice versa. There will probably never be prices close to the price caps due to the large capacities of the interconnector lines and the fixed trading price. Nevertheless, it is evident from Figure 15 that the price varies according to the production from renewables and that the consumption responds to price variations. The large fluctuations in consumption is due to the charging patterns for EVs and production patterns for HPs, electrolysers and other electricity consuming production units. Thus, the flexibility in consumption is mainly obtained from the optimised operation of the large electricity consuming production units. The flexibility of the classic consumption is as mentioned in *Modelling of Fuel Production Pathways and the Surrounding Energy System* limited to a small share of the industry corresponding to 2.5 % of the total classic consumption.

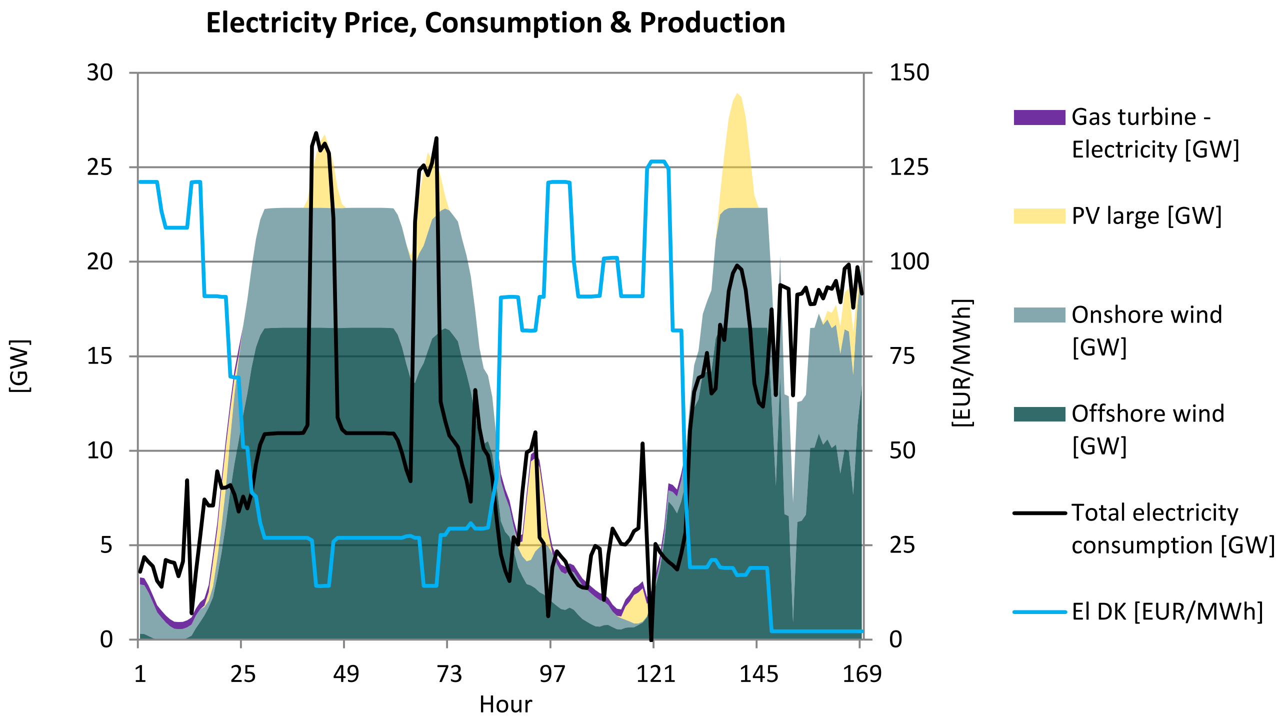


Figure 15 – Electricity price (on the right y-axis), consumption and production (on the left y-axis) on an hourly resolution for a randomly chosen week (168 hours). The results are from the simulation "DG Slight". The electricity consumption is the sum of batteries, EVs, individual and large HPs, fuel production units, classical and the small amount of flexible consumption. The difference between production and consumption is exactly the sum of what is traded on the interconnector lines to neighbouring countries.

Figure 16 shows the electricity price for the same week as Figure 15 along with the total production of jet fuel from the FT process and the hydrogen production from the hydrogen producing SOEC electrolysers. The storage levels of jet fuel and hydrogen in % are also included. The syngas and hydrogen production from co-electrolysis is not included. As expected the production of hydrogen responds to the fluctuations in the electricity price. When the price is below 30 EUR/MWh the hydrogen production from electrolysers is at maximum for both the regular and the co-electrolysers, though the latter is not shown in the figure. The hydrogen storage is an investment opportunity given to the model and is therefore not larger than what is economically optimal. The size of the jet fuel storage is fixed. It is able to contain one month's worth of demand for jet fuel. The hydrogen storage cannot contain one month's worth of the total hydrogen demand, as evident from the figure. When the electrolysers ramp down due to high electricity prices, the level of the hydrogen storage quickly decreases.

The jet fuel production also responds to the electricity price. The electricity input to the FT process is only 2 % of the energy, as shown in Table 7. Hydrogen and syngas covers the remaining 98 % of the input. The hydrogen and syngas are produced from the electrolyser units, the thermal gasification and steam methane reforming (SMR). The available woody biomass for the thermal gasification is not sufficient to cover the entire syngas demand. When the electricity price is high methane can be utilised in the gas turbines as well as in the SMR. Hence, the willingness-to-pay (WTP) for methane increases. The result is that the price of syngas and hydrogen increases in periods with high electricity prices and therefore the production of jet fuel decreases. Due to the relatively large storages for hydrogen and jet fuel, large variations are seen for the production units. It has been discussed in the project whether the FT process should be able to ramp this quickly up and down. Since the project found no valid sources on the matter, the ramping of the FT process is not restricted. The storages and the large production unit capacities reduce the peaks and valleys for the price of hydrogen, syngas, jet fuel etc.

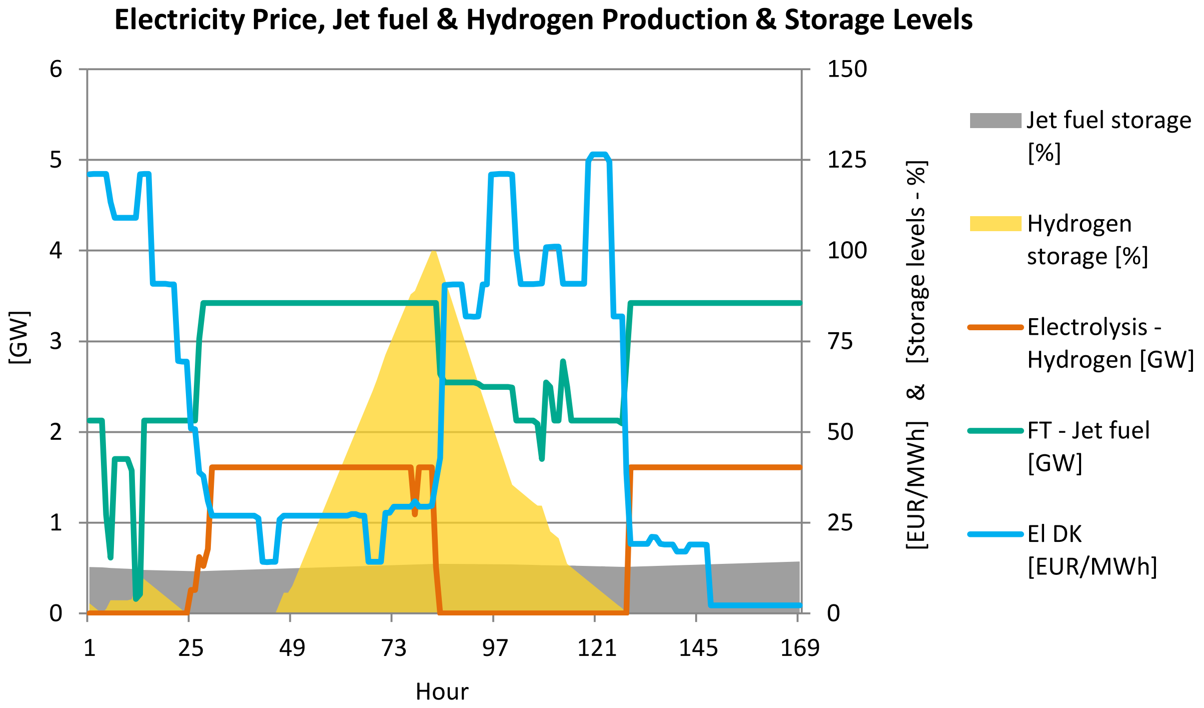


Figure 16 – Electricity price (on the right y-axis), jet fuel production from the FT process and hydrogen production from SOEC electrolysers (on the left y-axis) on an hourly resolution for the same randomly chosen week as in Figure 15 (168 hours). Furthermore the storage levels in % are included for jet fuel and hydrogen (on the right y-axis). The results are from the simulation DG "Slight".

Having validated and shown few of the dependencies of the model, the project will in the following sections compare the yearly balances, invested capacities and socio economics of the simulations.

9 Simulation Results

The results from the 15 simulations of the model are first analysed on a general level. Again, the 15 simulations are the combination of the five electrification scenarios, "Full", "Ambitious", "Moderate", "Slight" and "Conservative" and the three European framework conditions, ST, DG and GCA. The general analysis will only touch the surface of the massive amount of information from every simulation. However, when the general trends have been shown the more specific information will be discussed for the three European framework conditions for "Moderate" and for the five electrification scenarios for DG. Lastly the production costs of the fuels for transportation are presented and discussed across the electrification scenarios.

9.1 Key Results for all Scenarios

The general results shown below are consumed fuels for transportation, utilised carbon resources and socio economics for the 15 simulations shown on Figure 17, Figure 18 and Figure 19 respectively. The consumed fuels for transportation are very close to the approximated fuel demands from Figure 13. The total amount of fuel increases as the share of electrification of the transportation decreases because of the higher efficiency of electric engines compared to ICEs. For the "Full", "Ambitious" and "Moderate" scenarios the spread of the consumed fuels is determined beforehand. "Full" is obvious as it only demands electricity for transportation. The latter two are because of over production of gasoline. Gasoline is a by-product from the production of jet fuel in the FT process which is the only path to jet fuel to cover the demand for jet fuel. For one output unit of jet fuel produced from the FT process, 0.64 units of gasoline are also produced. As seen on Figure 17 the demand for other carbonaceous fuels than jet fuel is not above 64 % of the jet fuel demand for "Ambitious" and "Moderate". Hence, only gasoline, jet fuel and electricity are utilised as fuels for transportation in these two scenarios. The consumed fuels for the two scenarios are equal across the European framework conditions since the demands are equal. The only difference between the consumed fuels across the European framework conditions is for "Conservative" and "Slight". The total amount of fuel is almost equal but there is a small shift from CNG towards methanol in GCA compared to ST. DG is right in between the two. An explanation can be that the larger variations and higher peaks for the electricity price in GCA, seen in Figure 3*,* cause the methane to be utilised for balancing instead of as input to CNG. The possibility to import cheaper electricity in GCA can also reduce the OPEX for the electrolysis units that produce syngas and hydrogen which are inputs to the methanol synthesis.

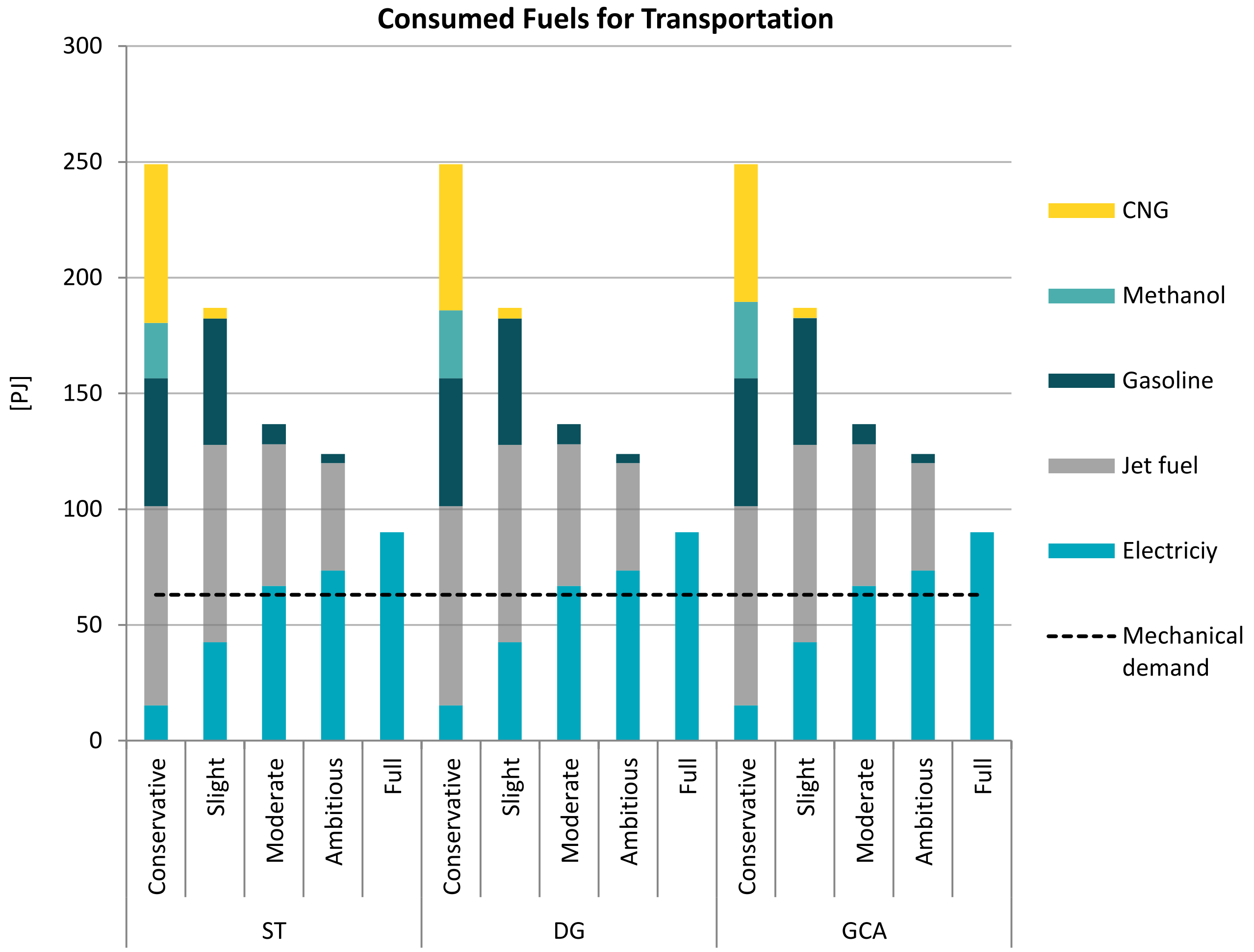


Figure 17 – Total consumed transport fuels divided by fuel for all simulations. It is comparable to the approximated fuel demands for the different electrification scenarios in Figure 13, though with more detail on "Other fuels".

Figure 18 shows the total utilised carbon resources for all simulations. It is proportional to the consumed amount of carbonaceous fuel. Besides, the carbon is used to produce electricity and heat in CHP plants and boilers which explains the non-zero value in the three "Full" scenarios. The carbon can be harvested by four units, DAC, anaerobic digestion, thermal gasification and as a direct fuel for CHP and boilers. However, the biomass resources are not used as direct fuel for CHP and boilers in any of the simulations. If the model chooses not to invest in CO_2 storage or if the storage is full and there is no demand for CO_2 in the system, the CO_2 from CO_2 stripping of biogas can be exported to a price of zero to avoid over production. This option is utilised in the three "Full" scenarios and a little in the more electrified scenarios where carbon is not a scarce resource. The potential domestic biomass resource, equal to 198 PJ, is shown measured in weight of carbon in the far left column of Figure 18. Hence, when the total utilised carbon is near or above the domestic potential the export goes towards zero.

The same argument for the shift from CNG to methanol on Figure 17 can explain the amount of utilised carbon resources in the "Full" scenarios. The value of methane or syngas to balance the electricity grid is higher in the GCA and DG scenarios compared to ST and therefore the produced amount of biogas from anaerobic digestion increases. In general the anaerobic digestion is chosen over the thermal gasification. It has lower CAPEX and since the wet biomass is assumed cheaper than solid the OPEX is lower as well. The amount of carbon from the DAC technology is also affected by the electricity price. The inputs to the DAC TSA, which is the only DAC technology invested in, are electricity, DH and a small fraction of LTPH. Most of the DH is produced from HPs (above 90 % for all simulations) where electricity is the only input. Hence, if the DAC technology is to be feasible a significant amount of hours with low electricity price and/or large peaks in the electricity price with demand for controllable peak load capacity fuelled by e.g. gas are needed. If both are present as shown later in Figure 24 for GCA and a little less for DG, DAC becomes competitive with carbon from thermal gasification. It is also evident from Figure 18.

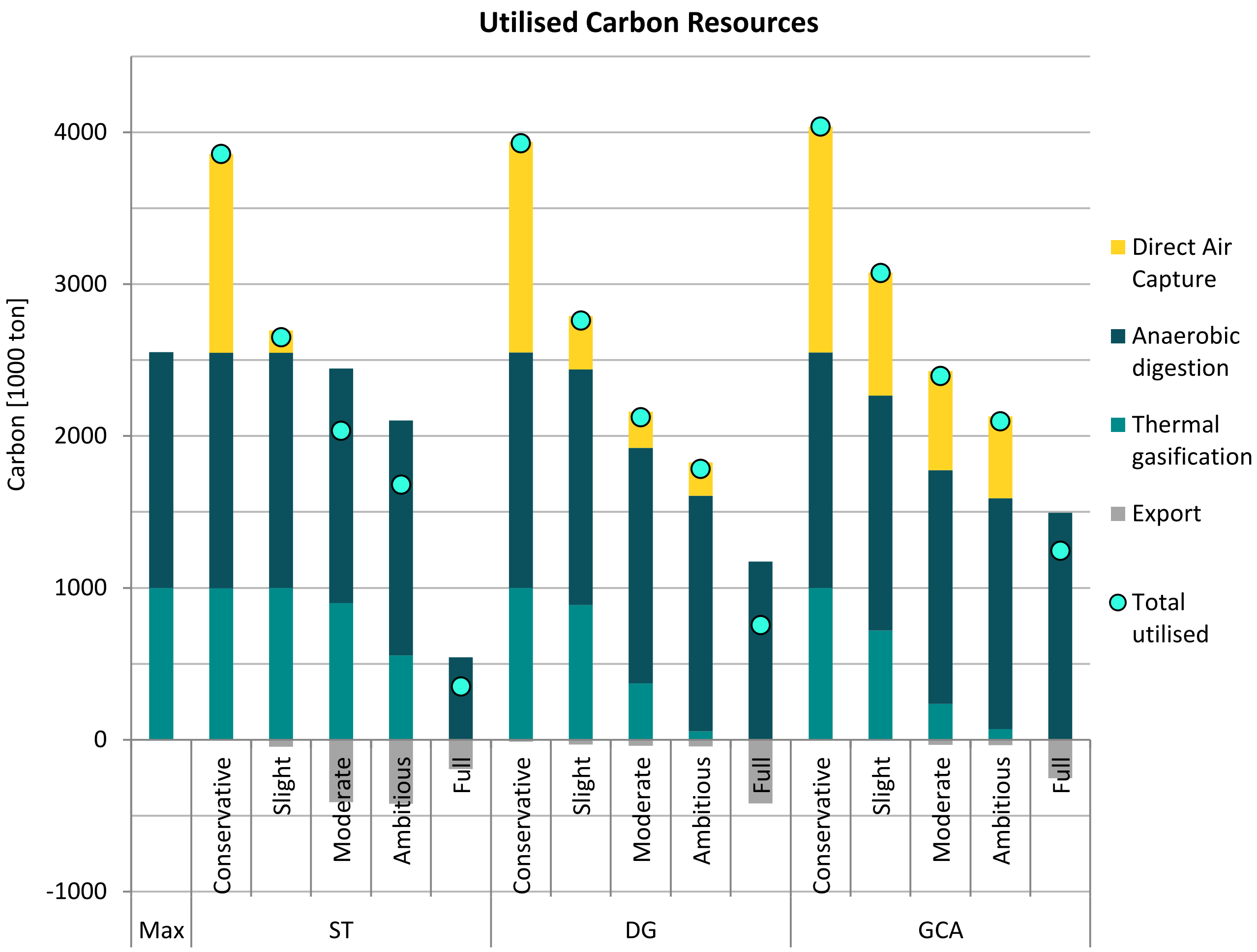


Figure 18 – Total utilised carbon resources divided by harvesting technology for all simulations compared to the domestic potential biomass resource named "Max". The measurement unit is 1000 ton of carbon molecules and compares between the different available sources.

Figure 19 shows the socio economics, namely the total yearly costs of all production units for the 15 simulations. The production units include all technologies used for production of carbonaceous fuels for transportation, storages, CHP plants, boilers, turbines, renewables and HPs. Basically all the units included in the optimisation module, ADAPT, of the model and onshore wind turbines. It is important to stress that the infrastructure costs for the grids, gas, DH and electricity grid, is not included. The costs for fuel infrastructure, charging facilities and the vehicles themselves, are not included either. It is assumed that the costs are comparable across all the simulations. This assumption is among other based on the peak power capacity of the electricity grid being almost equal for all the 15 simulations. The electrolysis units compared to the direct charging of EVs does not affect the peak consumption. The electrolysis pathway has larger losses than EVs but more of the energy is provided from biomass in the non-electric fuel pathways. By implementing hydrogen storage the electrolysers can operate more flexible than EVs regarding electricity consumption and therefore the peak consumption is quite equal even though the total electricity consumption for satisfying the transportation demand increases with the decrease in electrification, as seen later in Figure 29. As seen in Figure 15 the peak consumption is around 30 GW, hence an expansion of the current grid is assumed to be necessary when comparing with the present peak levels of approximately 7 GW.

The total costs illustrated in Figure 19 are calculated as the sum of CAPEX, OPEX and fixed O&M subtracted the bottleneck revenues and the revenue of all the production units in the system. OPEX represents both the OPEX of all production units in the system and the costs for the consumers in the system, including electricity, heat and transport. The revenues are calculated based on the prices determined in Sifre, e.g. the revenue for the thermal gasification unit is based on the price of syngas. It is necessary to subtract the revenue to avoid costs accumulating through the system and thereby including them multiple times. When including all revenues and calculating the OPEX from the inputs to a process, the reallocation of resources is not included as a socio economic cost, hence the method just presented gives the actual socio economic cost of the system without externalities. Externalities are not included since the energy system is neutral regarding CO_2 emissions from production of energy and fuel. However, emission of CO_2 is not the only externality traditionally included and the production of energy and fuel is not the only part of the life cycle that emits particles. The negative externality of e.g. local air pollution and noise from ICEs compared to EVs, which differs across the electrification scenarios, is not included either. Basically, the socio economic cost calculated for the system is for an unregulated renewable market that reveals the winners if no political regulation is performed. It will be further elaborated in the *Discussion*.

From Figure 19 it is obvious that the degree of electrification of the transport sector has a large impact on the cost of the system. It follows the same pattern for the five electrification scenarios for the three European framework conditions. Hence, the total cost of the system is proportional to the total fuel demand and the utilised carbon resources. From the figure it is also evident that the GCA simulations have lower investment costs than both ST and DG, where DG has the highest costs. It is again because of the lower electricity prices in the neighbouring price areas in GCA. In GCA the investment in renewables is lower as a result of the possibility of importing electricity at low prices for a large share of the year. A more thorough discussion of the invested capacities across the electrification scenarios and the European framework conditions can be found in the following sections *Moderate Electrification Scenario* and *DG Electrification Scenarios.* The total yearly cost of the systems presented here is 2-6,000 m. EUR. This corresponds to 1-2 % of the Danish BNP. Compared to a similar study, "*Energiscenarier frem mod 2020, 2035 og 2050"* by the DEA, which finds total system costs of 5-7 % of BNP, the costs in this project may seem quite low [39]. However, when comparing the two it is important to be aware of the cost included in the results. The costs presented in Figure 19 are only the ones included in the modelling and thus influencing the optimisation. This implies that costs for vehicles, fuelling infrastructure, interconnectors and infrastructure for electricity, gas and heat are not included. Since the main purpose is to compare costs between the scenarios, the costs that are assumed comparable across the scenarios are not included. In the DEA study on the other hand, all costs are included to be able to compare with a fossil reference scenario. Furthermore, DEA includes costs for energy savings where this project takes the reduced energy demands as a given. The costs for energy savings, vehicles, grids and interconnectors, assumed to be identical to all scenarios in the DEA analysis, are found to equal 9,000 m. EUR. Subtracting these costs from the total costs in DEA brings the yearly costs to around 10,000 m. EUR. It has not been possible to quantify other costs included in the DEA such as heating and gas grids. With this in mind it is assumed that the total system costs in this project and in the study from DEA are of the same magnitude. The comparison to the DEA is included as a rough validation of the results in this project. In the remainder of the project, the socio economic costs are only compared between the different scenarios in this project.

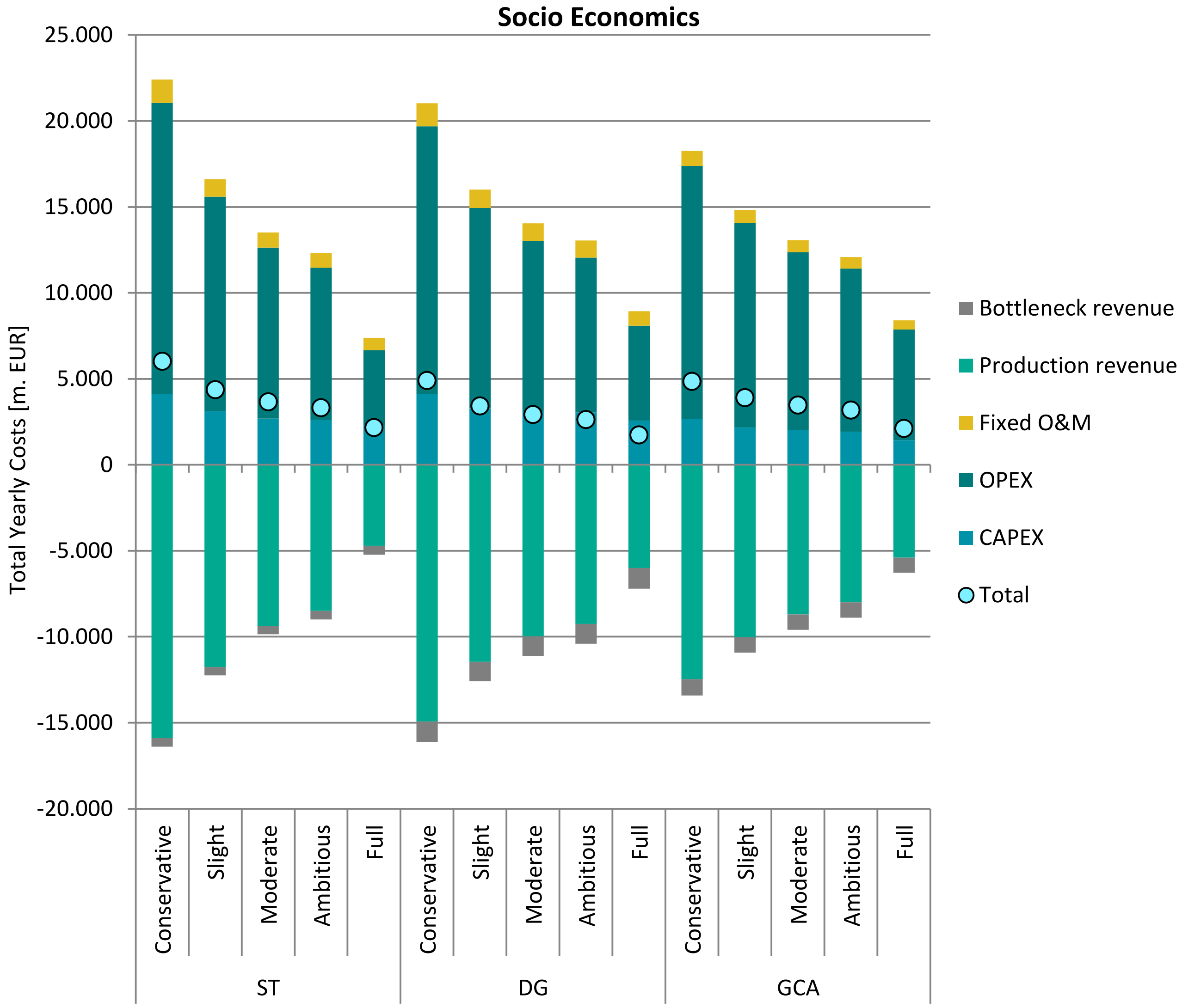


Figure 19 – Socio economics found as the total yearly cost of the energy system for all simulations divided into fixed O&M, OPEX, CAPEX, bottleneck revenue and production revenue. The production revenue is included to avoid the reallocation of resources between production units as a socio economic cost. Furthermore, externalities are not included.

9.2 Moderate Electrification Scenario

The ”Moderate” electrification scenario is assumed to be one of the more likely scenarios for the development within electrified transport since it is based on assumptions not far from what is currently possible or expected to be possible within the nearer future. Both the “Conservative” and especially the “Full” scenarios are, as stated previously, included as extreme cases to analyse the effect of such extreme scenarios. The “Ambitious” and “Slight” scenarios are more likely scenarios but still deemed less likely than the “Moderate” scenario. In “Ambitious” 100 % of heavy road transport and flight distances up till 2000 km are electrified, which is assumed to be very ambitious. In “Slight” on the other hand, only trucks travelling up to 250 km and light vehicles up to 150 km are electrified. This is less than what is currently possible or will be within the coming years with Tesla semi-truck promising distances up to 800 km. Therefore, ”Moderate” is analysed in more detail in this section. This is done both to analyse which technologies are used to satisfy the transport demand and to investigate the effect of the different European framework conditions on the results. The effects are analysed both regarding invested capacities, electricity balance, electricity prices and fuel production prices.

In Figure 17 it is illustrated, that the same fuels are used to satisfy the transport demand in all three European scenarios for the moderate electrification scenario. The share covered by electricity is fixed as an external parameter in all electrification scenarios and is therefore naturally the same. The demand for jet fuel is also the same. Thus, the only part of the transport demand where the model is able to optimise how the demand is satisfied is the 7 % of heavy road transport and 80 % of sea transport that is not electrified in “Moderate”. However, since 0.64 PJ of gasoline is produced for every PJ of jet fuel produced in the FT process, the gasoline by-product is sufficient to satisfy the remaining demands in this scenario and thus, there is no need for other carbonaceous fuels. In fact, a surplus of 30 PJ of gasoline is produced. In the modelling the surplus gasoline is exported at a price of zero to not influence the optimisation. In reality, it would be possible to sell this gasoline and obtain a profit. Since the fuels are the same, the difference between the different scenarios lies in the technologies used to produce the syngas for the FT process.

The capacities of all production units except for renewables resulting from the optimisation of the investments can be seen in Figure 20. As mentioned, the capacities are based on the primary output of the units. It is evident that the optimisation results in an almost identical capacity of the anaerobic digester of approximately 2200 MW. This corresponds to the results presented in Figure 18 where the total carbon resource used in each simulation is illustrated. It is evident that the entire biogas resource is used in all “Moderate” simulations, implying that this resource is the cheapest independent of the European framework conditions. The entire biogas production is stripped in the CO_2 stripping unit, and thus none of it is upgraded directly with hydrogen. The other sources of carbon: thermal gasification and direct air capture (DAC), are utilised at different extends in the three scenarios. In ST, thermal gasification is the only one of the two utilised where DAC is utilised to some extent in DG and the most in GCA. The balance between the investment in thermal gasification and DAC is primarily governed by the electricity prices. The GCA European framework conditions provide both the lowest average price and the largest standard deviation for the neighbouring price areas resulting in many hours with low prices which are beneficial for the investment in DAC. In DG, the relatively high prices in Europe result in more investments in RE capacity which also leads to many hours with low prices in Denmark.

The CO_2 from both the CO_2 stripping and DAC can be converted to syngas either through co-electrolysis or by converting it to CO in the reverse water gas shift (RWGS) unit and combining it with hydrogen. Lastly, the model includes the possibility of exporting the excess CO_2 to a market with a zero price, as for the surplus gasoline. If this was not possible the model would attempt to minimise the overproduction of CO_2, which is not intended. In reality it is expected that you would be able to obtain a profit from selling the excess CO_2. However, to avoid this possible and uncertain profit from influencing the optimisation the price is set to zero. In ST, almost 75 % of the CO_2 stripped from the biogas is exported. Thus, in Figure 18 the total carbon resource harvested and utilised deviates. This distinction is made since the resources to produce the biogas are consumed and thus not available for other purposes, but the entire resource is not utilised in the system. In DG, 20 % of the CO_2 that is not exported is transformed with hydrogen to form CO in the RWGS unit where almost the entire CO_2 resource is dissociated in the co-electrolysis unit in GCA. This is related to the differences in the type of electrolysis units invested in. The largest capacity of co-electrolysis is in GCA where largest capacity of hydrogen electrolysis is in DG. The large capacity of co-electrolysis in GCA is driven by the larger CO_2 resource from DAC. In DG, the larger capacity of thermal gasification requires a larger capacity of hydrogen electrolysis to adjust the syngas composition for the FT process. Furthermore, DG results in the highest average electricity price which increases the incentive to invest in more hydrogen capacity and store the excess hydrogen production for hours with high electricity prices. This corresponds well with the fact that the largest investment in hydrogen storage capacity is found in DG. This increased hydrogen electrolysis and storage capacities provide the possibility of utilising the hydrogen from the storage in the RWGS unit to produce syngas from CO_2 in hours with high electricity prices.

The last way to produce syngas is through steam methane reforming (SMR). Along with thermal gasification this is by far the largest source of syngas in ST. Even though the largest investment is performed in DG more syngas is produced in ST. In ST the prices are relatively stable at a price where it is cheaper to produce syngas through SMR than through co-electrolysis or RWGS. SMR results in an excess hydrogen production which can be used to adjust the syngas composition from the thermal gasification to match the requirements of the FT process, implying a reduced need for hydrogen electrolysis. The relatively high average electricity price and large standard deviation in DG result in both a large hydrogen electrolysis capacity and large SMR capacity.

A significant element in a 100 % renewable energy system is the renewable capacity. The renewables included in this project are onshore and offshore wind, solar heating, small and large PV units. In Figure 21 the capacities installed in each of the “Moderate” scenarios are shown. Onshore wind is not included in the figure as the capacity is limited to a maximum of 9 GW which is utilised in all scenarios. Small PV units and solar heating are not included in the figure since no investments are made in these units. The capacity invested in is strongly related to the prices in the neighbouring price areas. To compensate for the higher prices in DG and ST compared to GCA more renewable capacity is invested in to produce cheaper electricity.

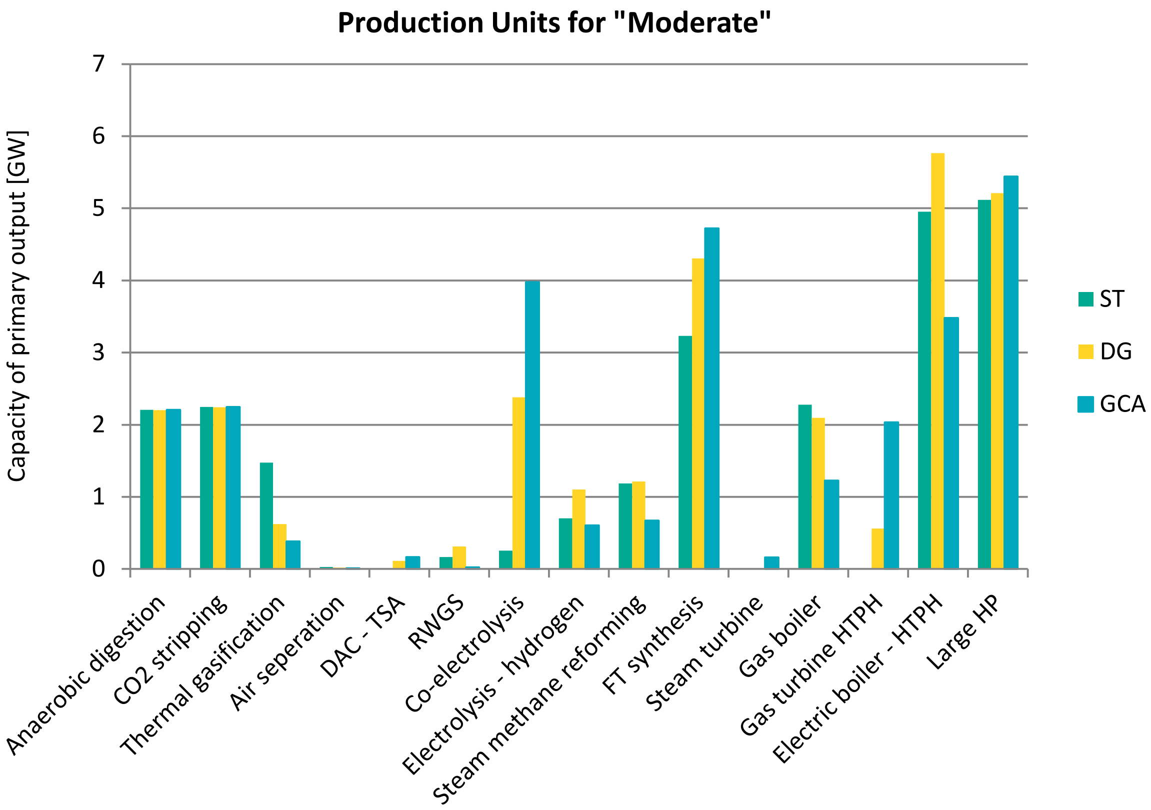


Figure 20 - Invested production unit capacities in "Moderate". The capacity is for the primary output of the production units.

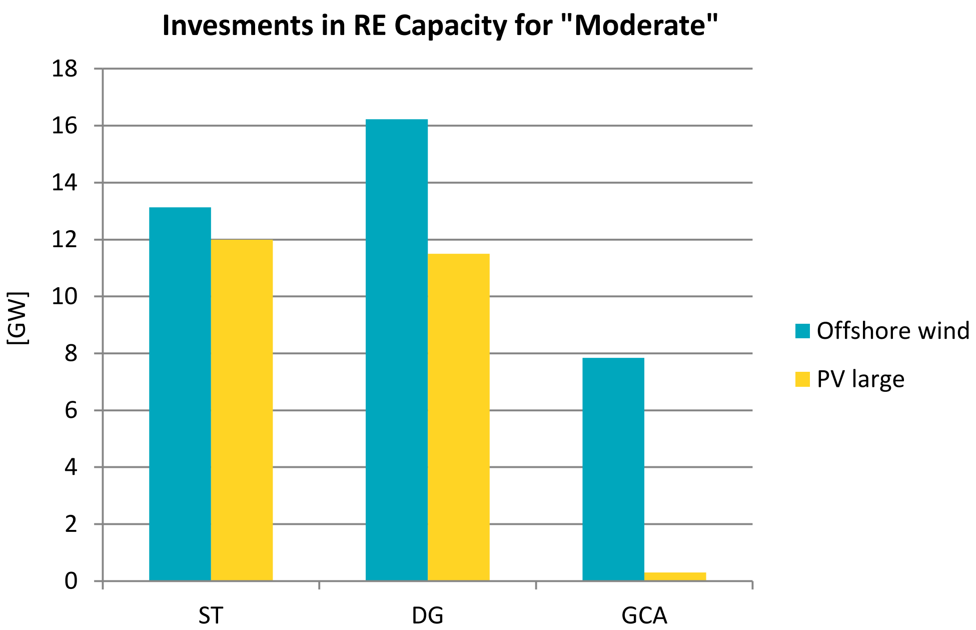


Figure 21 - Total invested renewable production capacity in GW for "Moderate". Onshore wind turbines are not included as the installed capacity is fixed to 9 GW for all simulations. Small PV units and solar heating are not included because the invested capacity is zero for the three scenarios.

Besides the excess heat production from the fuel production pathways, the process heat and district heating demands are mainly balanced by large heat pumps and boilers operating primarily on electricity and methane. No investments are made in neither boilers nor CHP units fuelled by wood chips in any of the scenarios. As seen in Figure 20 the heat pump capacity is almost equal in all scenarios, around 5000 MW. The only production unit in the fuel pathways producing HTPH is the thermal gasification. This unit has the largest capacity in ST which however also has the largest use of SMR that uses HTPH. Thus, the need for heat production from either boilers or CHP units is comparable in the simulations. In ST all the process heat demand is covered by electric and gas boilers and thus no investments are made in CHP units. In DG there is around 500 MW CHP gas turbine which produces HTPH and electricity primarily from methane. GCA has the most peak power capacity in the system – around 2000 MW gas turbine and 150 MW steam turbine. It is a result of the electricity prices in Europe where GCA is the scenario with the highest price spikes which reduces the incentive to import electricity in periods with low production from renewables. Furthermore, it increases the incentive to produce power for export during the price spikes. ST has the lowest price spikes and thus it is more profitable for the system to be balanced through interconnectors than through national peak production capacity. This can be seen in Figure 22 where the electricity balances for the three simulations are illustrated. The left columns illustrate the electricity production including import and the right columns illustrate the consumption including export. In ST, the grid is balanced entirely through the interconnectors. Denmark is however still a net exporter of electricity due to the high production capacity of renewables. The relatively stable prices in ST imply that there are not high enough price spikes in Europe to justify the investment in national peak capacity. Of course, it makes the system heavily reliant on available capacity for controllable production units in the neighbouring areas and on the interconnectors. Nevertheless, it results in the CO_2 stripped from the biogas being exported instead of being utilised in the system. The DG scenario has the highest electricity production resulting from the largest renewable production capacity. The high prices in Europe in this simulation make it possible to obtain a profit from exporting the excess electricity, and thus Denmark is a net exporter in this simulation as well. It also has sufficient high price spikes to justify the investment in small gas turbines. GCA is the only simulation where Denmark is a net importer. This is due to the low prices in Europe and low renewable production capacity in the Danish system. This simulation does however have the largest price spikes and thus the largest investment in national peak power capacity for balancing in critical hours where it is too expensive to balance the system through interconnectors. Furthermore, a profit is obtained by exporting this peak power to the neighbouring areas during the price spikes.

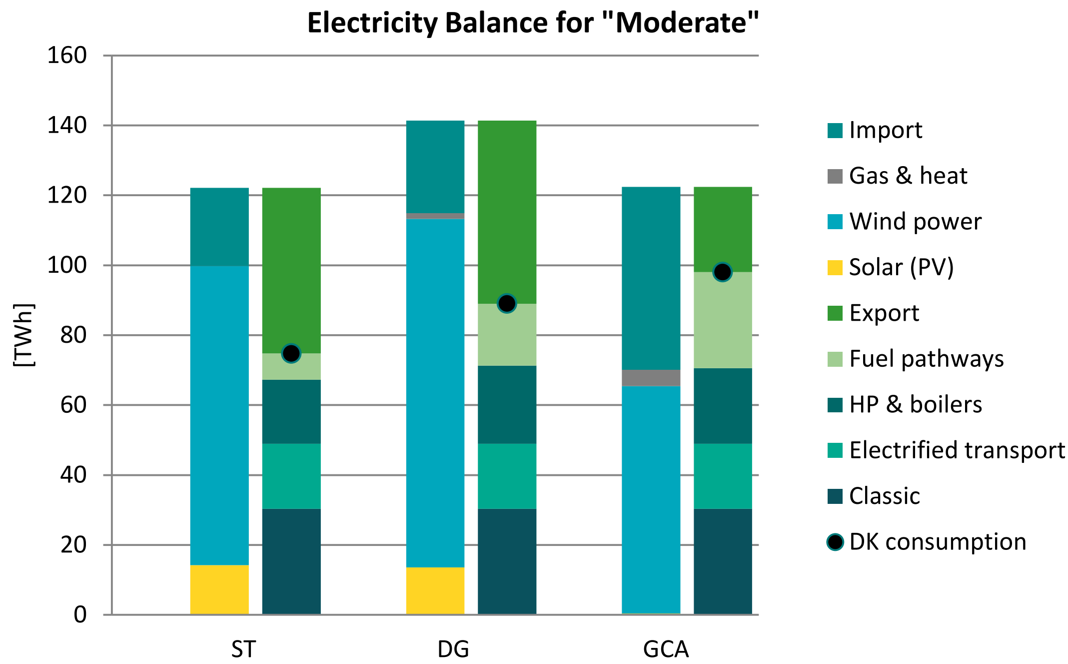


Figure 22 - Electricity balance in "Moderate". "Fuel pathway" includes the electricity consumption for the production of fuels for both transport, heat and power production.

The total national consumption, illustrated by the black dots in Figure 22, is lowest in ST and largest in GCA. There is a correlation between the total consumption and the carbon resources utilised as illustrated in Figure 18. Electricity is needed both to extract and to further process the carbon resources for different purposes. Thus, an increased use of carbon resources implies increased electricity consumption. Since the total amount of carbon resources needed to satisfy the transport demand is almost the same in the three "Moderate" simulations, the difference in the carbon utilised must be the amount of carbon resources used for either heating or power purposes in the system. This is also seen in Figure 22 where the electricity production from gas and heat is zero in ST and largest in GCA. GCA is ideal for the peak power capacity since it is possible to utilise the many hours with low prices to produce the fuels for the few critical hours with very high prices.

As mentioned, DG has the largest investment in hydrogen storage. In general, DG has the largest investment in storage opportunities with the largest capacity in CO_2 storage as well. Furthermore, it is the only scenario with investments in battery capacity. The 200 MWh batteries are used continuously over the year to balance the production from renewables to the demand. In general, it is assumed that the large investments in fluctuating production from renewables in DG are what drive the investments in storage units for balancing. Investments are made in CO_2 storage in both DG and GCA, corresponding to approximately 20,000 ton carbon storage capacity. The anaerobic digestion operates almost continuously throughout the year and no investment is made in biogas storage. Thus, the CO_2 must be stripped from the biogas immediately and the CO_2 storage can be used to balance the demand for CO_2. In ST most of the CO_2 is exported and therefore there is no need for storage. However, ST is the only scenario where an investment is made in oxygen storage. This is needed to balance the oxygen supply for the thermal gasification which has the largest capacity in this simulation while the electrolysis units that supply the oxygen have the lowest capacity.

The investments and system described and analysed above results in the energy flows for DG "Moderate" illustrated in the Sankey diagram in Figure 23. The CO_2 streams are included as well and are based on the arbitrary LHV of 1 MJ/kg but scaled with a factor ten in the figure to make them more visible. It is clear that the largest resources in the system are wind power along with straw, slurry and waste for biogas. Also, it can be seen that the syngas is produced through a combination of thermal gasification, steam methane reforming, co-electrolysis and a small amount from RWGS. The RWGS unit in the Sankey diagram includes the mixing of the CO with hydrogen to form syngas. From the flows in to and out of the *Methanol, gasoline & jet fuel* box it is clear that there is an over production of gasoline in the system. In the gas CHP and boilers primarily methane, but also a small amount of syngas and hydrogen, is used to produce heat and a small amount of electricity. The electrolysis box includes both hydrogen and co-electrolysis. From the arrows it can be seen that on an energy basis, almost the same amount of hydrogen and syngas is produced. This can seem surprising since there is a significantly larger capacity of co-electrolysis than hydrogen electrolysis in the system. It is due to the fact that the co-electrolysis in the system also produces a hydrogen stream due to the fixed composition of the syngas leading to seemingly large production of hydrogen. The Sankey diagrams for all the scenarios can be found in *Appendix H – Sankey Diagrams*. The capacities and energy flows result in the yearly socio economic costs for each scenario presented in Figure 19. The total costs of all "Moderate" simulations are quite similar. The main difference is that the investment and fixed O&M costs are largest in DG and lowest in GCA due to mainly the differences in invested renewable production capacity. Furthermore, the bottleneck revenue is largest in DG and lowest in ST which reflects the utilisation rate of the interconnectors. It could also be a reflection of the magnitude of the price difference when the interconnectors are utilised.

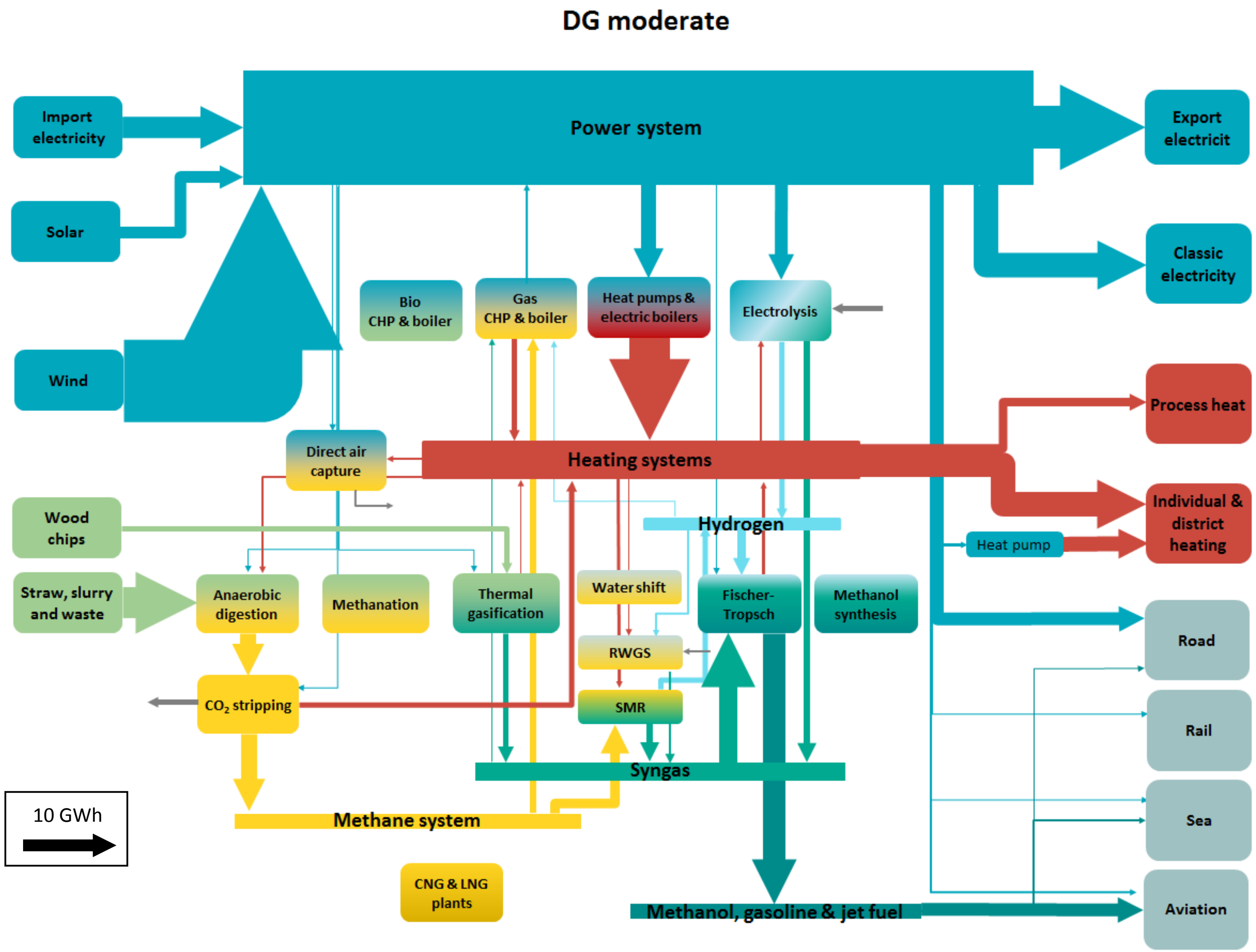


Figure 23 - Sankey diagram illustrating energy flows for DG "Moderate". CO_2-streams are based on the arbitrary LHV of 1 MJ/kg and scaled by a factor ten. The RWGS unit in the Sankey diagram includes the mixing of the CO with hydrogen to form syngas.

As mentioned, the European electricity prices have a large impact on the simulations. The investments made in ADAPT and the resulting production and consumption will however also impact the prices in Denmark. In Figure 24, the prices found through the Sifre modelling are illustrated along with the prices in DK1 found from the BID simulations that are used to determine the European framework conditions. The BID prices are illustrated by the dotted lines. The BID prices for DK1 have been determined in BID based on the expectations in the TYNDP18 work to the development in Denmark towards 2040. It has the same trading conditions as implemented in the Sifre model and is therefore comparable with the prices obtained from Sifre. The comparison illustrates how the transition to a 100 % renewable energy system will influence the price duration curves, given that the prices in Europe remains unchanged. The latter is of course a rough assumption. However, it is assumed that the comparison can be used to make general conclusions on tendencies for the electricity price. In ST the impact is quite limited. In both duration curves, there is a relatively large share of the year, where the price is around 50 EUR/MWh. However, the decline from this level to prices of zero is more gradual for the Sifre prices than the BID prices. This is most likely a result of the increased renewable capacity along with flexible consumption. In GCA the impact may seem limited as well, but the numbers of hours with prices of zero decrease significantly from around 2600 hours to approximately 400 hours. This is a result of the relatively small domestic renewable capacity and the large amount of flexible consumption from the fuel production pathways as also indicated in Figure 22. Furthermore, the large amount of import from the neighbouring price areas implies that the prices are more similar to the prices in Europe. The average price duration curves for the European price boundary can be seen in Figure 3 for reference. In DG the same tendency as for ST is evident. The prices in BID are relatively constant for a longer period than in Sifre and in Sifre the price declines more gradual towards zero. This arises from a combination of large renewable capacity along with a larger flexible consumption. Also, due to the large amount of export, the price in Denmark becomes more similar to the prices in Europe.

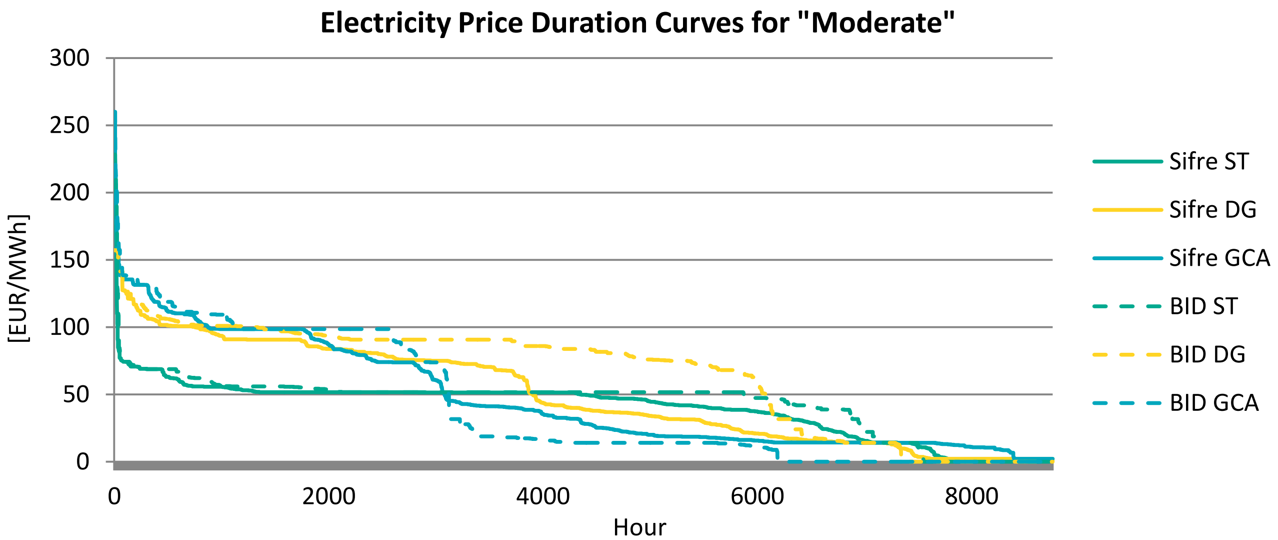


Figure 24 - Comparison of prices in DK1 from the BID simulations and the prices in DK after the Sifre optimisation of both investments and operation.

Due to the flexibility of the large electricity consumers, e.g. electrolysers, electric boilers, HPs, EVs and battery storage the consumption is large when the price is low and vice versa, as seen on Figure 15 that illustrates a peek into the dynamic operation of the electricity system. The large consumers are able to mainly consume electricity when the renewables are producing and the price is low. Hence, the weighted average price for electricity becomes almost equal. Thus, even though the price duration curves are quite different for the three scenarios, the weighted average electricity prices are 32.96, 32.09 and 32.64 EUR/MWh for DG, GCA and ST respectively. The results indicate that through a balance of import/export based on the prices in the neighbouring countries and investments in RE capacity and flexible consumption units it is possible to obtain almost equal weighted average prices. Because of the similar weighted average electricity prices, the weighted production costs for the fuels for transport are also quite similar. The weighted costs for the produced fuels in the simulations are shown in Figure 25 are not produced in the three simulations. As mentioned, for an output unit of jet fuel produced from the FT process, 0.64 units of gasoline are also produced. In the moderate electrification scenario approximately 61 PJ of jet fuel and only 9 PJ of other carbonaceous fuels are demanded. Gasoline can thus cover the entire demand of other carbonaceous fuels. Hence, no other fuels than electricity, jet fuel and gasoline are produced in the three simulations. Other fuels are produced in the “Slight” and ”Conservative” electrification scenarios, while no other fuel than electricity is going to be produced in “Full” and the same fuels are going to be produced in ”Ambitious” as in “Moderate”.

The costs for the produced fuels on Figure 25 are found from the OPEX and CAPEX pr. primary output fuel with the revenue from by-products subtracted from the costs. The revenue from the by-products is found as the sum product of the output market prices determined in Sifre and the produced volumes pr. primary output on an hourly resolution. The OPEX is also found on an hourly resolution as the sum product of the input markets and the consumed volumes pr. primary output. The total CAPEX is depreciated over the lifetime to find a yearly CAPEX which is divided to each produced primary output. For jet fuel and gasoline the costs are divided pr. energy content so that the jet fuel and gasoline get 60.9 % and 39.1 % of the total costs of production respectively.

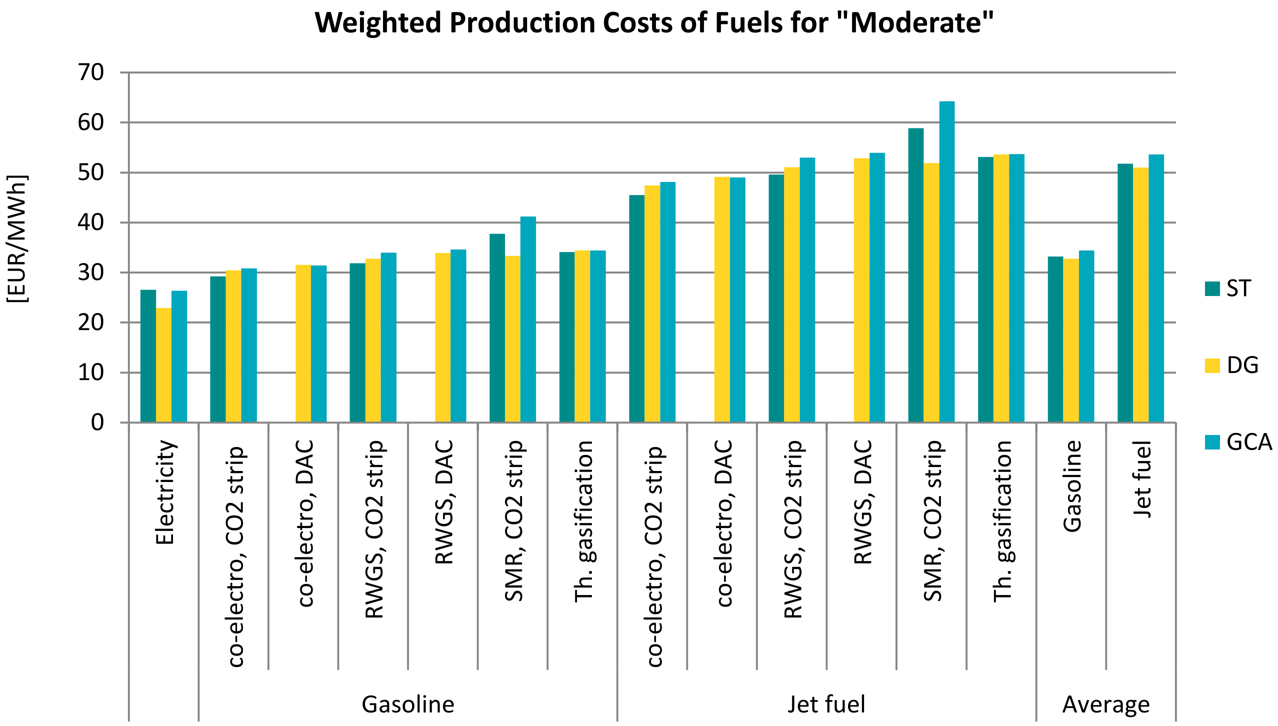


Figure 25 – Weighted average production prices for the produced fuels for the three European framework conditions for "Moderate". No methanol, CNG or LNG is produced in this electrification scenario. The different types of gasoline and jet fuel come from the different pathways to the end product, e.g. syngas from thermal gasification or CO_2 from stripping of biogas to co-electrolysis to produce syngas. The pathways are explained in Table 8.

Table 8 explains the differences between the many pathways to gasoline and jet fuel included in Figure 25 but also the ones not utilised in the three moderate simulations which are all methanol, LNG and CNG pathways and gasoline and jet fuel from SMR and methanation. The pathways are divided by the origin of the inputs. Syngas, the main input to the FT and methanol synthesis, can be produced through seven different paths. Methane, the main input to LNG plants and CNG compressors, can be produced through two different paths. The two categories to the right in Figure 25 are average prices for gasoline and jet fuel based on all the different paths to each fuel.

Abbreviation in Figure 25	Description
Pathways for jet fuel, gasoline and methanol	
Co-electro, CO_2 strip	Syngas from co-electrolysis, CO_2 to electrolysis from CO_2 stripping
Co-electro, DAC	Syngas from co-electrolysis, CO_2 to electrolysis from DAC
RWGS, CO_2 strip	Syngas from RWGS, CO_2 to RWGS from CO_2 stripping
RWGS, DAC	Syngas from RWGS, CO_2 to RWGS from DAC
SMR, CO_2 strip	Syngas from SMR, methane to SMR from CO_2 stripping
SMR, methanation	Syngas from SMR, methane to SMR from methanation
Th. gasification	Syngas from thermal gasification
Pathways for CNG and LNG	
CO_2 strip	Methane from CO_2 stripping
Methanation	Methane from methanation

Table 8 – Pathways to fuels for transportation based on different origins of inputs.

The amount of produced fuel and the average price of each fuel can be used to create a merit order curve for fuels for transportation as shown in Figure 26. The amount of produced fuel in the moderate scenario is not equal to the demand because of the overproduction of gasoline. As seen from the figure electricity is the cheapest fuel, next is gasoline and then jet fuel. The order of the latter two is because of the split of costs for the two outputs from the FT process. When considering engine efficiencies for the fuels, electricity becomes even cheaper compared to the others pr. supplied mechanical energy. The average weighted costs for the fuels are quite similar for the three simulations for “Moderate”. Hence, the European framework conditions do not affect the socio economics, the total carbon balance or weighted fuel costs significantly. It affects the invested capacities both for renewables and for fuel production and it also affects the electricity balance.

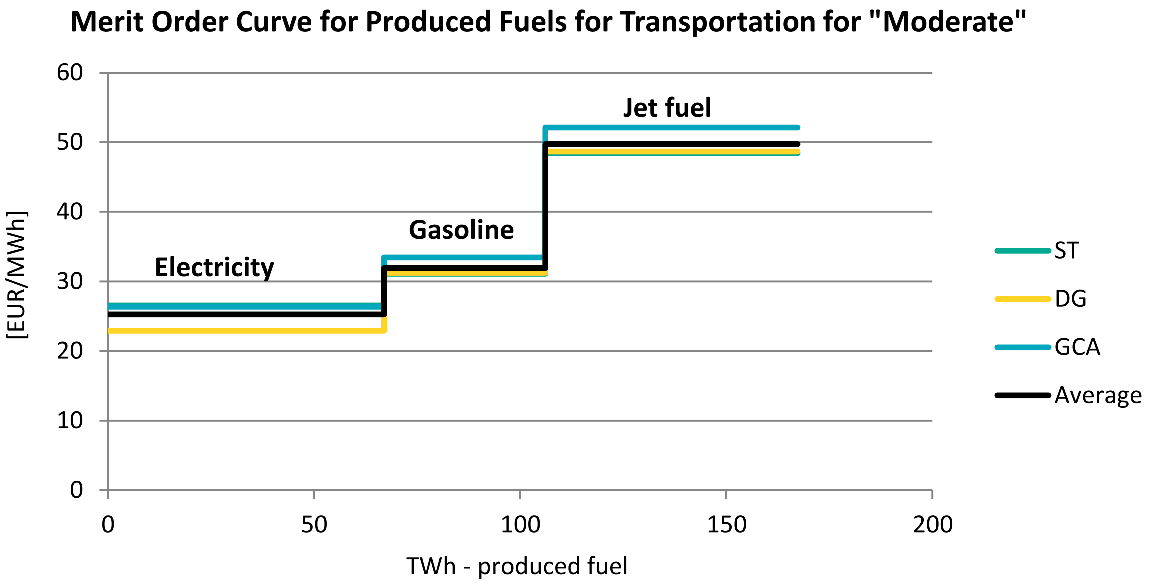


Figure 26 – Merit order curves for produced fuels for the three European framework conditions in “Moderate”. The prices are averages of the production costs for the different pathways utilised in the simulation.

9.3 DG Electrification Scenarios

Having thoroughly analysed the impact of the different European framework conditions, a comprehensive but briefer analysis of the impact of the electrification scenarios for DG is next. As the previous section described, there are small differences in the systems across the European framework conditions for the “Moderate” scenario. Hence, it is assumed less significant which European framework conditions are chosen to analyse the different electrification scenarios for. However, DG is often in-between the two others for the different analysed parameters and is therefore chosen. The analysis will look at relative differences not absolutes. This section will, as the previous but for the different electrification scenarios, compare and analyse the differences for fuel production, socio economics, carbon balance, invested capacities, electricity balance and electricity price duration curves.

When looking at the fuel consumption for the five DG scenarios in the middle of Figure 17, it is not surprising that “Conservative” consumes the most and “Full” consumes the least as the mechanical demands from fuels are fixed. The utilised carbon is of course highly affected by the demanded carbonaceous fuels for transportation, and the same order as for the consumed fuels is present as seen in the middle of Figure 18. Furthermore, the socio economics is a product of the cost of producing fuels and is naturally higher the more carbonaceous fuel is consumed. Hence, the same pattern is evident once more in Figure 19. For the above three parameters it is more interesting to analyse the results across the European framework conditions as done in the previous section. Looking at the invested capacities for both fuel production units and renewables, as seen below on Figure 27 and Figure 28 respectively, there is a tendency that the more carbonaceous fuel that is demanded the more capacity is invested in. Hence, “Conservative” has the most capacity and “Full” the least. It is only in “Full” that the maximum potential of wet biomass is not utilised as the invested capacity in the anaerobic digestion is not 2240 MW as for the others. This was also illustrated in the carbon balance in Figure 18. The capacity of the fuel production units is decreasing with the lower demands for the fuels, e.g. thermal gasification, DAC, electrolysis, CNG compression and FT and methanol synthesis. Some fuel producing units do not follow that order, i.e. RWGS and SMR. As evident on Figure 30, where the electricity price duration curves for the five DG electrification scenarios are shown, “Full” has the most hours with both low and high electricity prices. The gradient around hour 4000 on the graph is very steep and splits the curve in two, one half with prices well above 60 EUR/MWh and one half with prices well below 40 EUR/MWh. When electrifying less and introducing more flexible consumption in the form of electrolysers the price duration curves are levelled out, meaning that the plateaus are shortened and the slope is more constant. The amount of hours with a price of zero is also reduced. “Full” has almost no demand of syngas or hydrogen besides to produce the demanded fuel to balance the system. Hence, the invested capacity of RWGS and SMR is zero. With the most hours, except for “Full”, with high prices and also a demand for syngas and hydrogen for transportation, “Ambitious” has the highest invested capacity in RWGS. Hereafter comes “Moderate”, “Slight” and “Conservative” in that order. It correlates with the incentive to invest in hydrogen storage capacity with more hours with high electricity prices. Hence, the stored hydrogen is used together with CO_2 through the RWGS to produce syngas in hours with high electricity prices. High electricity prices also make it cheaper to produce syngas through SMR than through co-electrolysis or RWGS. Hence, relative to the fuel demand “Ambitious” also has the most invested capacity in SMR.

The invested capacity in gas turbines and electric boilers also vary significantly between the different DG electrification scenarios. As the carbon resources become scarce with the increased carbonaceous fuel demand less gas turbine and more electric boiler capacity is invested in. The production of fuels for transportation also demands process heat, hence the large increase in electric boilers for “Conservative”. At last, “Conservative” invests in methanol synthesis and CNG compression to meet the demand for carbonaceous fuels for light and heavy duty vehicles, ships and trains that is not met by the gasoline by-product from the jet fuel production from the FT process. “Slight” also invests in a small amount of CNG compression capacity for the same reason.

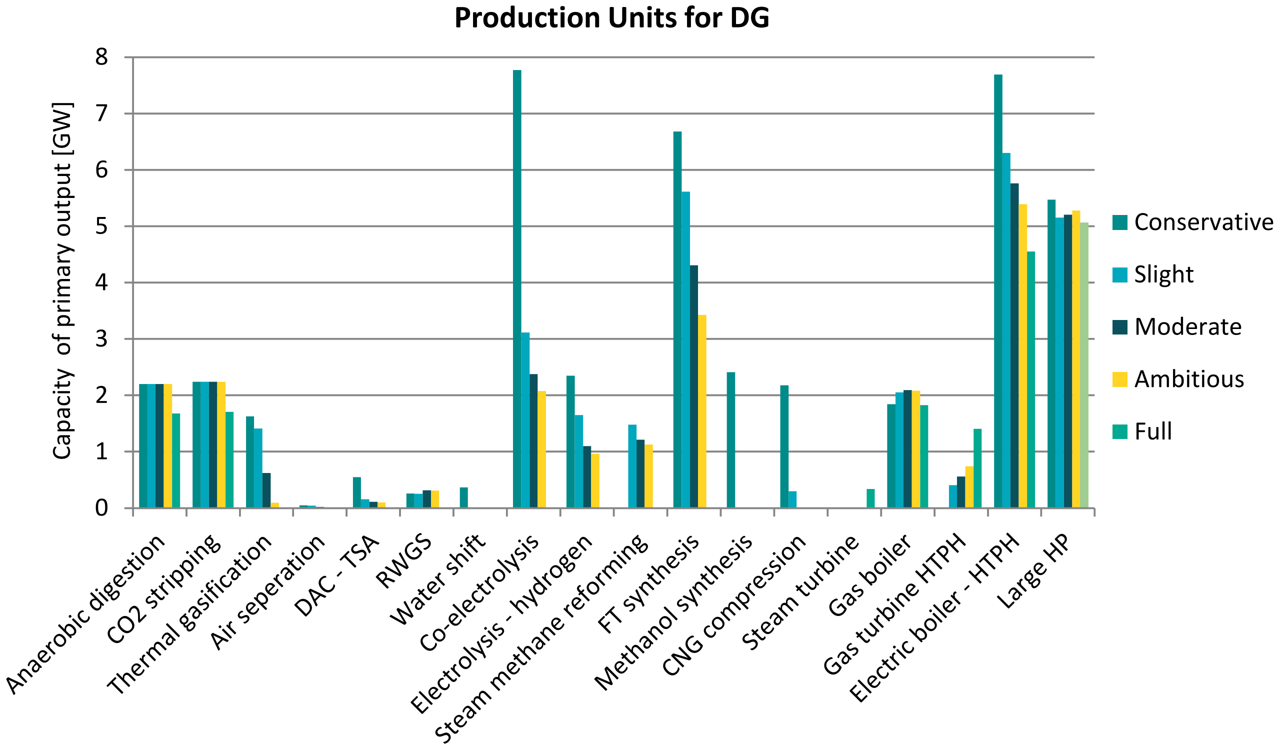


Figure 27 - Invested production unit capacities in the five DG scenarios. The capacity is for the primary output of the production units.

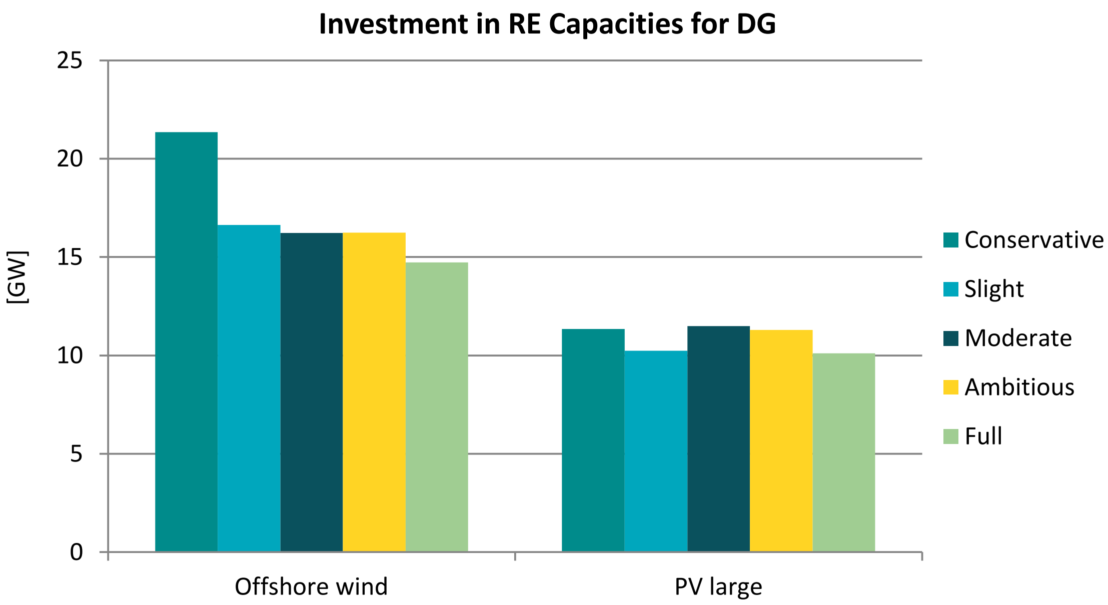


Figure 28 - Total invested renewable production capacity for DG. Onshore wind turbines are not included as the installed capacity is fixed to 9 GW for all scenarios. Small PV units and solar heating are not included because the invested capacity is zero for all scenarios.

The invested capacity of offshore wind and large PV panels is shown in Figure 28. The onshore wind capacity is fixed to 9 GW and small PV panels and solar heating are not invested in, hence they are not shown in the figure. The total demand of electricity, shown in Figure 29, correlates with the installed capacities. “Conservative” has the highest electricity consumption and “Full” has the lowest because of lower total efficiencies from well-to-wheel for carbonaceous fuels than for electricity to transportation. For carbonaceous fuels a lot of the energy comes from the biomass resource, but the treatment and upgrading of the biomass demands inputs of heat and electricity. As most of the heat is also produced by electricity, the increased fuel demand is evident from the electricity balance. For the three non-extreme scenarios, “Slight”, “Moderate” and “Ambitious”, the total electricity consumption is almost equal. The increase in electricity demand for the electrified transportation is equivalent to the decrease in the electricity demand for the fuel production pathways. The demand for fuel for heat and power purposes is also increasing with more electrification of the transport. The fuel for the heat and power purposes is produced with electricity from the category *Fuel pathways*. The utilisation of the RGWS also influences the electricity consumption. To store hydrogen from electrolysis to use if for CO production in the RWGS and to add more hydrogen afterwards to obtain syngas, demands much more electricity than to produce syngas from the thermal gasification. Hence, if the demand for carbonaceous fuels for heat and power purposes and the utilisation of RWGS were equal for “Slight”, “Moderate” and “Ambitious”, the electricity demand in “Slight” would have been the highest followed by “Moderate” and then “Ambitious”. Nevertheless, the equal electricity demands result in almost identical investments in renewable production capacity. The Sankey diagram for “Moderate” can be seen in the previous section in Figure 23, and the other four Sankey diagrams can be seen in *Appendix H – Sankey Diagrams*.

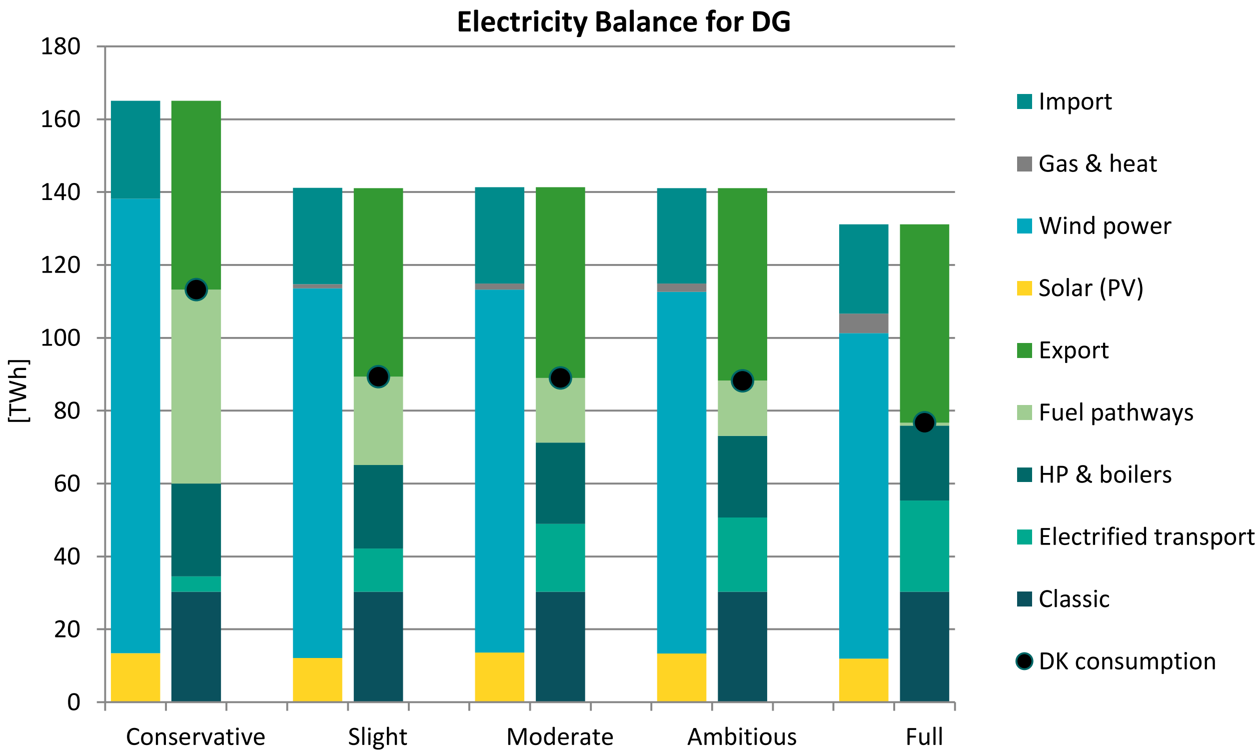


Figure 29 - Electricity balances in the five electrification scenarios for DG.

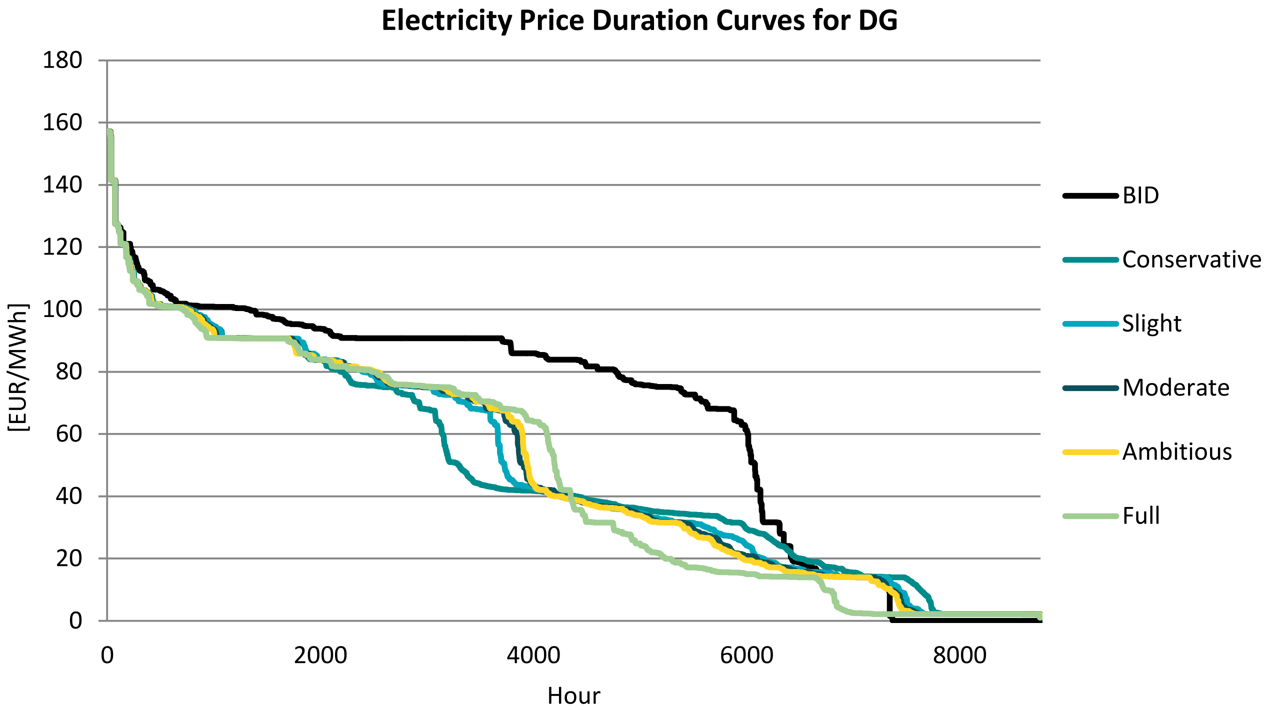


Figure 30 - Comparison of prices in DK1 from the BID simulation and the prices in DK after the Sifre optimisation of both investments and operation for the DG electrification scenarios.

9.4 General Tendencies

Based on the comparison and analysis of the simulation results it is possible to determine general tendencies across the different European framework conditions and electrification scenarios. Both have large impact on the results but in different ways. The impacts are described in overall terms in this section, first for the electrification scenarios and hereafter for the European framework conditions.

The results vary significantly between electrification scenarios since the amount of carbonaceous fuel to be produced naturally has a large impact on the entire system. The general tendency is larger invested capacities in the less electrified scenarios. Some units are even only invested in, in the scenarios with lowest electrification. This goes for the methanol synthesis and CNG compression, which are only needed when the gasoline from the FT process is not sufficient to cover the remaining demands. This stresses the importance of accounting for the by-product of gasoline from the FT process when optimising the transport sector, since the gasoline will be sufficient to cover the demand in many scenarios. The biogas resources are the cheapest resource and utilised fully as soon as the entire transport sector is not electrified. When the degree of electrification decreases more capacity of thermal gasification and DAC is needed to supply the necessary carbon resources. The need for carbon resources also entails a shift from gas turbines to electric boilers for HTPH production when less of the transport is electrified. In the less electrified scenarios the carbon resources are needed in the transport sector and thus not available for heat and peak power production. Nevertheless, not at a price that is competitive with the alternatives. For renewables the general tendency is increasing capacity when the electrification decreases. This is closely related to the increasing electricity consumption. The three middle electrification scenarios do however result in almost identical electricity consumption due to increasing use of fuel for heat and power when the need for fuels for transportation decreases. Therefore, the invested renewable capacity is almost identical in these three scenarios. Naturally, the increasing capacities and need for carbon resources entails that the socio economic cost of the system increases significantly when the degree of electrification decreases.

The variations between the different TYNDP scenarios that result in the European framework conditions are less significant. The European price boundary does have a large impact but the possibility of investing in sufficient renewable capacity makes it possible to obtain similar weighted average electricity and fuel prices. Higher prices in Europe entail a larger investment in national renewable capacity and vice versa. Not only the general price level but also the price variations influence the system. In general, large variations result in investments in larger capacities for both production and storage units, enabling increased production in hours with low prices and reduced production in hours with high prices. Looking at the carbon resources used in the system large variations in price, or more specifically hours with low prices, induces a shift from thermal gasification towards DAC. The biogas resources on the other hand are the cheapest resource independent of the European price boundary. Large price variations also provide the incentive for investment in peak power capacity. The resources needed for the back-up can be produced in hours with low prices and then utilised for peak power production in critical hours where it is more expensive to balance the system through interconnectors. Lastly, the prices in Europe and the renewable capacity are decisive for the net import/export in the system, where high prices in Europe in general leads to large investments in renewable capacity and thus more export in hours with excess production and vice versa. All in all, the European conditions are decisive to the system configuration, but less important for the prices of the end fuels for transportation. As also presented in the section *Moderate Electrification Scenario* in Figure 26, it is reasonable to make the approximation of one average merit order curve for fuels for transportation for each electrification scenario across the European framework conditions.

Figure 31 presents the merit order curves for each electrification scenario based on average fuel prices along with average production of the fuel from the three European framework conditions. Each fuel is represented by a colour as also indicated by the colour of the text of each fuel. Each electrification scenario is represented by different line styles as indicated both by the text in the figure and the legend on the figure. The figure represents the fuel produced for transportation for each scenario. Thus, not all the gasoline produced in e.g. “Moderate” is consumed in the system. The electricity production indicated in the figure is only for electrified transport and not for the remaining demands for electricity in the system. As already presented, Figure 31 clearly illustrates that it is only in “Slight” and “Conservative” that other carbonaceous fuels than jet fuel and gasoline are produced. Generally, the endpoint of the merit order curve indicating the total fuel production in each scenario increases as the degree of electrification decreases. As stressed earlier, this is related to the higher efficiency of EVs compared to ICEs. In general, the price of each specific fuel, e.g. gasoline also increases as the degree of electrification decreases. It is natural that when more fuel is needed the more expensive the scarce resources for the production of the fuel become, especially when economy of scale effects are not considered. “Ambitious” deviates from this tendency with gasoline and jet fuel prices above that of “Moderate”, where more fuel is needed. The price of electricity for EVs is lowest in the conservative scenario and increases when more transportation is electrified. This may seem counter intuitive since the total electricity consumption is the lowest in the fully electrified scenario. However, the concurrency of the demand for transportation from EVs implies a larger consumption at the same time with a limit to its flexibility. In all scenarios, electricity is the cheapest fuel. If the efficiency of the individual engine types where included in the figure, the price pr. mechanical energy supplied would be even lower for electricity compared to the other fuels. Jet fuel on the other hand would be seemingly more expensive due to the low efficiency of jet engines. It should be noted that the prices presented here do not include tariffs for electricity, heat or gas. The effect of this omission is analysed in overall terms in the *Discussion*.

An addition to Figure 31 is a reference price of the production costs for fossil fuels. To find a comparable price of the fossil fuels to the sustainable fuels of Figure 31, the fossil fuels are converted to EUR/MWh diesel equivalent. From [112]–[114] the production costs are approximated for each fossil source in each individual country producing fossil fuels. No externalities e.g. cost of pollution or emissions of greenhouse gasses are included, it is the pure cost of production of the fuel. It is found that the cheapest 8,000 EJ of oil can be produced at an average price of approximately 21.5 EUR/MWh diesel equivalents, as shown in Figure 31. With a present annual global primary energy consumption of 470 EJ and a total fossil reserve capacity of around 44,000 EJ there are plenty of fossil resources to power transportation at prices outcompeting all of the sustainable fuels except for electricity [115]. Due to the scarcity of fossil reserves it might drive the market price up to a level comparable to the synthetic fuels. In [116] the external cost of emissions from a diesel car is estimated to be 0.27 EUR/L corresponding to 27 EUR/MWh. If this cost is included the socio economic cost of diesel becomes 48.5 EUR/MWh, which is above the renewable gasoline price calculated in all scenarios. Thus, if the externality costs are reflected in the cost of fossil diesel through taxes, the fossil and renewable fuels are more equal. Having the engine efficiencies in mind electricity is unconditionally the cheapest fuel. It is not in the scope of the project to further analyse the matter of realising the system, though it is highly relevant if a 100 % renewable energy system is ever going to become reality.

The total cost for the production of the fuels for transportation for each scenario can be found as the area below the merit order curve for each scenario. Again it is quite obvious that delivering the fuels for transportation becomes more expensive when a smaller share of the transportation sector is electrified. The conclusion is that the electrification scenarios have significant impact on the prices of the fuels delivered for transportation. The European framework conditions have less impact on this and more an impact on the system configuration and the technologies used to supply the demands.

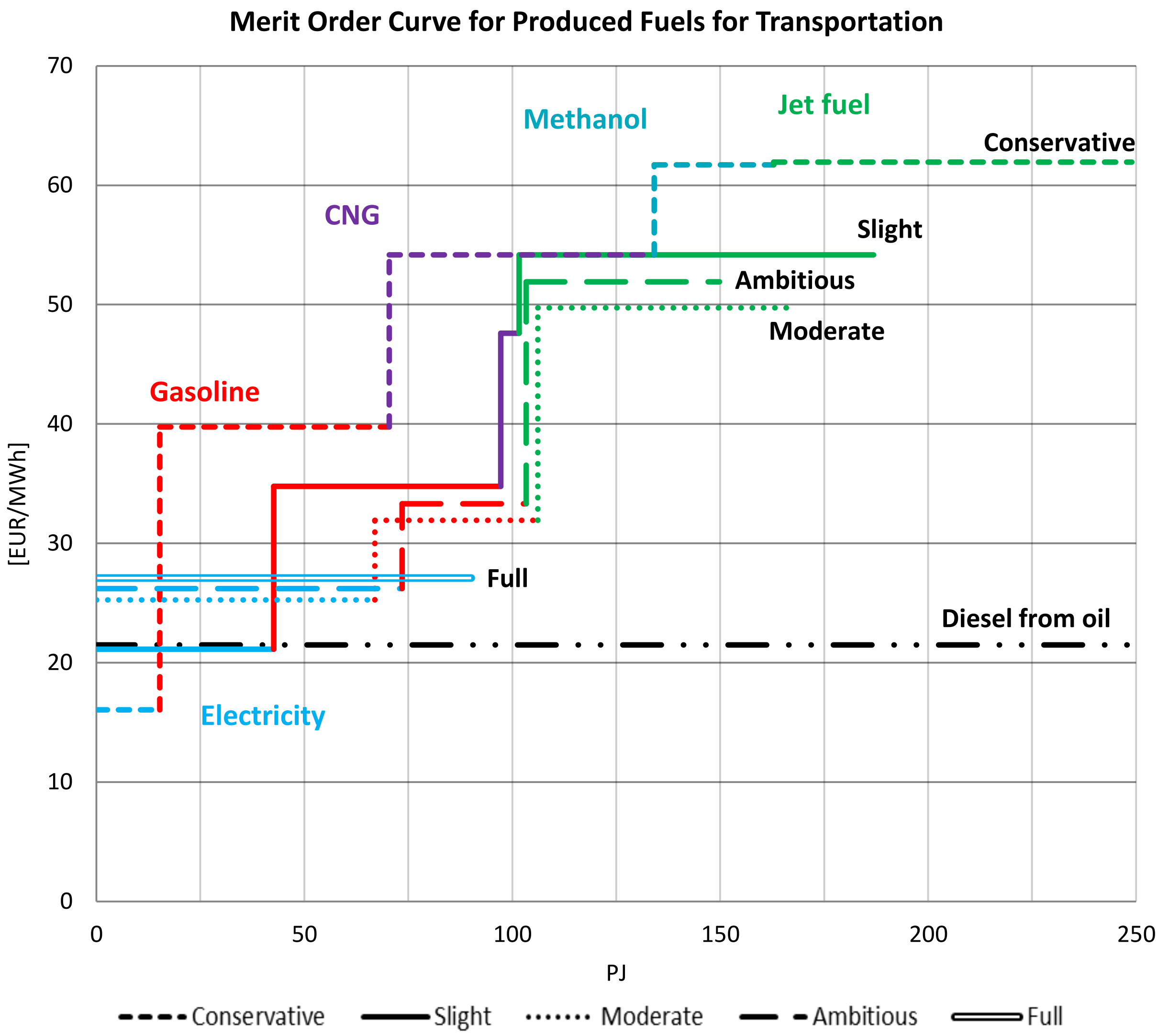


Figure 31 – Merit order curve for fuels for transportation for the five electrification scenarios based on the weighted average production cost pr. primary output for all produced fuels. The specific fuels are represented by different colours shown as the colour of the text. The different scenarios are also represented with text. Note that not all of the gasoline is consumed, hence the difference from Figure 17. Diesel from fossil oil reserves without externality costs is shown as a reference.

10 Sensitivity Analyses

The project is based on assumptions, approximations and projections for future values of the energy system where most, if not all, of the estimated values are very uncertain. Even though all inputs are based on literature reviews and acknowledged sources it is still just qualified estimates. Hence, the outcomes of the model are recalculated under alternative assumptions to determine the impact of a single or multiple variables. The sensitivity analysis of this project includes simulations where the biomass available for the energy sector is changed to the global average of 15 GJ/person, where the capacity of the interconnectors of the electricity grid is halved, where Denmark is isolated by setting the capacity of the interconnectors to zero and the global biomass potential is used, where the estimated Danish part of the international sea transport is included and at last where the transport demand is increased by 50 %. The results presented and analysed from these simulations will only include the main differences from the original simulations. The results from the 15 original simulations will be referred to as "Base" results. Other variables could also have been tested, but due to limited time the above mentioned were deemed the most important.

10.1 Global Biomass

In this sensitivity analysis the global biomass potential of 15 GJ/person/year is set as a hard constraint instead of the domestic potential of 33 GJ/person/year, as discussed in the section *Sustainable Biomass Potential*. The same relative reduction is used for all types of biomass input. This simulation is included in the sensitivity analysis due to the large uncertainty of the future potential biomass and to see the effect of operating the energy system with a heavily reduced source of biomass input to fuel production and to balance the grid in critical periods. Furthermore, it provides a perspective on the scalability of the system. The simulation with the global biomass potential is run for "Full", "Moderate" and "Conservative" for the three European framework conditions. The analysis will mostly focus on the DG "Moderate" simulation except the utilised carbon resources as shown in Figure 32 which is for DG for the three included electrification scenarios.

Figure 32 shows the utilised carbon for DG with the domestic and global biomass for "Conservative", "Moderate" and "Full" compared to the global biomass potential corresponding to 15 GJ/person. An obvious and expected trend is the increased use of DAC in "Conservative" and "Moderate". The increased utilised carbon resources in "Conservative" are due to a shift in fuel production from CNG to methanol with a lower overall efficiency from carbon to wheel. The methanol pathway is not limited by the biomass resources as CNG is due to the availability of DAC. For all three simulations the amount of carbonaceous fuel used for electricity production decreases to zero and it decreases for heat production as well even though the gas boiler capacities increase in "Moderate" and "Full". In "Conservative" a large increase in carbon from DAC is seen to meet the carbon demand of the system. For "Moderate" the carbon supplied by both DAC and thermal gasification increases. Thermal gasification competes with DAC and due to a reduction in the constant stream of carbon from anaerobic digestion the thermal gasification is superior to DAC because it can deliver carbon at a stable price even with fluctuating electricity prices. Hence, the full biomass potential from thermal gasification is utilised in DG "Moderate".

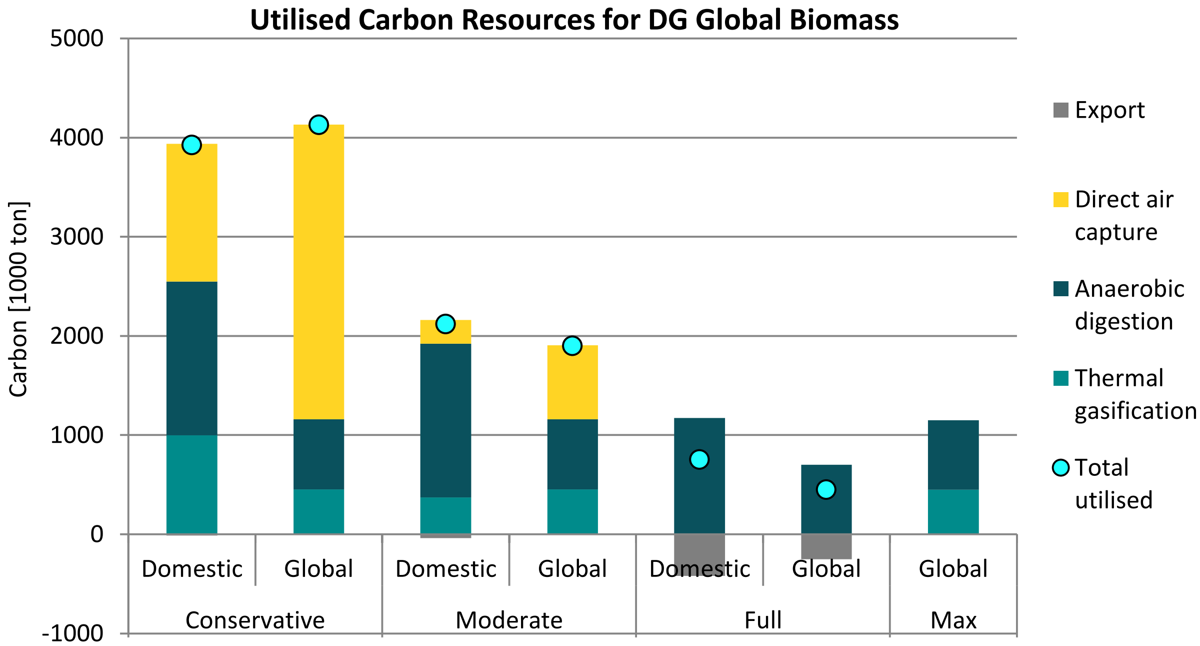


Figure 32 - Total utilised carbon resources divided by harvesting technology for DG with domestic & global biomass compared to the global potential biomass resource.

Operating the system with the global biomass potential does not have a large effect on the invested renewable capacity in the system. In ST "Moderate" with global biomass there is 18 GW offshore wind capacity compared to 13 GW for the domestic biomass potential, where DG "Moderate" only increases from 16.2 to 17.8 GW and GCA "Moderate" from 7.8 to 8.3 GW. The onshore wind capacity is still fixed to 9 GW and the large PV units barely increase. For the fuel production units the patterns for the "Moderate" simulations are comparable to each other. Hence, only DG "Moderate" is shown in Figure 33. The capacity of anaerobic digestion, CO_2 stripping and thermal gasification obviously decreases. The capacity of DAC increases as also evident from Figure 32. With the increase in DAC, the SOEC co-electrolysis capacity also increases to convert the captured CO_2 to syngas. With the increase in renewable capacity and most likely more production in hours with cheap electricity, the capacities of the FT synthesis, electric boiler, large HP and hydrogen electrolysis also increase. SMR and gas turbines, the methane consuming units, naturally decrease as the output from the anaerobic digestion is more than halved. For "Conservative" the same pattern as for "Moderate" is evident. For "Full" there is a slight increase in electric boilers and large HPs, but also only a slight decrease in anaerobic digestion capacity. The gas turbine capacity is heavily reduced which is counterbalanced by a small increase in import.

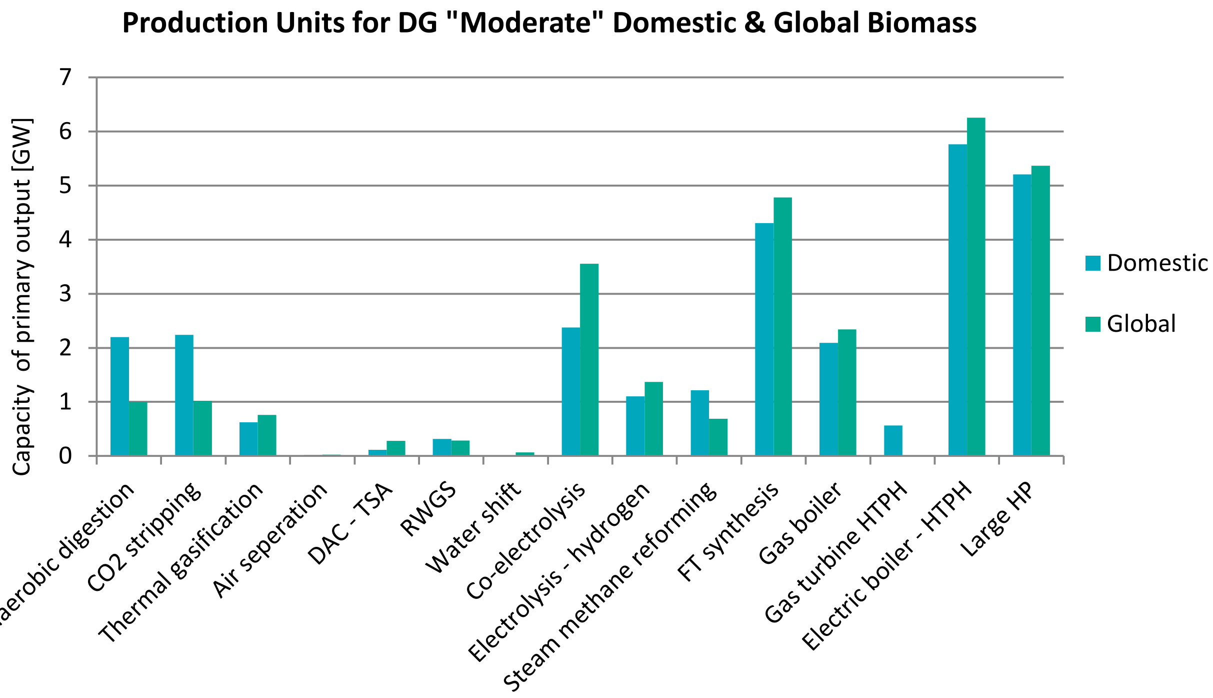


Figure 33 – Invested production unit capacities in DG Domestic & Global Biomass. The capacity is for the primary output of the production units.

The result of the change in invested capacities is a slightly different electricity balance for the system. The consumption increases from 89 to 97 TWh in DG "Moderate" and the production from renewables increases from 114 to 122 TWh for the domestic to the global biomass constraint, while the controllable power production on gas is reduced. This reduction compares to the slight increase in import. Hence, the interconnectors are utilised to balance the system at all periods with low power production from renewables. The largest difference is the increased consumption for fuel production with the global biomass potential. It increases from 18 to 25 TWh which almost corresponds to the total increase in electricity consumption. It is due to the low electricity consumption for syngas production from biomass compared to the high electricity consumption for syngas production from DAC and co-electrolysis. The result on the socio economics is an increase of 6 %.

As expected the sensitivity analysis shows that the DAC technology is used to balance the carbon supply when the biomass resources are scarcer. Furthermore, the use of carbon resources for heat and power production is reduced to a minimum and the system is to a higher degree balanced through interconnectors. On average the socio economic cost increased by 4 % when relying only on the global biomass resources.

10.2 Reduced Interconnector Capacity

In this sensitivity analysis, the capacity of all interconnectors (ICs) connecting Denmark to the neighbouring price areas is halved. As mentioned, the prices in the neighbouring price areas are not modelled in Sifre but are an exogenous variable. Thus, the price in each hour in the neighbouring areas is fixed and will not change as a result of trading with the Danish system, as would be the case in reality. The only parameter which will limit the use of the ICs is if the price in Denmark changes sufficiently. These conditions result in a high utilisation rate of the ICs. The entire capacity of the ICs in either direction is on average utilised 70-85 % of the hours in all scenarios. This is far from the current use of ICs, where the energy flow is limited by reserved capacity for ancillary services, internal congestions and changing prices in both price areas. In an attempt to achieve a more realistic representation of the ICs, the capacities of all ICs are halved. The sensitivity analysis is performed for “Moderate” for the three European framework conditions. This is chosen to investigate if the implications of the reduced IC capacity vary depending on the European framework conditions. In this section it is analysed how the changes affect the results in overall terms.

The reduced IC capacity results in changes in the invested capacities. In Figure 34 the changes are illustrated for GCA excluding the anaerobic digestion, CO_2 stripping, large HP and steam turbine since they are unaffected. It indicates that the biogas resources are still the cheapest to utilise. Looking at the capacity of the other resources providing carbon resources for the system; DAC and thermal gasification, a change is apparent. The reduced IC capacity entails a shift from DAC towards thermal gasification. The feasibility of the DAC in the base simulations depends on import of electricity at low prices from the surrounding price areas. This is especially the case in GCA, where there are many hours with very low prices, but the same tendency is seen in DG. The shift from DAC towards thermal gasification also entails a shift from co-electrolysis towards more hydrogen electrolysis. The increase in hydrogen electrolysis capacity does however not correspond to the decrease in co-electrolysis capacity. Since the amount of power that can be imported at low prices is reduced, so is the capacity of several of the electricity consuming units including electric boilers. The reduced capacity is outweighed by an increase in operating hours. This further entails a general reduction in the storage capacities in the system. In DG the general tendencies are the same as for GCA. In ST, on the other hand, the changes in the invested capacities are minor since the system in the reference is already based solely on anaerobic digestion and thermal gasification.

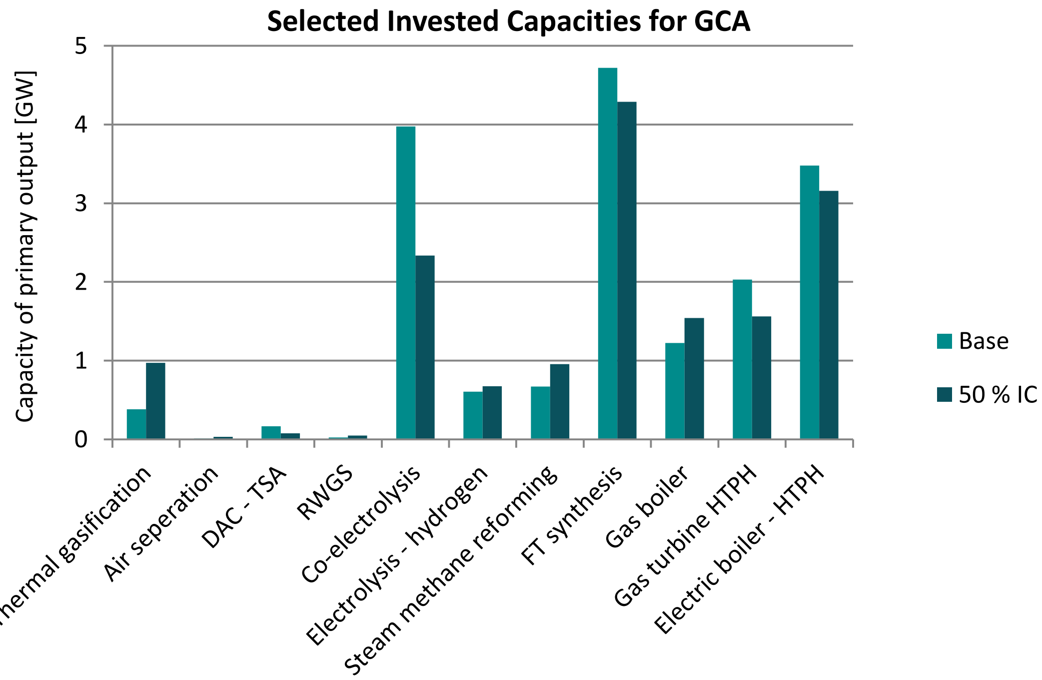


Figure 34 - Selected invested capacities in GCA "Moderate" for the base simulation and with 50 % IC capacity. Investments in anaerobic digestion, CO_2 stripping, large HP and steam turbine are omitted from the figure due to only minor changes. The capacity is for the primary output of the production units.

For renewables the invested capacities increase in GCA but decrease in ST and DG. This is related to the net import or export in the base simulations. GCA with net import in the base simulations requires more domestic renewable capacity to supply the demand with the reduction of the ICs. ST and DG with net export have less possibility of exporting the excess production and thus the renewable capacity is reduced.

The changes in invested capacities result in a change in the carbon resources utilised in the system as illustrated in Figure 35. The differences in the total resources consumed are limited. Since the demand for carbon for transportation is more or less fixed in all scenarios the variations arise due to changes in the use of fuels for power and heat production. The decrease in total carbon resources utilised in GCA implies that some of the resources in the base simulations are used to produce fuel for power which is exported to neighbouring countries in hours with high prices. Since the capacity of the ICs is reduced the potential for this export has reduced as well. In ST and DG, where the peak power production were quite limited in the base simulations, the changes in the total utilised carbon are insignificant. There are however, both in DG and GCA, a significant shift in the source of the carbon resources from DAC towards more thermal gasification.

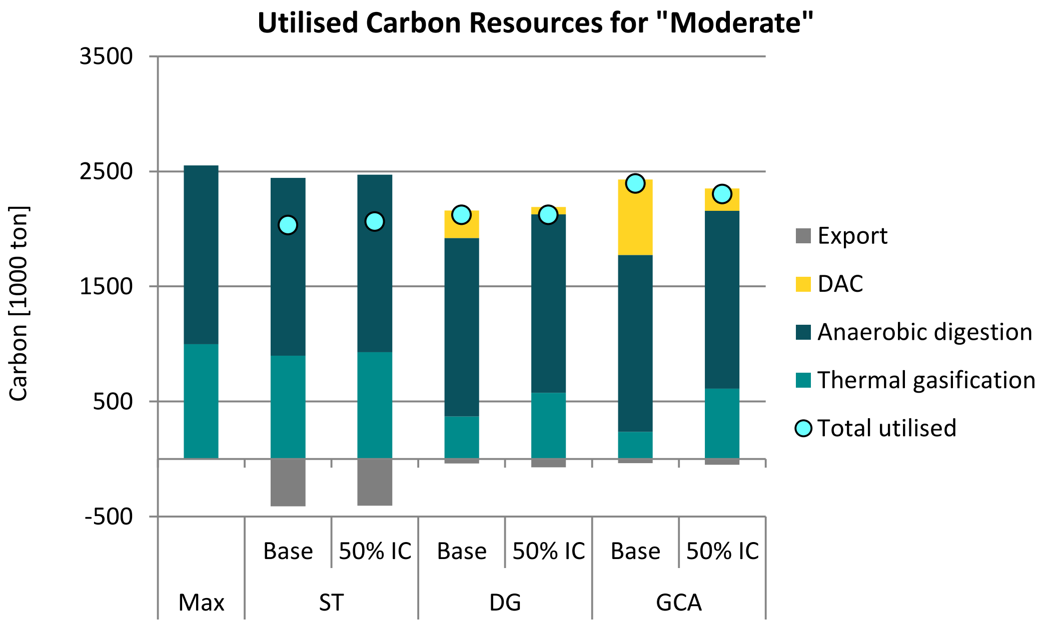


Figure 35 – Utilised carbon resources divided by harvesting technology in "Moderate" for all European scenarios. "Base" refers to the original simulation, where "50% IC" refers to the results from the simulation with 50 % interconnector capacity.

The shift from DAC to more thermal gasification also results in a reduction in the total electricity consumption in DG and GCA. In general, it could have been expected that the reduced IC capacity would provide the incitement for larger investments in peak power capacity. This is however not the case in any of the scenarios, on the contrary. This indicates that some of the capacity in the base simulations was used to produce power for export in hours with high prices in Europe. Furthermore, it proves that the system can be balanced without relying on the entire IC capacity. Thus the sensitivity analysis indicates that the system does not rely too heavily on the IC capacity, but that it does affect the investment decisions made. A more realistic picture would thus be a reduced investment in DAC capacity and a correspondingly increased investment in thermal gasification capacity.

10.3 Isolated Denmark & Global Biomass

The Danish projected transport demand in the form of transport activity was briefly analysed and compared to Europe in the section *Consumption in Denmark Compared to Europe* where Figure 9 showed that Denmark was close to the European average. Hence, the analysed Danish system can be scaled to all of Europe regarding transport demand. To analyse the scalability of the system, a sensitivity analysis of an isolated system is performed by removing all interconnector capacity from the model. It is done to be more realistic about the possibility to trade electricity for Europe with neighbouring countries where few opportunities exist. There are many differences across Europe that is not accounted for, e.g. load factor values for renewables, electricity and heat demand pr. capita, demand profiles, biomass resources, existing storages, time zones, concurrency of wind etc. Furthermore, the sensitivity analysis is performed with the global biomass potential to not exclude the possibility to scale it to a global level. It is also interesting to see how the isolated system responds to longer periods with low production from renewables with reduced biomass resources. For comparability the simulations are performed for Denmark to see the differences from the base simulations. The simulations are run for “Conservative”, “Moderate” and “Full” with no European framework conditions applied since the interconnectors are removed.

When running the simulations the model had under production in up to 1000 hours of the year for the different fuel areas including electricity, meaning that the production unit could not meet the demand at a price less than the price cap. It did not help to increase the price caps of the markets from the standard of 3,000 EUR/MWh. The issue seems to be the difference in foresight of the ADAPT module and the sequential planning module in Sifre, referred to as layer 1 and 3 in the section *Generic Method of Sifre and ADAPT*. With large periods with low production from renewables, the utilisation of storages is essential. The ADAPT module, layer 1, is fully deterministic and has perfect foresight of the entire year. In January it knows how much the wind is going to blow in November. Hence, it optimises the use of storages perfectly. The sequential planning module, layer 3, has full foresight a week at the time. In this layer, the model gives incitement to store energy based on the expected revenue later in the year. In an extreme scenario with no interconnector capacity the price signal of storing electricity and other fuels for transportation is not high enough. Hence, the stored capacity is not large enough to meet demands in longer periods of scarcity. It results in under production regardless of the costs for not meeting the demand. The three simulations performed with Denmark as an isolated system is therefore performed without the sequential planning module and therefore has perfect foresight for the whole year. The consequences are uncertain but it is discussed when analysing the results.

Figure 36 shows the socio economics for an average of the three European framework conditions for the base simulations compared to the isolated system with the global biomass potential available for “Conservative”, “Moderate” and “Full”. It shows that the CAPEX and OPEX of the system are increasing. This is especially a consequence of the increased investments discussed further below. Furthermore, the operating costs of the system increase especially due to increasing electricity prices as illustrated in Figure 38. The prices of the different fuels in the system increase in general, which also leads to increased revenue for the production units. In “Conservative”, the revenue increases more than the OPEX increases. Obviously there are no bottleneck revenues in the isolated system. On average the total system costs increase by 58 % when the system is isolated and only the global biomass potential is available compared to the average of the base simulations. It should however be noted that this percentage only refers to the costs included in the optimisation as discussed in *Key Results for all Scenarios*. Thus looking at the total system costs the relative increase would be significantly lower.

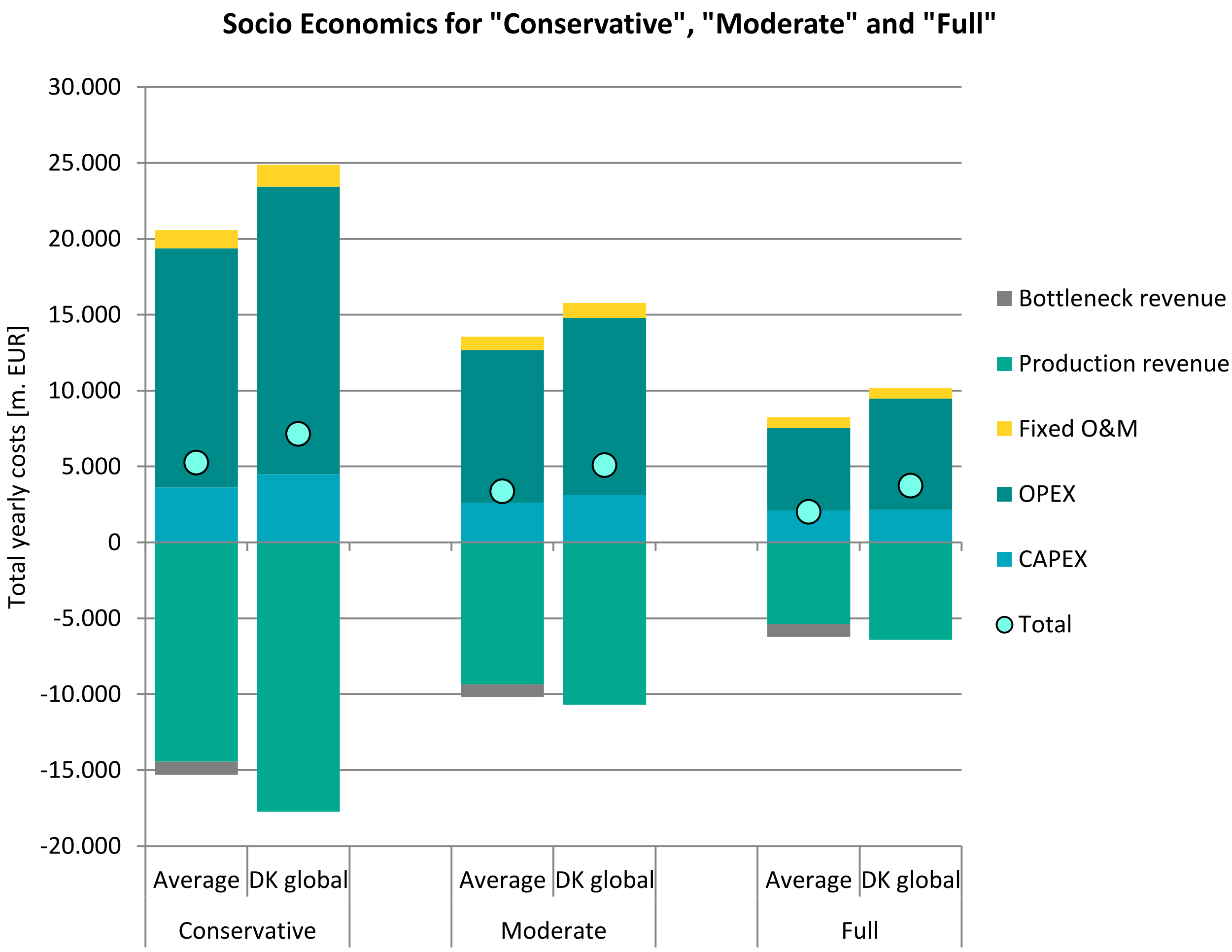


Figure 36 – Socio Economics for "Conservative", "Moderate" and "Full" for an average of the three European framework conditions for the base simulations compared to the isolated system with the global biomass potential available. The production revenue is included to avoid the reallocation of resources between production units as a socio economic cost, and externalities are not included either.

When analysing the increase in CAPEX in depth it is among other things due to an increase in invested storage and controllable power production capacity. As expected, the isolated system must have peak power units and larger storages to be able to balance the system in critical periods. In the isolated system for "Moderate" the gas turbines have a capacity of 3,328 MW and operate in what corresponds to 1072 hours of full load operation. For "Moderate" in the interconnected system the gas turbines have an average capacity of 864 MW but operate for what corresponds to 1,765 hours of full load operation. The higher number of operating hours in the interconnected system is because the electricity price is above the marginal cost of the gas turbines in more hours. The invested peak power capacity and battery storage for "Conservative", "Moderate" and "Full" for an average of the three European framework conditions for the base simulations compared to the isolated system with the global biomass potential is shown in Figure 37. The increased investments in controllable production units are caused by the removal of the interconnectors and the fixed trading price in the neighbouring price areas. It is even possible that the need for investments in the flexible production units is underestimated due to the nature of the ADAPT layer in the optimisation. The fact that the problem is LP-relaxed implies that the need for flexibility is underestimated since units can be partly turned on. For “Conservative” the additional investment in renewables is larger than for “Moderate” and “Full” to cover the larger demand for fuels for peak power capacity. As for the sensitivity analysis regarding the global biomass potential, the invested capacities in co-electrolysis and DAC increase. However, the invested capacity is even larger for the isolated system than for the interconnected system shown in Figure 33, hence the CAPEX are further increased. The interconnectors smoothen out the electricity price and act as a large reserve capacity at a fixed price. When isolated there are more hours with both very high and low electricity prices as seen on Figure 38. Especially the number of hours with high prices increases significantly. This is a natural consequence of the increased demand to be supplied by the national production units. It is also worth noticing that the price duration curve for the isolated system resembles the curve for GCA the most. This could be an indication that the GCA scenario is the scenario that best represent a similar development in the rest of Europe.

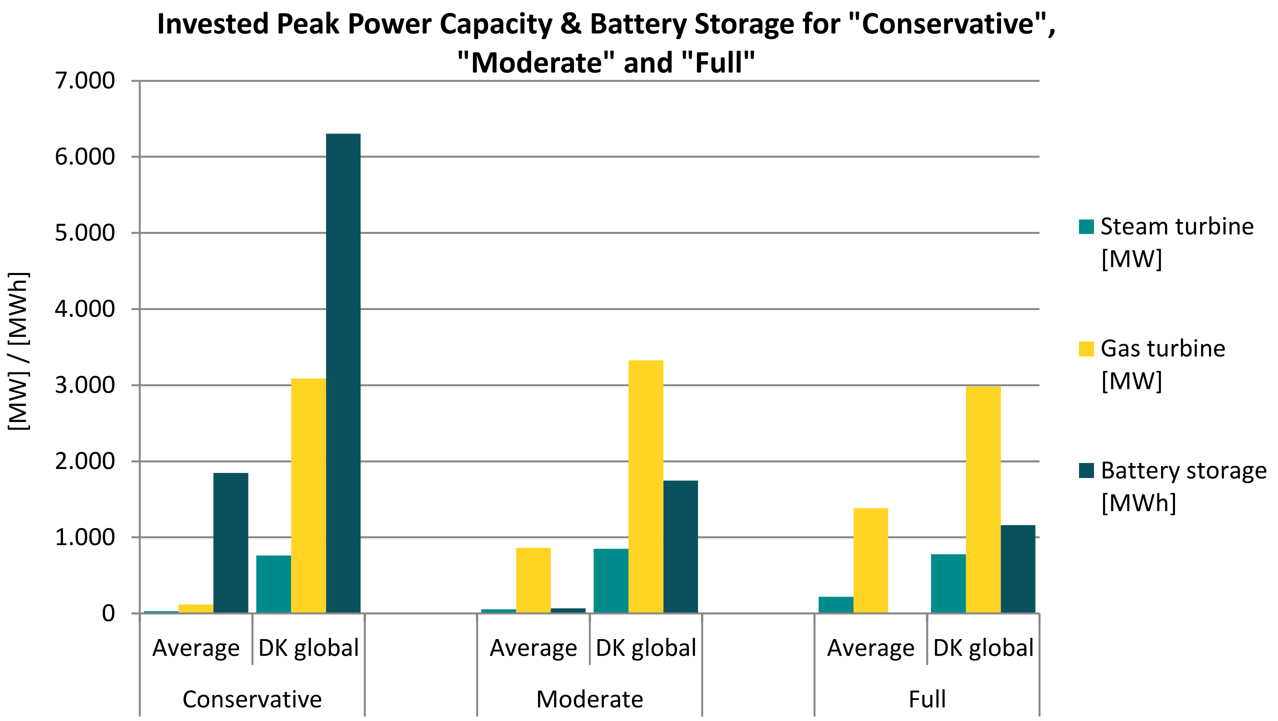


Figure 37 – Invested peak power capacity and battery storage for “Conservative”, “Moderate” and “Full” for an average of the three European framework conditions for the base simulations compared to the isolated system with the global biomass potential. The capacity is for the primary output of the production units.

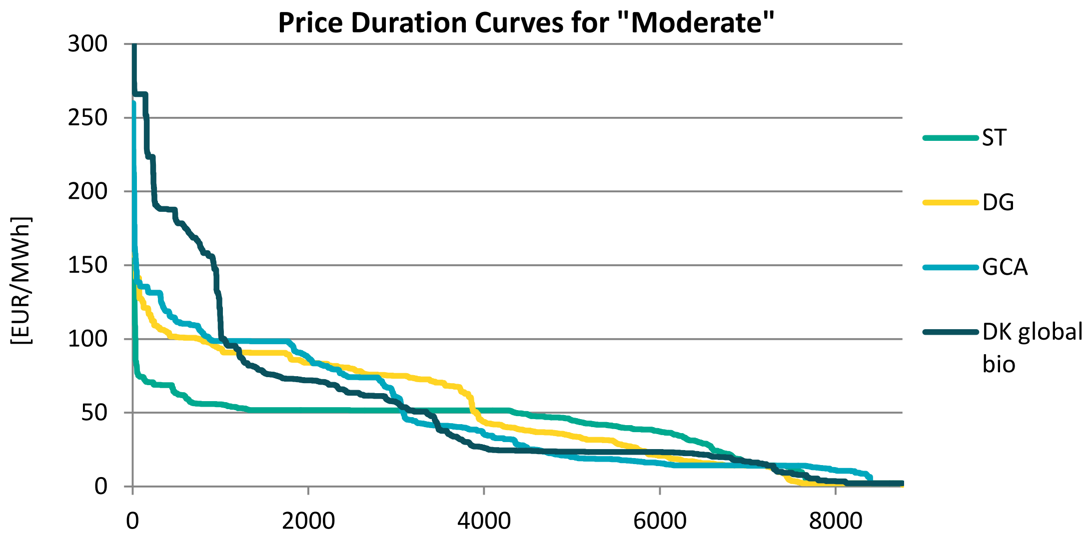


Figure 38 – Price duration curves for "Moderate" for the base simulations of ST, DG and GCA and for the isolated system with global biomass availability.

The electricity balance for the three European framework condition simulations for "Moderate" for the interconnected system is compared to the isolated system, all with the global biomass availability. It is shown in Figure 39. As evident from the figure, the total electricity consumption increases. It is because of the increased demand for electricity for production of fuels for balancing purposes and the shift from CNG to methanol because of the scarcity of methane. The increase in total consumption is relatively small, at least compared to what was expected. For fuel production it increases from an average of 26 TWh to 35 TWh in the isolated system.

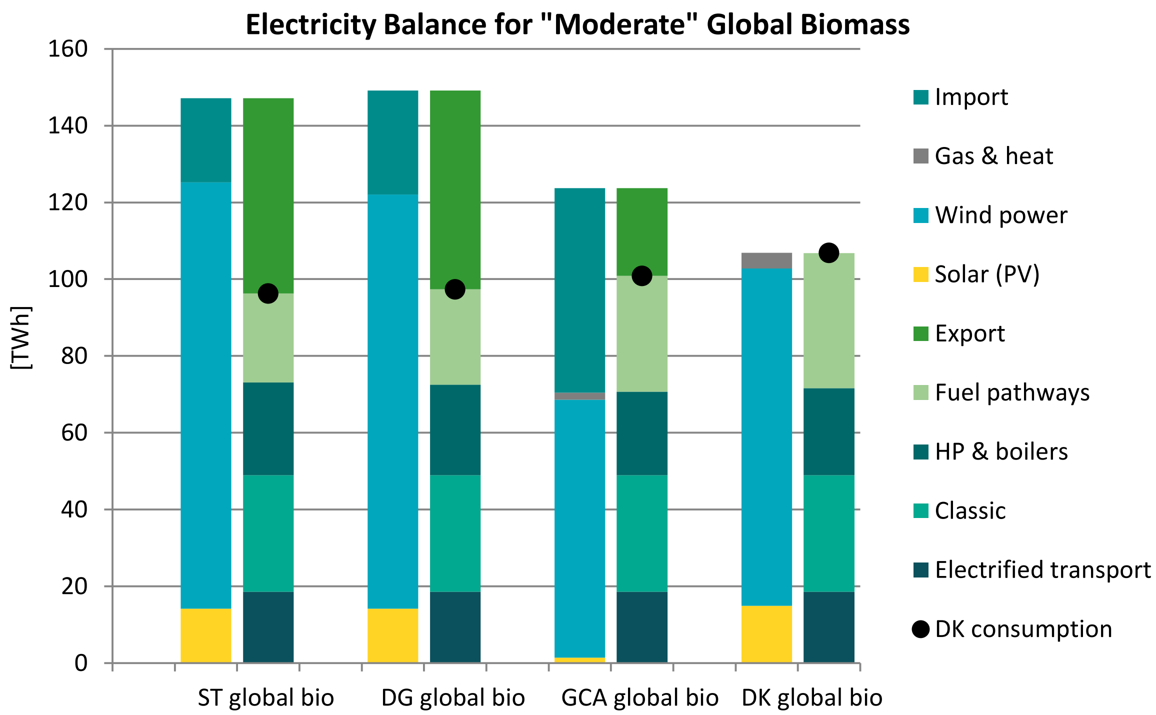


Figure 39 – Electricity balances for "Moderate" global biomass for ST, DG, GCA and the isolated system, DK.

As for the base simulations, a merit order curve for the produced fuels based on the weighted average costs of producing the fuel is shown for the isolated system in Figure 40. The weighted fuel production costs have increased compared to the interconnected system. Without the possibility to trade with the neighbouring price areas in long critical periods with high electricity prices it becomes necessary to either invest in over capacity of production units and storages or to produce despite high electricity prices. It results in an increase in the total cost of fuel production of 49 %, 46 % and 30 % for “Full”, “Moderate” and “Conservative” respectively. As reflected in the socio economic cost of the system. The isolated system is more expensive than the interconnected ones but it is possible to maintain the balance of the system, at least without the sequential planning layer. With only one week of foresight at the time and weak price signals for storing energy, the model could not balance the isolated system based on the investments made with perfect foresight. If the model is to keep the system in balance while running with the sequential planning layer, additional investments in renewables, storages and fuel producing units are most likely necessary, hence making the isolated system more expensive.

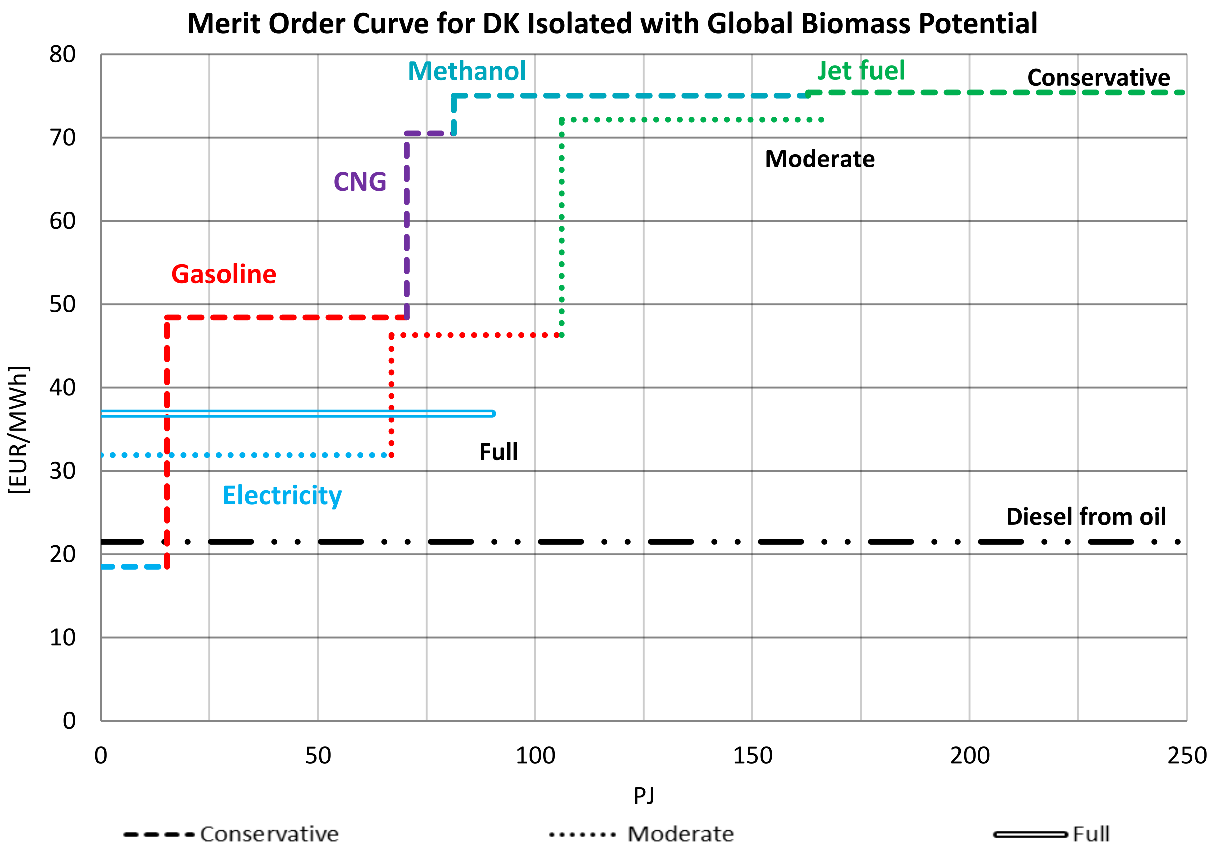


Figure 40 – Merit order curve for fuels for transportation for “Conservative”, “Moderate” and “Full”, for the isolated system with the global biomass potential, based on the weighted average production cost pr. primary output for all produced fuels. The specific fuels are represented by different colours shown as the colour of the text. The different scenarios are also represented with text. Diesel from fossil oil reserves without externality costs is shown as a reference.

10.4 International shipping

The DEA model used to project the transport demand does not include international shipping, as described in the section *Transportation Demand*. This is a large consumption that is omitted and thus to analyse the effect of this a sensitivity analysis is performed where international shipping is included. It is challenging to determine the demand from international shipping. A preliminary study from DTU indicates that the mechanical energy demand for international shipping in 2050 is around 35 PJ compared to a national demand around 2 PJ [117]. This implies an increase in the total mechanical energy for the transport demand of more than 50 %. Thus, the change is expected to have a significant impact on the system. Significant uncertainties are related to the projection. However, it is assumed to be accurate enough for the sensitivity analysis to see the effects on an aggregated level.

The sensitivity analysis is performed for DG “Full”, “Moderate” and “Conservative” with the domestic biomass potential since the major differences are expected to be between electrification scenarios rather than between European framework conditions. In “Full” the demand from international shipping is electrified as well. This is not expected to be a likely scenario, but again included as an extreme case. In “Moderate” and “Conservative” the entire demand for international shipping must be covered by carbonaceous fuels – the electrified part remains unchanged. The added demand is expected to be for heavy cargo for long distances and thus not suitable for electrification. It could be possible that some of the demand could be electrified, e.g. the part of the routes travelled in ports to reduce the emissions. This is however not included here.

The fuels consumed for transportation are illustrated in Figure 41 for both the base simulations and the sensitivity analysis simulations with international shipping. It is clear that the inclusion of international shipping has enormous impact on the results. In “Full” the electricity consumption is naturally just increased to cover the entire demand. For the first time LNG plays a role in satisfying the transportation demand in “Moderate”. When including the demand for international shipping, the gasoline by-product from the FT process is no longer sufficient to cover the remaining demands in the system. Thus, both methanol and LNG are produced as well. In this case where shipping constitutes such a large share of the total demand, the gas resources are used to produce LNG instead of CNG. When the gas resources are exhausted methanol is used to supply the remaining demand. In “Conservative”, where the gas resources are already used to supply demand in the form of CNG, LNG is not implemented. Instead, methanol is used to supply the increased demand from shipping. This is an example of a situation where the degree of electrification is decisive for the fuels produced in the system.

The amount of fuel needed naturally also influence the amount of carbon resources utilised in the system, as illustrated in Figure 42. In “Full”, where it is only the demand for electricity that changes, the impact on the carbon resources is insignificant. In “Moderate” and “Conservative”, the amount of carbon resources utilised increase significantly. In “Moderate” this leads to a full utilisation of the resources for thermal gasification as well as an increase in the use of DAC. This implies that it is cheaper to utilise thermal gasification than to just increase the amount of DAC, since the use of DAC affects the electricity prices. In “Conservative”, where the biomass resources are fully utilised already in the base simulation, the only possibility is to increase the use of DAC to supply the needed carbon.

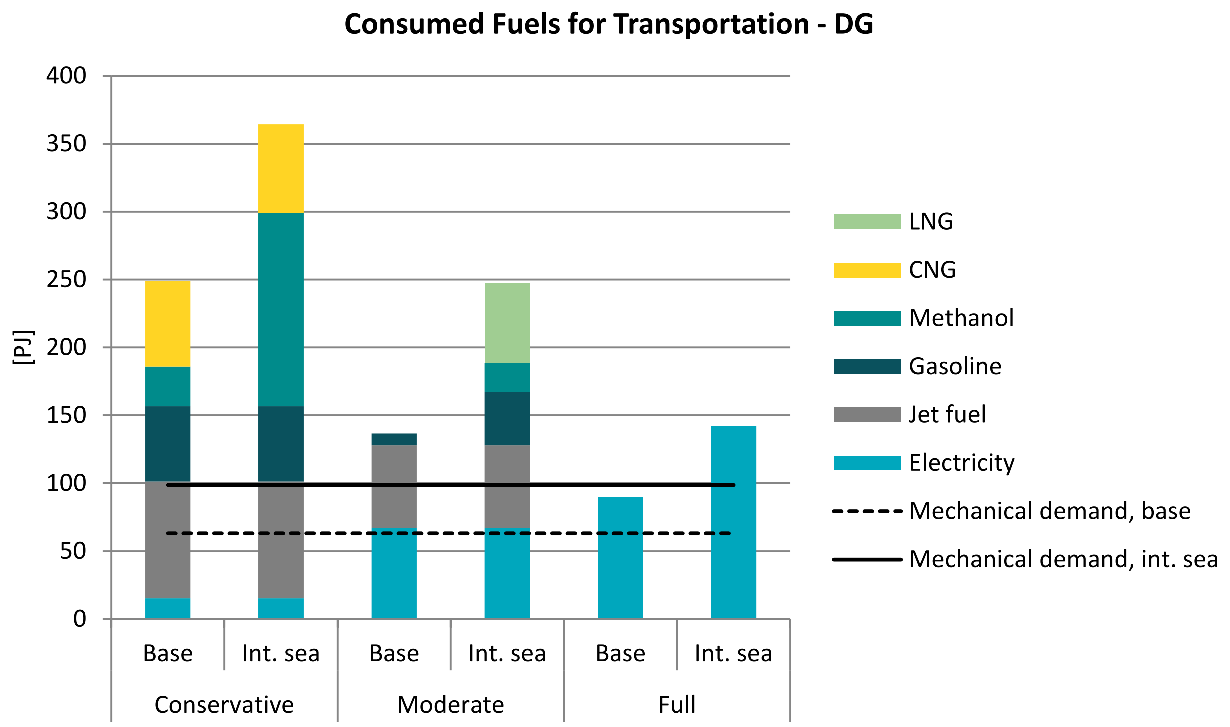


Figure 41 - Consumed fuels for transportation in DG for "Full", "Moderate" and "Conservative". Results are both from the reference simulations called "Base" and the sensitivity analysis including international shipping "Int. Sea".

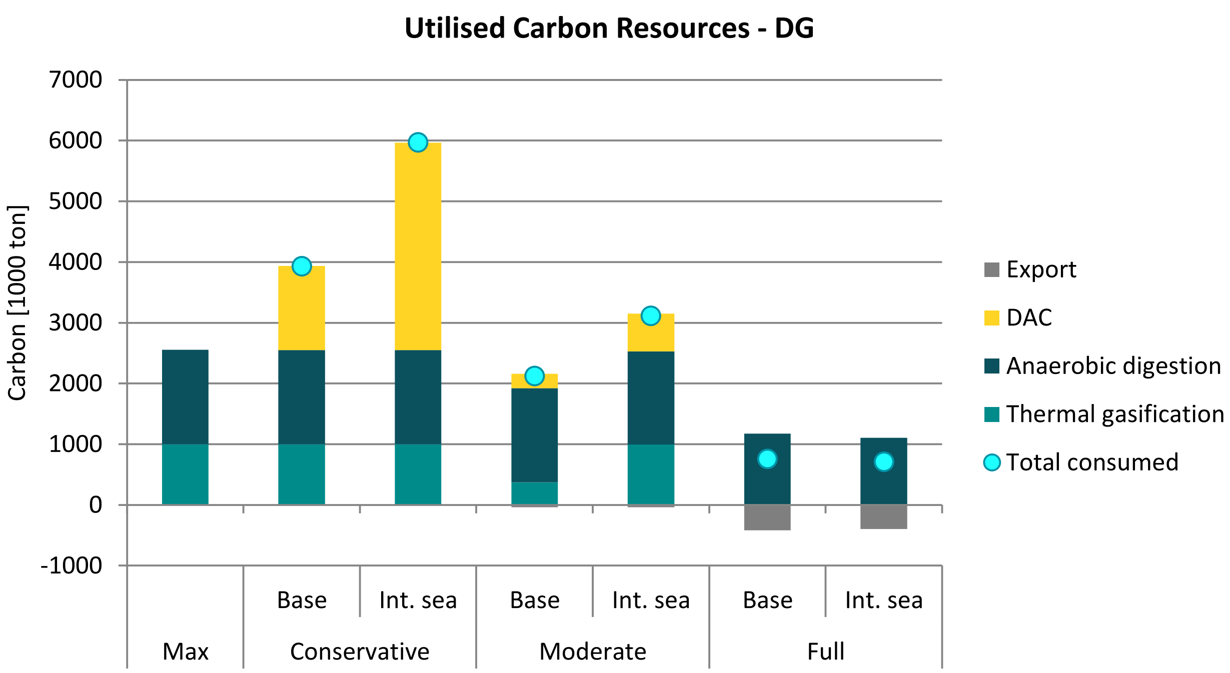


Figure 42 - Utilised carbon resources divided by harvesting technology in DG for "Full", "Moderate" and "Conservative". Results are both from the original simulations called "Base" and the sensitivity analysis including international shipping "Int. Sea". The domestic biomass resources are included as reference as "Max".

Naturally, the inclusion of international sea transport implies changes in the invested capacities as well. Mainly the investments in thermal gasification increase in “Moderate” and both DAC, co-electrolysis and electrolysis increases in both “Moderate” and “Conservative”. Furthermore, SMR is no longer used in “Moderate” since the gas resources can be utilised as LNG for transportation. The investments in renewable capacity increase as well to supply the increasing demand. Even the smaller and more expensive PV panels are used in “Conservative” since the technical maximum of 12 GW large PV panels is reached. The increased investments naturally also increase the socio economic costs. The costs increase on average 48 % for the three scenarios. It should be noted that this increase is based on the cost included in the optimisation and the relative increase would be smaller if all costs for the system were included. The changes in the price duration curve for electricity is especially clear in “Conservative” as illustrated in Figure 43. The level at which the prices are relatively constant is increased as well as the number of hours with this price level. This is a consequence of the large capacity of electricity consuming units such as electrolysis and DAC.

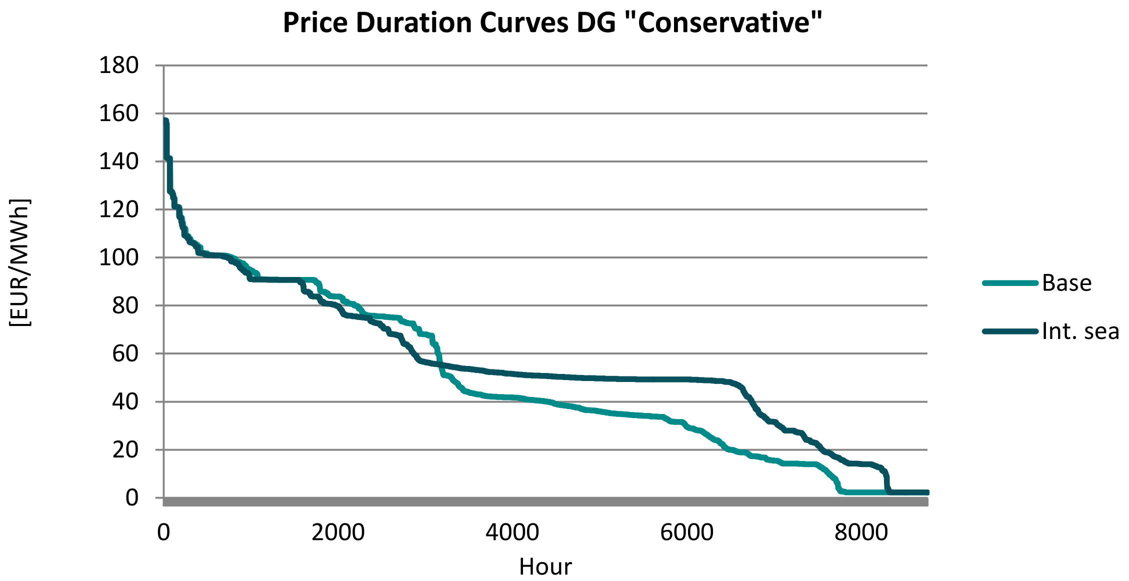


Figure 43 - Electricity price duration curves for DG "Conservative" - both for the base simulation and the sensitivity analysis simulation with international shipping.

A sensitivity analysis where all transport demands in the system are increased by 50 % and with the same share of electrification for all modes as for the base simulations is performed since the projection of the transport demands is related to large uncertainties. The analysis is performed for the same scenarios as for the international shipping sensitivity analysis. The resulting total demand for fuels is overall comparable to the demand from international shipping, especially in “Conservative” but with a different distribution between the fuels, as illustrated in Figure 44. The differences arise due to the increase in demand for jet fuel and the resulting increase in gasoline production. Thus, in “Moderate” there is still no need for other fuels than jet fuel and gasoline. In “Conservative” the increased gasoline production reduces the need for methanol while the amount of CNG remains unchanged. The other results and the impact on the electricity balance and price duration curves are very similar to the analysis with international shipping. The main differences are in the fuel synthesis used to produce the end fuels while the carbon resources are very similar.

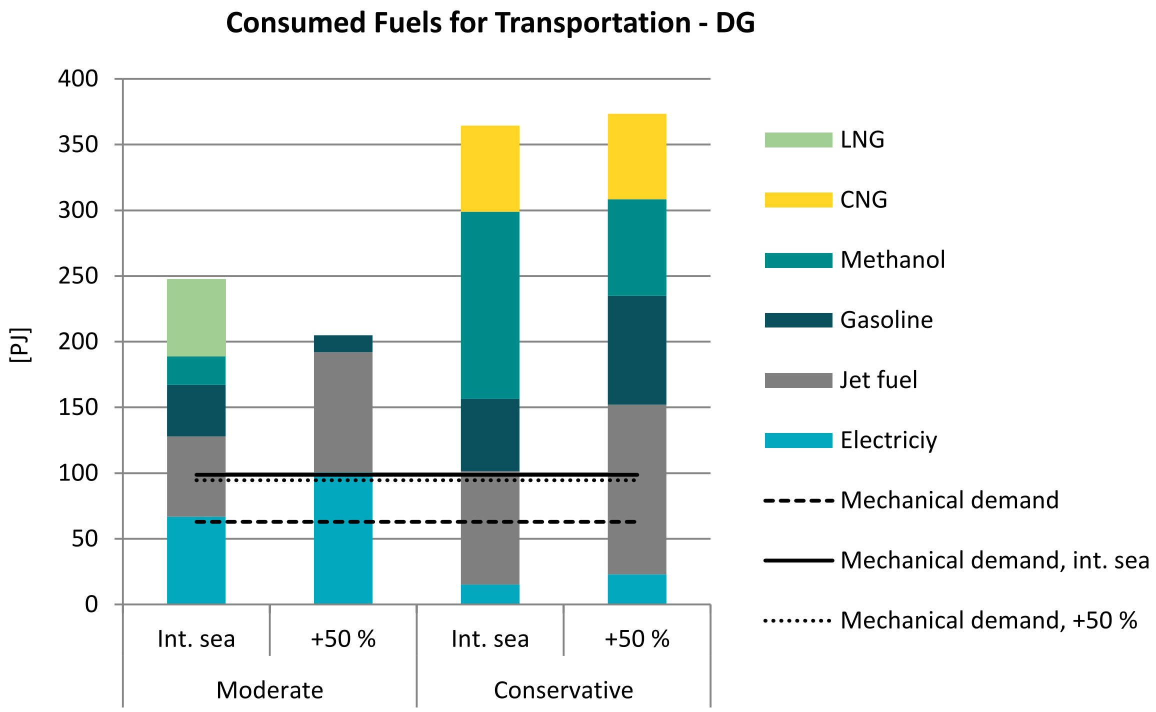


Figure 44 - Consumed fuels for transportation in DG "Moderate" and "Conservative" with international shipping and a 50 % increase in all transport.

The sensitivity analysis proves that it is essential for the system to include international shipping since it is an extremely large consumption that is otherwise omitted. Especially when looking at it from the angle where the solution should be exportable and feasible globally this demand cannot be neglected. Furthermore, it also showed that the system costs increase significantly when the transport demand increases. Thus, this demand is a key parameter with substantial impact on the results.

11 Discussion

The many assumptions regarding inclusions, delimitations and omissions of different aspects and technologies have given plenty of input to a discussion. The validity of the results from the many simulations is of course the main concern of the project. This discussion will attempt to turn every significant stone regarding decisions that have or might have influenced the results. Due to the many stones the discussion is split into subheadings, including aviation, delimitations, assumptions, modelling and realisation.

Aviation

The demand for aviation consists of 25 % of the projected mechanical transport demand in Denmark in 2050. When converting to the fuel consumption utilising the engine efficiencies the share increases. The system configuration is highly influenced by the gasoline by-product from production of jet fuel, as the only technology included that is able to produce jet fuel is the Fischer-Tropsch process. It is a very important conclusion of the project, though it can be affected by many factors. First, it is possible that another sustainable and renewable production pathway to produce jet fuel in large scale plants emerges in the near future. This is deemed unlikely, especially since the implementation of such a technology must reach a commercial state within the relatively short time period before the two degree goal of the Paris Agreement is breached. The three pathways to jet fuel omitted in the project, SIP, ATJ and HEFA, are not seen as potential winners because of the biomass input of oil or sugar. Hence, it will compete with food production. Second, the rigid standards for jet fuel may be lowered if the demand is difficult to satisfy in the future. It will give incitement for other fuels to join the market, e.g. LNG [118]. Both will influence the system a lot since the gasoline by-product will be reduced. It will open up the fuel markets for the non-electrified heavy road and sea transport for methanol, LNG, CNG, etc. Third, if the demand for jet fuel for aviation is going to be difficult and expensive to satisfy because of the dependency of a single technology, the demand may decrease. This will probably not have as large an affect as the first and second factor.

Delimitations

Hydrogen as a direct fuel and the fuel cell technology have been excluded in the project. It is based on the low energy density of hydrogen, even when hydrogen is compressed to 700 bar. Hence, hydrogen powered FC vehicles compete with the superior EVs [80], [81]. Furthermore, there is a large loss in the compression. It is theoretically possible to compress hydrogen from 1 to 700 bar, in an adiabatic compression with cooling of the gas between each stage to reach a more isothermal process, utilising approximately 13 % of the energy content in hydrogen [79]. At any pressure, the volumetric energy density of methane gas exceeds that of hydrogen by a factor 3.2 [79]. Nevertheless, if hydrogen FC vehicles were to penetrate the market instead of EVs for short and medium distance transportation on road it would affect the system marginally when analysing the total energy balance. The well-to-wheel efficiency for EVs is higher because of significant losses in the electrolysis, compression and FC, resulting in a larger electricity demand. The electricity is consumed by electrolysers and stored as hydrogen instead of being directly stored in batteries. However, with hydrogen storage the consumption of the electrolysers become more flexible than the charging of EVs as seen from the results of the project. Hence, the system configuration will not change significantly. On the other hand, if hydrogen supresses the use of carbonaceous fuels for short and medium distance transportation on road in the less electrified scenarios the system configuration will change. The decreased demand of carbon because of the shift from e.g. methanol to hydrogen reduces the demand for biomass resources and/or carbon from DAC. Either way it greatly reduces the complexity of the system by cutting the first and last part of the fuel production pathway off, the first part being the carbon source and the last the synthesis plant. Only the electrolysis in the middle endures. Furthermore, hydrogen FC plants could be used as peak power to balance the grid if the technology is developed for large scale and the price drops and hence decrease the demand for carbon even further. If the FC technology is also developed for methanol resulting in an increase of the engine efficiency from 23-31 % for the ICEs for the different transport modes to 50-60 %, the total fuel demand for methanol would decrease. It will obviously reduce the needed production capacity, consumption and costs for the system, while the system configuration is unaffected. Given that the FT process supplies the entire demand for jet fuel, FCs could only be applied in the least electrified scenarios since these are the only scenarios with a need for other fuels than electricity and jet fuel and gasoline from FT. As "Moderate" is deemed the most likely future scenario, the role of hydrogen as a fuel for transportation is limited.

When discussing hydrogen as a direct fuel for transportation, one should also include ammonia. It has not been included earlier because of a late discovery of the possibility. Hydrogen can together with atmospheric air at a synthesis plant, quite similar to that for methanol, be used to produce ammonia. The efficiency from electricity to ammonia in newly designed plants from Halder Topsøe[2] is found to be 71-72 % utilising SOEC electrolysis to obtain N_2 and H_2 as inputs for the synthesis. For transportation ammonia is used in FCs with comparable efficiencies to methanol powered FCs. Ammonia is not suited for everyday use for light duty vehicles due to security aspects, but it can be used in professional environments for long distance transportation for sea and heavy road. The LHV for ammonia is similar to that of methanol, equal to 5.18 and 5.54 kWh/kg respectively at standard conditions of 0 $°C$ and 1 bar [119]. When liquid the energy density of ammonia is close to that of LNG. Hence, ammonia gives the opportunity to further break the biomass bottleneck for the system since heavy and long distance transportation can be covered by carbon free fuels. If the technology becomes competitive the carbon source can potentially be excluded from the system except for non-energy purposes, aviation and the by-products from the production of jet fuel. This directs us towards another delimitation, namely neglecting the carbon demand for non-energy purposes. In [10] it is estimated that the future demand of biomass by the industry for production of chemicals and materials in Denmark will be up to 100 PJ. Hence, half of the domestic biomass residue potential could be unavailable for energy purposes. By taking the global average of potential biomass residues, then no biomass is available for energy purposes if the industry was to be satisfied first. In that case hydrogen and ammonia become very interesting to avoid massive utilisation of DAC.

In the model the excess production of gasoline from the FT process in "Ambitious" and "Moderate" is exported to a sink at a price of zero. The gasoline can potentially be a substitute for biomass in the chemical industry if not exported. It does not only contribute to a larger share of the biomass being available for energy and fuel purposes, it also solves the issue regarding export of gasoline to neighbouring countries if the global fuel demand for aviation is satisfied by the FT process. This will give a global excess production of gasoline if it is not utilised elsewhere. Nevertheless, the exported gasoline should introduce revenue to the society. As explained in the section *Modelling* this revenue is not included to avoid contortion of the investment decisions based on an uncertain gasoline price.

[2] Information from meeting with John Bøgild Hansen, Senior Scientist at Halder Topsøe.

From delimitation of fuels and technologies to the delimitation of cost of infrastructure. As the cost of infrastructure is assumed to be approximately equal across European framework conditions and electrification scenarios it is not included in the project. The assumption is based on the peak consumption for electricity in the system, which is almost identical. The maximum peak consumption is 31.5, 31.2 and 30.9 GW for DG "Full", "Moderate" and "Conservative" respectively. The yearly summed heat demands are increasing with the carbonaceous fuel production, from 39.3 TWh in DG "Full" to 50.8 and 58.9 TWh in "Moderate" and "Conservative" respectively. However, the process heat is assumed to be produced and consumed locally and the district heating demand is almost unchanged between the simulations. For methane, the yearly consumption that flows in the grid is 8.7, 18.9 and 19.0 TWh in DG "Full", "Moderate" and "Conservative" respectively. National grids for syngas, hydrogen, CO_2 and oxygen can be avoided by locating the fuel production plants strategically. As presented in [105], it is logical that the different plants are located together at e.g. an earlier power plant location close to district heating areas and transformer stations to the transmission lines or close to large renewable capacity. It is beneficial because of synergies to locate DAC, thermal gasification, electrolysis, synthesis plants, reforming plants, gas turbines, HPs and storages together. The anaerobic digestion is more difficult to locate centrally due to the biomass inputs from the agriculture but also less essential considering the possibilities of utilising synergies.

For the comparability of the socio economics to other energy system analyses, the infrastructure costs are calculated based on a "Back of an envelope" method. The method is to multiply the yearly flow of electricity, heat and methane in the grids by the present tariffs. The tariffs for transmission and distribution of electricity are found to be 10.8 and 45.7 EUR/MWh respectively [120], [121]. The tariff for district heating is found to be 16.7 EUR/MWh [122] and for methane it is 10.1 EUR/MWh based on an average of the different types of consumers [123]. The values for the tariffs can of course look very different in the future system, especially for flexible consumption that can help resolve internal bottlenecks or act as ancillary services. The total flow of electricity is, as shown in Figure 29, equal to 141 TWh in DG "Moderate". For the electricity grid it is assumed that half of the consumption only flows in the transmission grid and is not to pay the distribution tariff. Hence, the infrastructure cost for DG moderate becomes 5.02 billion EUR where the electricity grid constitutes 79 % of the total amount. In the DEA study "*Energiscenarier frem mod 2020, 2035 og 2050*" **[**39**]**, the yearly cost of operating and reinforcing the electricity grid is found to be 1.88 billion EUR corresponding to approximately half of the above found value. This almost corresponds to the difference in average electricity consumption for the simulation of this project of 91.2 TWh in DG compared to 57.2 TWh in the five DEA scenarios. The share of electricity assumed to flow in the distribution grid is possibly also too high, hence the costs should be reduced. Nevertheless, it is a significant cost that should be included in the modelling to include the possible contortion between invested capacities and difference between the scenarios. It is addressed in the section *Future Work*.

Regarding tariffs and omitted costs for the system, the fuel prices presented in the study are calculated without tariffs. Realistically, the tariffs should be included for inputs of electricity, heat and gas as it will increase the costs of production. The merit order curve for fuels for transportation shown in Figure 31 is recalculated to include the tariffs. The resulting plot is shown in Figure 64 in *Appendix I – Merit Order Curve for Fuels for Transportation with Tariffs.* The result of including the tariffs is that the production costs of the fuels increase by 20 to 40 %. The absolute increase in cost is quite equal across the simulations and fuels, hence the cheaper the fuel was in the original simulation the larger the relative increase is. When comparing to the fossil reference without externalities, diesel from oil, the gap between it and the renewable carbonaceous fuels increases. Hence, political involvement is still needed to promote the use of the renewable fuels, i.e. internalising the externalities of consumption of fossil fuels.

Regarding externalities, it was mentioned when analysing the socio economics presented in Figure 19 that externalities are not included since the energy system is neutral regarding emission of CO_2 from production of energy and fuels for transportation. However, other externalities such as local air pollution or noise from ICEs compared to EVs are also omitted. Furthermore, emissions and other externalities of the construction and decommissioning phases of plants and infrastructure are not included either. To find the exact socio economic cost of the modelled systems it is necessary to quantify and set a value for the externalities. Without externalities the cost of the found systems are for an unregulated renewable market, which is not necessarily the optimum. Externalities that differ across the different electrification scenarios and therefore should be included to be able to compare the socio economics of the simulations are local air pollution from CHPs and ICEs and noise pollution from ICEs. The result would be an ever larger favouritism of EVs and electrification of the transportation sector. However, it is not in the scope of the project.

Assumptions

The DAC TSA technology plays a central role in many of the simulations of the project, not only in the least electrified ones. However, the technology is not fully developed and only one plant is currently operating. The data for the technology used in the project are based on assumptions. Climeworks, the company behind the technology, revealed the expected reduction of CAPEX and the inputs and outputs of the process at a visit at the plant currently operating[3]. The predictions are very close to the data used in the project, hence it is reassured that the data is realistic while still having in mind that they are supplied by a commercial company selling the technology. If this, or other DAC technologies, do not reach a commercial level, it will in fact not be possible to balance the carbon supply in all scenarios without utilising other non-carbonaceous fuels such as hydrogen or ammonia. In this case decarbonisation through increased electrification of the transport sector becomes even more vital.

The European framework conditions are based on assumptions regarding the development of the European energy systems. The three different scenarios, ST, DG and GCA, are all included to see the effect of the varying electricity prices. However, it is most likely that if the energy system in Denmark develops towards being 100 % renewable, the same development happens in the surrounding countries. GCA is the scenario representing this development the most. In TYNDP18 in BID GCA has a large share of renewables but only little flexible consumption. It results in many hours with very low electricity prices across Europe. If electrolysers and other fuel production technologies penetrate the market in Denmark, it is unrealistic that it does not penetrate the markets in the surrounding countries. This will have a cannibalising effect on the electricity price and the incentive of investing in flexible consumption. The ideal European framework conditions could have been found from an iterative process by using the European Framework conditions to model the electricity price in the neighbouring price areas. In Sifre it is used as in input and results in invested capacities and yearly consumptions, as done in this project. However, if done for all European countries the BID model can be updated with data for the energy system. The European framework conditions will change

[3] Information from Anders Winther Mortensen and Kasper Dalgas Rasmussen – P.hD. students at KBM SDU.

accordingly which gives new results for invested capacities and yearly consumptions in Sifre. The process could be repeated until the changes in the results of the Sifre model are insignificant compared to the previous iteration. It will reduce the uncertainty regarding the input electricity prices but it is a very time consuming process, even for a single set of input electricity prices for a single electrification scenario. As identified from the sensitivity analysis with 50 % interconnector capacity it is expected that more realistic prices for Europe would reduce the invested DAC capacity as a result of the cannibalising effect on the electricity prices.

Another assumption is the possible utilisation of the different types of biomass. It relates to an error found late in the process for the CAPEX and fixed O&M for the anaerobic digestion. It was mistakenly set too low, however not unrealistically low. Due to limited time and resources it is not corrected but only discussed in the section *Future* Work. In the model, straw can only be used as an input for anaerobic digestion and not thermal gasification. Based on the uncertain estimates for the CAPEX for the investment in both technologies it could be beneficial to be able to use the straw as an input in the thermal gasification plants as well. If the future costs of the thermal gasification and anaerobic digestion become more equal, the model would be able to optimise the utilisation of the straw resource. This would however also effect the composition of the biogas since the methane content in the biogas changes when the inputs change. It would be challenging to model a varying biogas composition depending on the straw input to the digester. The use of straw for thermal gasification would also affect the recirculation of nutrients to the fields, hence the whole straw resource should not be utilised in thermal gasification. For the optimal allocation of the straw resource the value of the nutrients returned to the fields should thus also be included in the optimisation.

Modelling

Having touched upon the modelling, the effect of the simplified structure of the model will be discussed. The implemented technologies are represented by a single unit. The time of simulating increases rapidly when running the Sifre investment module, ADAPT, for a lot of technologies. It was therefore not possible to model the units as smaller geographically split capacities. The effect of having a single very large unit compared to many smaller is greater utilisation of the invested capacities, both for production and storage units. Ideally there would not be any difference, since the large units in the model operate to reduce the total cost of the system and the small commercial units in reality should be price takers in perfect markets. However, realistically the smaller units make irrational decisions and do often not contribute to lowering the costs to a minimum, especially in the longer course over a year when operating storages. It is partially reflected in Sifre with the sequential planning module that reduces the perfect foresight of units from a whole year to a week at the time. Since irrational behaviour cannot be modelled and the comparison is based on other studies that have the same uncertainty, it is not further discussed.

As mentioned, with the large units in the model it was not possible to model geographical challenges of the energy system. This also includes the location of plants to ensure the possibility of utilising the synergies. The model is simulated with the possibility to utilise output streams from all units as input streams for all units. It is assumed to have a minor effect on the configuration and cost of the energy system as most of the units probably will be located together. Some negligible costs are excluded, e.g. for transporting CO_2 produced at an anaerobic digestion plant where the CO_2 is stripped and utilised as input for co-electrolysis.

Realisation

The last part of the discussion regards the realisation of a 100 % renewable energy system with synthetic fuels to solve the issue of green transportation. First, the technologies included in the model must be developed and the costs driven down to a minimum, e.g. for DAC, SOEC electrolysis and thermal gasification. As 2050 is the year of simulation the assumed technology development is deemed realistic, in fact maybe a little conservative. A newly published report from Agora on the future cost of synthetic fuels reveals expectations for lower CAPEX than assumed in this project for DAC, SOEC electrolysis and the FT synthesis based on literature studies for 2050 [124]. The development of the technologies must be driven by financial support to R&D and political stability. Additional political initiatives are necessary to pave the way for synthetic fuels and a 100 % renewable energy system. Political consensus or agreement to phase out the use of fossil coal, oil and gas and to keep fossil reserves in the ground, or a comprehensive global emissions trading scheme including transportation and industry will both provide strong incentive for the market to invest in EVs and synthetic fuels. The *EU Fuel Quality Directive* and *EU Renewable Energy Directive* are examples of present directives that must become more ambitious in the future to the lead the way [125], [126]. If the market is to optimise the energy sector it is also important to incentivise the most efficient and cost-effective available technologies in each segment of each sector, e.g. EVs for transportation and HPs for heating. Furthermore, it will become necessary to introduce sustainability regulations regarding the use biomass and other carbon sources so only biogenic residual biomass resources and CO_2 from DAC or industrial processes is utilised.

All in all, even at this stage no significant elements have been identified that question the results in this project. Based on the best available knowledge the system modelled in this project is still deemed a possible outcome for a future 100 % renewable energy system. Still, the project acknowledges that the time frame is long and significant technological developments are necessary before a 100 % renewable system can become reality.

12 Conclusion

The goal of the project has been to investigate the possibilities of designing a 100 % sustainable transport system within the boundaries of a 100 % renewable energy system and to investigate the influence of varying framework conditions. The main conclusion is that, given the assumptions made in the project, it is in fact possible to design a sustainable energy system including transportation independent of the framework conditions.

Different European framework conditions were included to analyse the effects of them. They were found to have a significant impact on the investments in both renewable capacity and the optimal capacity of other production units in the system. In general varying electricity prices, or just low electricity prices, entails a larger investment in DAC and co-electrolysis, where more stable prices lead to full utilisation of the biomass resources through anaerobic digestion and thermal gasification. It was found that through investments in renewable production capacity it is possible to achieve similar weighted average electricity prices across the different European conditions. This in turn leads to similar fuel prices. The decisive factor for the fuel prices and the total cost of satisfying the fuel demand was found to be the degree of electrification of the transport sector. The fuel prices naturally reflects the socio economic costs of the system which are illustrated for all the systems optimised in the heat map in Table 9.

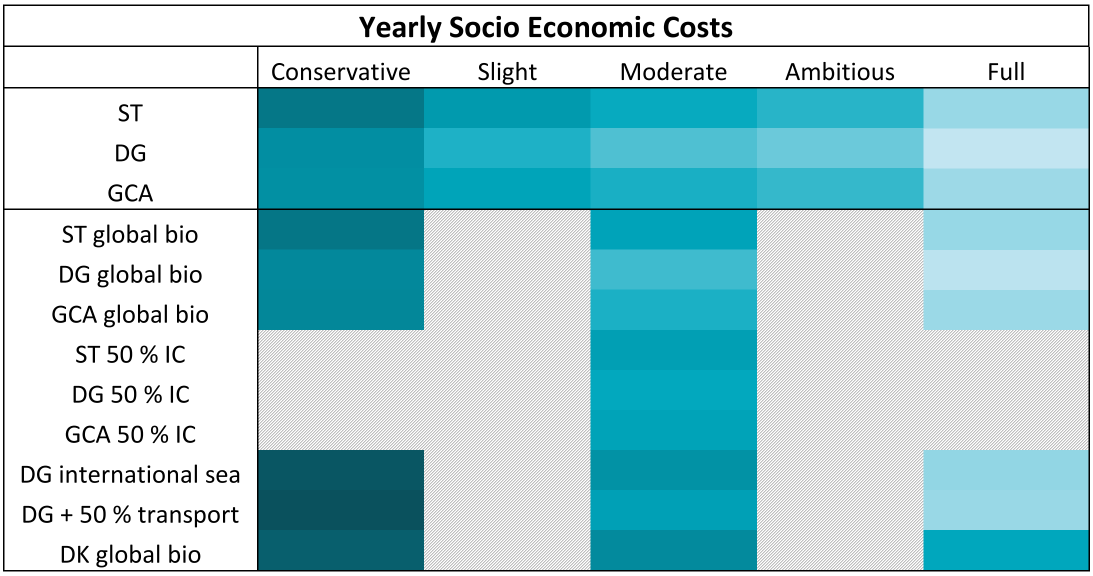


Table 9 - Heat map representing yearly socio economic costs without externalities where dark blue represents the highest costs and light blue the lowest. The shaded areas represent scenarios that have not been simulated.

The three top rows represent the original simulations and the remaining rows the sensitivity analyses. The shaded areas represent scenarios that have not been simulated. From the heat map it is clear that the system costs and thus the fuel costs decrease when the degree of electrification increases. This substantiates the initial assumption that electrification would be the cheapest alternative to fossil fuels. As mentioned it is however not expected that it will be possible to electrify the entire transport sector as it is the case in the "Full" scenario. The analysis does however show the value in continuing the research and development within the area to achieve as large a degree of electrification as possible. It is also important to stress that even the "Conservative" scenario represents a significant increase from the current level of electrification. The analysis thus shows that if the degree of electrification does not increase from the present level it will have severe consequences for the costs of achieving a 100 % sustainable energy system. The degree of electrification in the three more likely scenarios, “Ambitious”, “Moderate” and “Slight”, varies from 52 % to 84 % of the total mechanical transport demand and the socio economic costs vary 28 %. Hence, the initial enrolment of EVs gives a slightly larger socio economic benefit than the final. The sensitivity analyses furthermore show that cost of the “Moderate” scenario, which is assumed to be the most likely scenario, are relatively stable even with varying boundary conditions. The costs of the isolated system with global biomass resources are however relatively large for all electrification scenarios.

One of the key elements in the system is the supply of carbon for fuels. It has been found that neither direct air capture nor thermal gasification is utilised in the system before the biogas resources have been exhausted. With the limited biomass resources the direct air capture technology is a vital part of the system. The technology enables a sufficient carbon supply to the system no matter what restrictions you enforce. E.g. if the biomass potential is reduced to the global potential or the degree of electrification is limited, the DAC technology can always supply carbon resources. This is illustrated in the heat map in Table 10 where the lightest green represents no carbon from DAC and the darkest green the scenario with the most carbon from DAC. It is obvious that the less electrification of the transport, the larger utilisation of carbon from DAC. The project has also identified certain conditions at which DAC can compete with thermal gasification when it comes to carbon supply. With both the DG and GCA framework conditions, DAC is implemented before the resources for thermal gasification have been exhausted in the three medium electrification scenarios. This implies that varying electricity prices are beneficial for DAC. The hours with low prices can be utilised for production of resources from which you can earn a profit when producing fuels for transportation or balancing the grid in hours with high prices. The sensitivity analyses show that the capacity of DAC to some extent is dependent on the possibility to import a large amount of power from neighbouring countries at low prices. However, even with 50 % interconnector capacity, DAC was implemented before exhausting all the biomass resources.

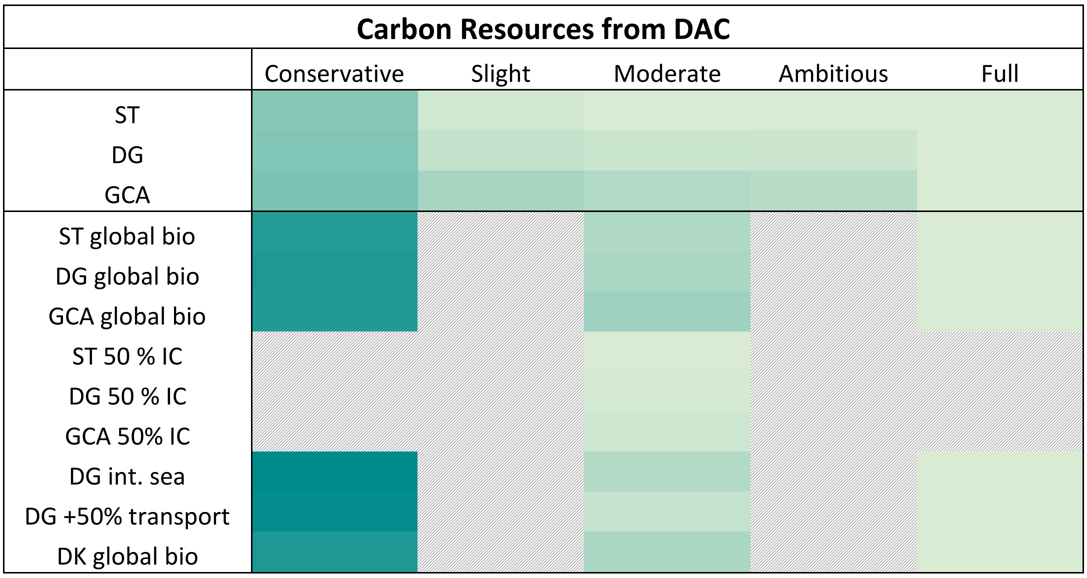


Table 10 - Heat map representing carbon resources utilised from direct air capture where dark green represents the largest resources and light green the smallest or none. The shaded areas represent scenarios that have not been simulated.

Another key technology in the system is the FT process which is the only technology included able to supply jet fuel for aviation. The gasoline by-product from the process makes the technology decisive for the results since no other synthetic fuels are needed in the “Full”, “Ambitious” and “Moderate” scenarios. If alternative technologies for jet fuel production proves to replace the FT process this would naturally also affect the rest of the system. The result would however primarily be an increased investment in methanol synthesis to provide methanol, for the transport demands that are not covered by the gasoline by-product from FT anymore. Since the inputs to the methanol synthesis are the same as for the FT process, namely syngas and hydrogen, the implications for the remaining system is expected to be limited. If the FT process however turns out to be the best solution for the production of jet fuel, it would have severe consequences if this was not included in the plans for the transition to renewable transport. If the transition starts with the part that may seem easier to transform, e.g. light or heavy road, it could lead to large investments in technologies that would prove to be redundant when implementing the FT process for jet fuel production.

The project has optimised and analysed the transport sector in the context of the entire energy system implying that both the heating and electricity sectors have been included as well. The analyses show that it is important to analyse and optimise the entire energy system together and not one sector at the time. If e.g. the electricity sector was optimised from an isolated perspective it would likely show a need for relatively large peak power capacity to balance the system. When optimising it from a system perspective as done in this project, it is found that the need for peak power capacity is quite limited. By utilising the flexibility in the storage options for heat and gas and not taking the consumption profile as a given it is possible to balance the system without large peak power capacity. In a 100 % renewable energy system a large share of the electricity consumption can operate flexibly according to the production from renewables. Also in the heat sector synergies can be achieved by connecting it with the transport sector since several of the fuel production units have an excess heat production that can be utilised for process or district heating. Thus, the system perspective can prevent investments in both heat and power capacity, which would also compete for the limited carbon resources in the system.

The fuel prices determined in the project in all scenarios are significantly higher than the pure production cost of fossil diesel. Only electricity would deliver mechanical energy at a price below that of fossil diesel. It is important to state that the price of diesel does not include externalities. When including the externalities, the renewable fuels were found to be more price competitive given the assumptions made in this report regarding efficiencies, CAPEX etc. Thus if the right tax scheme or another political tool is implemented, internalising the costs of externalities, the renewable fuels should be able to compete with fossil alternatives in a 100 % renewable energy system. This is however based on a technological development within several key technologies in the system allowing them to reach a certain cost and efficiency level in the long run. Therefore, it is assumed that there will be a period, where taxes or subsidies are needed to promote the production of renewable fuels for transport and kick-start the development. As it has been seen for wind turbines in Denmark, support and subsidies in the beginning of the technological development can drive the technologies to a place where they are able to compete on market conditions as well as provide export opportunities and growth for the Danish society.

Future Work

Throughout the project, specific points to pay attention to have been identified. Some of the points would have been included if the time allowed it and some are for future work in continuation of the project.

Late in the project it was identified that the CAPEX and fixed O&M used for the anaerobic digestion for biogas production were too low. Due to time limitations, numerous scenarios and extensive simulation time it was not possible to implement this correction. For future work a research should be made to identify the best estimate for the long-run costs of a biogas plant to implement in the model. Based on the simplicity of the biogas plant and the low cost of inputs for the plant it is however expected that the biogas resources would still be the cheapest carbon resource in the system. Therefore, the impact on the distribution between the carbon resources and the corresponding invested capacities is expected to be limited. Hence, the increased costs of the biogas production will almost be equal for all simulations and no large contortion between the socio economics will occur.

As mentioned in the *Discussion*, tariffs on all energy carriers in the system have been omitted from the modelling. This was chosen due to challenges in determining the future tariffs, due to an expectation that the total costs for the system would be comparable across scenarios and most importantly due to modelling challenges. In the *Discussion,* the total cost for the infrastructure which would be covered by tariffs was attempted quantified from the perspective that the total costs are comparable across the scenarios. Even if this in fact is the case, it could influence the system if the tariffs had been included. E.g. the OPEX of large electricity consuming units such as DAC and electrolysis would be highly affected by tariffs, especially DAC with low primary output efficiency. Hence, the inclusion of tariffs might influence the distribution between the different technologies in the system. As for the tariffs, externality costs have been omitted from the modelling, as mentioned in the *Discussion*. The cost of externalities will differ across the electrification scenarios, and it will influence the configuration of the system. For the system to be a true-cost socio economic optimal solution the externalities should have been included as well. For the difference between EVs and ICE vehicles the effect would be limited since the distribution between the two types of vehicles is fixed by the electrification scenarios. A difference could however arise when looking at the different possibilities for fuel production. All-electric synthetic fuels with no biomass input would result in fewer local emissions and pollutants and thus lower costs of externalities. This implies that the inclusion of externalities could influence the balance between e.g. thermal gasification and DAC as carbon sources. Thus for a more accurate and true-cost optimisation both the tariffs and externalities should have been included in the modelling.

As addressed in the *Discussion* technological developments as well as political actions are needed for the realisation of the system presented in this project. Even though the fuel pathways have proven to supply fuels at prices that, to some degree, are competitive with a fossil reference, these prices are based on expectations to the development of the technologies in the long run. This development does not come for free. It needs funds for R&D as well as a stable political environment to encourage investments. It is not within the scope of this project to further qualify these needs, but it is essential for the future work to get a better understanding of what is needed for a sustainable energy system as the one presented in this project to be realised. This includes an assessment of which technologies are essential for the system and which can be omitted as well as a logical order for the development and implementation of the different technologies. This would provide a pathway from the current energy system to a future 100 % sustainable energy system.

The most essential thing for the future work is undoubtedly to maintain an updated insight within technological developments in order to stay on top of changes in input parameters, new relevant technologies or technologies that do not live up to the expectations in this project. Attention should especially be paid to the development within electrified transportation since this is one of the key parameters with crucial impact on the optimal configuration of the entire energy system.

13 References

[1] B. V. Mathiesen, H. Lund, and P. Nørgaard, "Integrated transport and renewable energy systems," *Util. Policy*, vol. 16, no. 2, pp. 107–116, 2008.
[2] P. A. Østergaard and K. Sperling, "Towards Sustainable Energy Planning and Management," *Int. J. Sustain. Energy Plan. Manag.*, vol. 1, no. 0, pp. 1–5, 2014.
[3] D. Connolly, B. V. Mathiesen, and I. Ridjan, "A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system," *Energy*, vol. 73, pp. 110–125, 2014.
[4] International Energy Agency, "CO2 Emissions From Fuel Combustion Highlights," *IEA Stat.*, p. 158, 2013.
[5] IEA, "Key World Energy Statistics 2016," *Statistics (Ber).*, p. 80, 2016.
[6] C. Gutiérrez-Antonio, F. I. Gómez-Castro, J. A. de Lira-Flores, and S. Hernández, "A review on the production processes of renewable jet fuel," *Renew. Sustain. Energy Rev.*, vol. 79, no. January, pp. 709–729, 2017.
[7] United Nations, *Paris Agreement*, vol. 21932, no. December. 2015.
[8] B. V. Mathiesen *et al.*, "Smart Energy Systems for coherent 100% renewable energy and transport solutions," *Appl. Energy*, vol. 145, pp. 139–154, 2015.
[9] I. Ridjan, B. V. Mathiesen, and D. Connolly, "Synthetic fuel production costs by means of solid oxide electrolysis cells," *Energy*, vol. 76, pp. 104–113, 2014.
[10] H. Wenzel, "Breaking the biomass bottleneck of the fossil free society," *Concito*, pp. 1–34, 2010.
[11] ENTSO-E and ENTSOG, "TYNDP 2018 Scenario Report," 2018.
[12] Energistyrelsen, "Forbrugsmodel 2016 med 2020 som startår - 24_08_16." .
[13] V. Mathiesen, M. Pagh, N. Scott, P. Skougaard, and N. Scott, *CEESA 100% Renewable Energy Transport Scenarios Towards 2050: Technical Background Report Part 2.* 2014.
[14] The Danish Energy Agency, "Technology Data for Energy Plants," 2012.
[15] L. Raslavičius, M. Starevičius, A. KerŠys, K. Pilkauskas, and A. Vilkauskas, "Performance of an all-electric vehicle under UN ECE R101 test conditions: Afeasibility study for the city of Kaunas, Lithuania," *Energy*, vol. 55, pp. 436–448, 2013.
[16] N. Juul and P. Meibom, "Road transport and power system scenarios for Northern Europe in 2030," *Appl. Energy*, vol. 92, pp. 573–582, 2012.
[17] Z. Li and M. Ouyang, "The pricing of charging for electric vehicles in China-Dilemma and solution," *Energy*, vol. 36, no. 9, pp. 5765–5778, 2011.
[18] P. Finn, C. Fitzpatrick, and D. Connolly, "Demand side management of electric car charging: Benefits for consumer and grid," *Energy*, vol. 42, no. 1, pp. 358–363, 2012.
[19] Danish Energy Agency and Cowi, *Alternative drivmidler*. 2013.
[20] Energistyrelsen and Energinet.dk, "Technology Data for Energy Plants, updated 2017," 2012.
[21] M. Moser *et al.*, "Synthetic Liquid Hydrocarbons from Renewable Energy – Results of the Helmholtz Energy Alliance," *Chemie-Ingenieur-Technik*, vol. 89, no. 3, pp. 274–288, 2017.
[22] I. Ridjan, B. V. Mathiesen, D. Connolly, and N. Duić, "The feasibility of synthetic fuels in renewable energy systems," *Energy*, vol. 57, pp. 76–84, 2013.
[23] A. Tremel, P. Wasserscheid, M. Baldauf, and T. Hammer, "Techno-economic analysis for the synthesis of liquid and gaseous fuels based on hydrogen production via electrolysis," *Int. J. Hydrogen Energy*, vol. 40, pp. 11457–11464, 2015.
[24] D. H. König, N. Baucks, and R.-U. Dietrich, "Simulation and evaluation of a process concept for the generation of synthetic fuel from CO2 and H2," *Energy*, vol. 91, pp. 833–841, 2015.
[25] Q. Fu, C. Mabilat, M. Zahid, A. Brisse, and L. Gautier, "Syngas production via high-temperature steam/CO 2 co-electrolysis: an economic assessment," *Energy Environ. Sci.*, 2010.
[26] M. Larsson, S. Grönkvist, and P. Alvfors, "Synthetic Fuels from Electricity for the Swedish Transport Sector: Comparison of Well to Wheel Energy Efficiencies and Costs," *Energy Procedia*, no. 75, pp.

1875–1880, 2015.
[27] G. Liu, B. Yan, and G. Chen, "Technical review on jet fuel production," *Renew. Sustain. Energy Rev.*, vol. 25, pp. 59–70, 2013.
[28] I. Dimitriou, P. Garcí a-Gutié rrez, R. H. Elder, R. M. Cué llar-Franca, A. Azapagic, and R. W. K Allen, "Carbon dioxide utilisation for production of transport fuels: process and economic analysis," *Energy Environ. Sci. Energy Environ. Sci*, vol. 8, no. 8, pp. 1775–1789, 2015.
[29] C.-M. Gong, K. Huang, J.-L. Jia, Y. Su, Q. Gao, and X.-J. Liu, "Improvement of fuel economy of a direct-injection spark-ignition methanol engine under light loads," *Fuel*, vol. 90, no. 5, pp. 1826–1832, 2011.
[30] Sasol, "Sasol achieves approval for 100% synthetic jet fuel," 2008. [Online]. Available: http://www.sasol.com/media-centre/media-releases/sasol-achieves-approval-100-synthetic-jet-fuel. [Accessed: 02-Feb-2018].
[31] Cambridge Dictionary, "Sustainability Definition," *Defintion Sustainability*. 2016.
[32] PÖYRY, "PÖYRY ELECTRICITY MARKET MODELLING BID3."
[33] Energinet, "SIFRE : Simulation of Flexible and Renewable Energy sources."
[34] Energinet.dk, "Hvad påvirker elpriserne i Danmark?," 2016.
[35] Energinet, "COBRAcable: Elforbindelse til Holland." [Online]. Available: https://energinet.dk/Anlaeg-og-projekter/Projektliste/COBRAcable.
[36] Energinet, "Viking Link: Elforbindelse til Storbritannien." [Online]. Available: https://energinet.dk/Anlaeg-og-projekter/Projektliste/Viking-Link.
[37] European Commission, "2050 low-carbon economy," 2018. [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2050_en.
[38] Pöyry Management Consulting AS, "BID3 Manual."
[39] Energistyrelsen, "Energiscenarier frem mod 2020, 2035 og 2050," 2014.
[40] F. M. Andersen, L. P. Hansen, A. L. Bender, C. Olsen, C. M. V Larsen, and T. Thomsen, "EMMA10. Energi- og miljømodeller til ADAM," 2010.
[41] Energistyrelsen, *Energistatistik 2016*. 2016.
[42] Energistyrelsen, "EnergiBalanceModel (EBM). Offentlig udgave." .
[43] Energistyrelsen, "Baggrundsrapport til basisfremskrivning 2017," Copenhagen, 2017.
[44] J. W. Schultz and S. Huard, "Comparing AC Induction with Permanent Magnet motors in hybrid vehicles and the impact on the value proposition," pp. 1–15, 2013.
[45] VVT, "Vehicle energy efficiencies," *IEA EGRD Work.*, 2013.
[46] European Commission, *EU Reference Scenario 2016: Energy, Transport and GHG emissions trends to 2050*. 2016.
[47] Ea Energy Analyses and SDU, "Biogas og andre VE brændstoffer til tung transport Analyse af muligheder og udfordringer ved udfasning," 2016.
[48] H. Lund *et al.*, *Coherent Energy and Environmental System Analysis*. 2011.
[49] Energistyrelsen, "Analyse af bioenergi i Danmark," 2014.
[50] F. Creutzig *et al.*, "Bioenergy and climate change mitigation: An assessment," *GCB Bioenergy*, vol. 7, no. 5. pp. 916–944, 2015.
[51] IEA, "Energy Technology Perspectives 2017," 2017.
[52] The World Bank, "World Population," 2017. [Online]. Available: https://data.worldbank.org/indicator/SP.POP.TOTL. [Accessed: 21-Apr-2018].
[53] G. Meyer, R. Bucknall, and D. Breuil, *Electrification of the Transport System*. 2017.
[54] Energinet, "Energikoncept 2030 - Baggrundsrapport," 2015.
[55] B. V. Mathiesen, H. Lund, and K. Karlsson, "IDAs Klimaplan 2050," 2009.
[56] A. Huss, H. Maas, and H. Hass, "TANK-TO-WHEELS Report Version 4.0," Luxembourg, 2013.
[57] G. Crabtree, E. Kócs, and L. Trahey, "The energy-storage frontier: Lithium-ion batteries and beyond," *MRS Bull.*, vol. 40, no. 12, pp. 1067–1076, 2015.
[58] G. Berckmans, M. Messagie, J. Smekens, N. Omar, L. Vanhaverbeke, and J. Van Mierlo, "Cost

projection of state of the art lithium-ion batteries for electric vehicles up to 2030," *Energies*, vol. 10, no. 9, 2017.
[59] Danmarks Statistik, "Persontransportarbejde med fly efter transporttype." [Online]. Available: www.statistikbanken.dk/FLYV36. [Accessed: 26-Feb-2018].
[60] Danmarks Statistik, "Passagerer på udenrigsflyvninger efter rejselængde, flyvning og enhed." [Online]. Available: www.statistikbanken.dk/FLYV35. [Accessed: 26-Feb-2018].
[61] Danmarks Statistik, "National vejgodstransport efter enhed, kørselsart, vogntype/totalvægt, bilens alder og turlængde." [Online]. Available: 'www.statistikbanken.dk/NVG1. [Accessed: 26-Feb-2018].
[62] Danmarks Statistik, "International vejgodstransport efter enhed, vogntype/totalvægt, bilens alder og turlængde." [Online]. Available: www.statistikbanken.dk/IVG1. [Accessed: 26-Feb-2018].
[63] Danmarks Statistik, "Persontransport efter transportmiddel." [Online]. Available: www.statistikbanken.dk/PKM1. [Accessed: 26-Feb-2018].
[64] Danmarks Statistik, "National vejgodstransport efter enhed, kørselsart, vogntype/totalvægt, bilens alder og turlængde." [Online]. Available: 'www.statistikbanken.dk/NVG1.
[65] Danmarks Statistik, "International vejgodstransport efter enhed, vogntype/totalvægt, bilens alder og turlængde." [Online]. Available: www.statistikbanken.dk/IVG1.
[66] Danmarks Statistik, "Persontransport efter transportmiddel." [Online]. Available: www.statistikbanken.dk/PKM1.
[67] DTU, "Biltrafik i Danmark," pp. 30–31, 2014.
[68] U. S. D. of Energy, "Alternative Aviation Fuels: Overview of Challenges, Opportunities, and Next Steps," 2016.
[69] D. Sniderman, "New Options Emerge for Aviation Fuel," 2011. [Online]. Available: https://www.asme.org/engineering-topics/articles/aerospace-defense/new-options-emerge-for-aviation-fuel. [Accessed: 21-Sep-2017].
[70] P. Schmidt, W. Weindorf, A. Roth, V. Batteiger, and F. Riegel, "Power-to-Liquids Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel," 2016.
[71] K. Moirangthem, *Alternative Fuels for Marine and Inland Waterways*. 2016.
[72] EA Energianalyse, "Grøn Roadmap 2030 - Scenari er og virkemidler til omstilling af transportsektorens energiforbrug," 2015.
[73] S. Siegemund, "The potential of electricity-based fuels for low-emission transport in the EU An expertise by LBST and dena," 2017.
[74] J. Goodstein and C. Bonnerup, "Maskinmesteren - Samsø ferry fueled by LNG," 2015.
[75] T. Stensvold, "Verdens største containerskib skal sejle på gas," *Ingeniøren*, 2017. [Online]. Available: https://ing.dk/artikel/verdens-stoerste-containerskib-skal-sejle-paa-gas-209604. [Accessed: 12-Mar-2018].
[76] Energy Research Centre of the Neherlands, "Liquified Natural Gas in trucks and cars," *Climate Technology Centre & Netwrork*. [Online]. Available: https://www.ctc-n.org/technologies/liquefied-natural-gas-trucks-and-cars. [Accessed: 08-Mar-2018].
[77] G. Jacobs and B. H. Davis, "Conversion of Biomass to Liquid Fuels and Chemicals via the Fischer–Tropsch Synthesis Route," in *Thermochemical Conversion of Biomass to Liquid Fuels and Chemicals*, M. Crocker, Ed. 2010, pp. 95–124.
[78] W. L. Becker, R. J. Braun, M. Penev, and M. Melaina, "Production of Fischer-Tropsch liquid fuels from high temperature solid oxide co-electrolysis units," *Energy*, vol. 47, no. 1, pp. 99–115, 2012.
[79] S. S. Makridis, "Hydrogen storage and compression," in *Methane and Hydrogen for Energy Storage*, no. June, 2016, pp. 1–28.
[80] T. Seba, "Toyota vs Tesla: Can hydrogen fuel-cell cars compete with EVs?," *RenewEconomy*, 2016. [Online]. Available: https://reneweconomy.com.au/toyota-vs-tesla-can-hydrogen-fuel-cell-cars-compete-with-evs-11540/. [Accessed: 28-May-2018].
[81] S. Blanco, "Electric cars win on energy efficiency vs hydrogen, gasoline, diesel: analysis," *Green Car Reports*, 2017. [Online]. Available: https://www.greencarreports.com/news/1113175_electric-cars-

win-on-energy-efficiency-vs-hydrogen-gasoline-diesel-analysis. [Accessed: 28-May-2018].
[82] Shell, “Shell Aviation Fuels,” *Shell.Com*.
[83] JIG, “Product Specifications - Bulletin,” no. 29, 2016.
[84] Transport- Bygnings- og Boligministeriet, “Bestemmelser om tankning af luftfartøjer , tankningspersonale / tankningstjeneste og tankningsanlæg (BL 3-6 Udgave 3),” vol. 2010, no. 9736. 2018.
[85] T. Radich, “The Flight Paths for Biojet Fuel,” *Indep. Stat. Analy*, 2015.
[86] E. C. Wormslev *et al.*, “Sustainable jet fuel,” 2016.
[87] SkyNRG, “Systainable aviation fuel - Technology Section.” [Online]. Available: http://skynrg.com/technology-section/. [Accessed: 12-Mar-2018].
[88] UK Ministry of Defence, “UK Defence Standard 91-91,” vol. 2015, no. 7, 2011.
[89] IATA, “IATA Guidance Material for Sustainable Aviation Fuel Management,” Montreal-Geneva, 2015.
[90] A. Faaij and M. van Dijk, “White Paper on Sustainable Jet Fuel,” *SkyNRG*, no. June, pp. 1–19, 2012.
[91] A. B. Hansen and Energinet, “System Perspective 2035 - Modelling of Energy Plants - Bilagsrapport,” 2018.
[92] Bigadan, “Sådan fremstilles biogas,” *Bigadan*. [Online]. Available: https://bigadan.dk/p/om-bigadan. [Accessed: 14-Mar-2018].
[93] J. Witte, T. J. Schildhauer, A. Calbry-Muzyka, S. M. A. Biollaz, and A. Kunz, “Biomass for Power-to-Gas : Direct Methanation of Biogas,” *Biosweet Conf.*, 2017.
[94] M. I. Sosa, J. L. Silveira, and A. Fushimi, “Natural gas steam reforming for hydrogen production. An energetic approach,” *17th Int. Congr. Mech. Eng.*, 2003.
[95] C. J. Meinrenken and K. S. Lackner, “Options to dissociate CO2 and H2O for sustainable pathways: Comparative assessment of current R&D hurdles and future potential,” *J. Nat. Sci.*, vol. 3, no. 1, pp. 19–54, 2015.
[96] C. Graves, S. D. Ebbesen, M. Mogensen, and K. S. Lackner, “Sustainable hydrocarbon fuels by recycling CO2 and H2O with renewable or nuclear energy,” *Renew. Sustain. Energy Rev.*, vol. 15, pp. 1–23, 2010.
[97] B. Magill, “World’s First Commercial CO2 Capture Plant Goes Live,” *Climate Central*, 2017. [Online]. Available: http://www.climatecentral.org/news/first-commercial-co2-capture-plant-live-21494. [Accessed: 03-Oct-2017].
[98] Eric Johnson, “Carbon capture from ambient air goes commercial,” *Chemical Reviews*, 07-Sep-2017. [Online]. Available: https://www.chemistryworld.com/business/carbon-capture-from-air-goes-commercial/3007813.article. [Accessed: 03-Oct-2017].
[99] IPCC, “Carbon Dioxide Capture and Storage,” 2005.
[100] C. Malins, “What role is there for electrofuel technologies in European transport ’ s low carbon future ?,” no. November, 2017.
[101] P. R. Schmidt *et al.*, “Renewables in Transport 2050 Empowering a sustainable mobility future with zero emission fuels from renewable electricity,” 2016.
[102] Cameron LNG, “LNG and liquefication.” [Online]. Available: http://cameronlng.com/lng-liquefaction.html. [Accessed: 14-Mar-2018].
[103] D. Altenpohl, “Compressed Natural Gas (CNG): Potential Applications for Advanced Transportation Tanks and Vehicle Systems,” *Appl. Syst.*, no. June, 1988.
[104] U.S. Department of Energy, “Hydrogen Production: Natural Gas Reforming.” [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming. [Accessed: 19-May-2018].
[105] A. B. Hansen and Energinet, “Baggrundsrapport Systemperspektiv 2035,” 2018.
[106] Energinet, “SIFRE : Simulation of Flexible and Renewable Energy sources.” .
[107] Energinet, “ADAPT : Analyseværktøj for Et Samfundsøkonomisk Effektivt Energisystem,” 2014.
[108] Energinet, “Energinets modeller - ADAPT.” [Online]. Available: https://energinet.dk/Analyse-og-Forskning/Beregningsmodeller. [Accessed: 02-Mar-2018].

[109] Energinet.dk, "Analyse af potentialet for landvind i Danmark i 2030," 2015.

[110] A. P. E. York, J. B. Claridge, C. Márquez-Alvarez, A. J. Brungs, and M. L. H. Green, "Group (V) and (VI) transition metal carbides as new catalysts for the reforming of methane to synthesis gas," in *ACS Division of Fuel Chemistry, Preprints*, 1997, vol. 42, no. 2, pp. 606–610.

[111] M. Morandin and S. Harvey, "Methanol via biomass gasification," 2015.

[112] Knoema, "Cost of producing a barrel of crude oil by country - knoema.com," 2014. [Online]. Available: https://knoema.com/rqaebad/cost-of-producing-a-barrel-of-crude-oil-by-country. [Accessed: 04-Jul-2017].

[113] U. Remme, M. Blesl, and U. Fahl, "Global resources and energy trade: An overview for coal, natural gas, oil and uranium," Stuttgart, 2007.

[114] WSJ News Graphics, "WSJ News Graphics." .

[115] British Petroleum, "BP Statistical Review of World Energy 2017," *Br. Pet.*, no. 66, pp. 9–12, 2017.

[116] G. Santos, "Road fuel taxes in Europe: Do they internalize road transport externalities?," *Transp. Policy*, vol. 53, no. November 2016, pp. 120–134, 2017.

[117] System Analysis Division - DTU and M. B. Simonsen, "Internally estimated value by DTU." 2017.

[118] R. A. Roberts, S. R. Nuzum, and M. Wolff, "Liquefied natural gas as the next aviation fuel," in *13th International Energy Conversion Engineering Conference*, 2015.

[119] The Engineering ToolBox, "Fuels - Higher and Lower Calorific Values." [Online]. Available: https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html. [Accessed: 14-Mar-2018].

[120] Energinet, "Aktuelle Tariffer." [Online]. Available: https://energinet.dk/El/Tariffer. [Accessed: 20-May-2018].

[121] Dansk Energi, "Fakta: Nettarifferne er faldet," 2017. [Online]. Available: https://www.danskenergi.dk/nyheder/fakta-nettarifferne-er-faldet. [Accessed: 20-May-2018].

[122] TREFOR, "Tariffer Fjernvarme – TREFOR Varme," 2017.

[123] Dansk Gas Distribution, "Distributionstarif," 2016.

[124] A. Lövenich *et al.*, "The Future Cost of Electricity-Based Synthetic Fuels: Conclusions Drawn by Agora Verkehrswende and Agora Energiewende.," 2018.

[125] European Parliament, "Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009," *Off. J. Eur. Union*, vol. 140, no. 16, pp. 16–62, 2009.

[126] European Parliament, *Directive 2009/30/EC of the European Parliament and of the Council*. 2009.

[127] Banedanmark, "Om elektrificering." [Online]. Available: https://www.bane.dk/da/Borger/Baneprojekter/Elektrificeringsprogrammet/Om-elektrificering. [Accessed: 22-Feb-2018].

[128] Banedanmark, "Banedanmark elektrificerer," 2014.

[129] CIA, "The world factbook - Denmark," 2018. [Online]. Available: https://www.cia.gov/library/publications/the-world-factbook/geos/da.html#Trans. [Accessed: 22-Feb-2018].

[130] Z. Shahan, "10 Electric Cars With Most Range — New! –," *EV Obsession*, 2017. [Online]. Available: https://evobsession.com/10-electric-cars-range-new/. [Accessed: 26-Feb-2018].

[131] S. Bachmann, "VW-topchef: Nu kommer elbilen til almindelige bilbrugere," *Børsen*, 2017. [Online]. Available: http://pleasure.borsen.dk/bilen/artikel/1/353918/vw-topchef_nu_kommer_elbilen_til_almindelige_bilbrugere.html. [Accessed: 26-Feb-2018].

[132] C. Tryggestad, N. Sharma, J. van de Staaij, and A. Keizer, "New reality: electric trucks and their implications on energy demand," *Energy Insights By McKinsey*. [Online]. Available: https://www.mckinseyenergyinsights.com/insights/new-reality-electric-trucks-and-their-implications-on-energy-demand. [Accessed: 26-Feb-2018].

[133] F. Lambert, "Daimler starts delivering all-electric trucks in Europe," *Electrek2*, 2017. .

[134] J. Muller, "Cummins Beats Tesla To The Punch, Unveiling Heavy Duty Electric Truck," *Forbes*, 2017. [Online]. Available: https://www.forbes.com/sites/joannmuller/2017/08/29/take-that-tesla-diesel-

engine-giant-cummins-unveils-heavy-duty-truck-powered-by-electricity/#5782fafd78f1. [Accessed: 26-Feb-2018].
[135] F. Lambert, "Daimler unveils its first all-electric eTruck: 26 tonnes capacity, massive 212 kWh battery for ~125 miles of range," *Electrek2*, 2016. [Online]. Available: https://electrek.co/2016/07/27/daimler-etruck-first-all-electric-truck-125-miles-range/. [Accessed: 26-Feb-2018].
[136] F. Lambert, "Volvo announces that it will put electric trucks on the road this year," *Electrek*, 2018. [Online]. Available: https://electrek.co/2018/01/24/volvo-electric-trucks/. [Accessed: 26-Feb-2018].
[137] A. Vance, "This Electric Truck Will Probably Beat Tesla's to Market," *Bloomberg Businessweek*, 2017. [Online]. Available: https://www.bloomberg.com/news/articles/2017-12-13/this-electric-truck-will-probably-beat-tesla-s-to-market. [Accessed: 26-Feb-2018].
[138] Z. Estrada, "Daimler shows off an electric truck ahead of Tesla," *The Verge*, 2017. [Online]. Available: https://www.theverge.com/2017/10/25/16548638/daimler-electric-truck-e-fuso-vision-one-concept. [Accessed: 26-Feb-2018].
[139] T. Randalll and J. Lippert, "Tesla's Newest Promises Break the Laws of Batteries," *Bloomberg Technology*, 2017. [Online]. Available: https://www.bloomberg.com/news/articles/2017-11-24/tesla-s-newest-promises-break-the-laws-of-batteries. [Accessed: 26-Feb-2018].
[140] O. R. Valmot, "Kæmpebatterier giver elbus rækkevidde på 300 km," *Ingeniøren*, 2017. [Online]. Available: https://ing.dk/artikel/kaempebatteri-giver-elbus-raekkevidde-paa-300-km-207733. [Accessed: 14-Mar-2018].
[141] K. L. Jørgensen, "Roskilde først med elektriske busser på alle ruter," *Ingeniøren*, 2018. [Online]. Available: https://ing.dk/artikel/roskilde-foerst-med-elektriske-busser-paa-alle-ruter-211032. [Accessed: 14-Mar-2018].
[142] Ship Technology, "Ampere Electric-Powered Ferry," *Ship Technology*, 2015. [Online]. Available: https://www.ship-technology.com/projects/norled-zerocat-electric-powered-ferry/.
[143] F. Lambert, "Two massive ferries are about to become the biggest all-electric ships in the world," *Electrek*, 2017. [Online]. Available: https://electrek.co/2017/08/24/all-electric-ferries-abb/. [Accessed: 26-Feb-2018].
[144] Ærø kommune, "El-færgeprojektet E-ferry - Grundfakta." [Online]. Available: http://www.el-færgeprojekt.dk/om-e-ferry/grundfakta. [Accessed: 28-Feb-2018].
[145] Ærø kommune, "Om E-ferry." [Online]. Available: http://www.el-færgeprojekt.dk/om-e-ferry. [Accessed: 28-Feb-2018].
[146] Energy Supply, "Danish Ferries Are Riding the Green Wave," *State of Green*, 2017. .
[147] E. Adams, "The Age of Electric Aviation is Just 30 Years Away," *Wired*, 2017. [Online]. Available: https://www.wired.com/2017/05/electric-airplanes-2/. [Accessed: 26-Feb-2018].
[148] F. Lambert, "Airbus' E-Fan is the first electric plane to successfuly fly across the English Channel," *Electrek*, 2015. [Online]. Available: https://electrek.co/2015/07/13/airbus-e-fan-electric-plane-fly-across-english-channel/. [Accessed: 26-Feb-2018].
[149] F. Lambert, "Airbus partners with Rolls-Royce and Siemens to build an electric airplane," *Electrek*, 2017. [Online]. Available: https://electrek.co/2017/11/28/airbus-partners-rolls-royce-siemens-build-electric-plane/. [Accessed: 26-Feb-2018].
[150] F. Lambert, "Electric plane startup steps out of stealth mode to announce plan for 150-seat battery-powered plane," *Electrek*, 2017. [Online]. Available: https://electrek.co/2017/03/22/electric-plane-startup-150-seat-battery-powered-plane/. [Accessed: 26-Feb-2018].
[151] S. Hanley, "Wright Electric Planning Short Haul Electric Airplane Within Ten Years," *Gas2*. [Online]. Available: http://gas2.org/2017/03/29/wright-electric-airplane-ten-years/. [Accessed: 26-Feb-2018].
[152] T. Turula, "Norwegian aviation boss: 'Commercial electric airplanes a reality by 2025,'" *Business Insider Nordic*, 2017. [Online]. Available: https://nordic.businessinsider.com/norwegian-aviation-boss-commercial-electric-airplanes-could-be-reality-by-2025-2017-9/. [Accessed: 26-Feb-2018].
[153] Energistyrelsen, "Alternativ Drivmiddel - model." 2018.

[154] Argonne National Laboratory (ANL), “Case Study - Liquefied Natural Gas,” 2013.
[155] M. Hepperle, “Electric Flight–Potential and Limitations,” 2012.
[156] P. Wu, “Marine Propulsion Using Battery Power,” 2016.
[157] International Maritime Organization, “Methanol as marine fuel: Environmental benefits, technology readiness, and economic feasibility,” 2016.
[158] P. Spath, A. Aden, T. Eggeman, M. Ringer, B. Wallace, and J. Jechura, “Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier,” 2005.
[159] I. Hannula, *Hydrogen production via thermal gasification of biomass in near-to-medium term*. 2009.
[160] J. B. Hansen and M. Mogensen, “GreenSynFuels,” 2011.
[161] Energinet.dk and Danish Energy Agency, “Technology Data for energy carrier generation and conversion June 2017,” 2017.
[162] Y. Zhang, “Anaerobic digestion system: Energy balance,” 2013.
[163] R. Mei, T. Narihiro, M. K. Nobu, K. Kuroda, and W. T. Liu, “Evaluating digestion efficiency in full-scale anaerobic digesters by identifying active microbial populations through the lens of microbial activity,” *Sci. Rep.*, vol. 6, pp. 1–10, 2016.
[164] The Engineering ToolBox, “Gases - Density.” [Online]. Available: https://www.engineeringtoolbox.com/gas-density-d_158.html. [Accessed: 14-Mar-2018].
[165] A. Martin, D. Türks, H. Mena, and U. Armbruster, “Hydrogenation of carbon dioxide to synthetic natural gas : impact of catalyst bed arrangement 二氧化碳加氢合成天然气 ： 催化剂床安排之影响,” vol. 3, no. 1, pp. 25–30, 2016.
[166] N. B. Rasmussen, “Technologies relevant for gasification and methanation in Denmark,” 2012.
[167] M. Götz *et al.*, “Renewable Power-to-Gas: A technological and economic review,” *Renew. Energy*, vol. 85, pp. 1371–1390, 2016.
[168] M. Götz, A. M. Koch, and F. Graf, “State of the Art and Perspectives of CO2 Methanation Process Concepts for Power-to-Gas Applications,” *Int. Gas Union Res. Conf.*, 2014.
[169] J. Jechura, “Hydrogen from Natural Gas via Steam Methane Reforming (SMR),” 2015.
[170] M. Melaina and M. Penev, “Hydrogen Station Cost Estimates - Comparing Hydrogen Station Cost Calculator Results with other Recent Estimates,” *Natl. Renew. Energy Lab.*, 2013.
[171] F. Zeman, “Energy and material balance of CO2 capture from ambient air,” *Environ. Sci. Technol.*, vol. 41, no. 21, pp. 7558–7563, 2007.
[172] J. Wilcox, “Direct Air Capture,” *CCS Leaders Forum*, 2016. .
[173] Q. Fu, C. Mabilat, M. Zahid, A. Brisse, and L. Gautier, “Syngas production via high-temperature steam/CO 2 co-electrolysis: an economic assessment,” *Energy Environ. Sci.*, vol. 3, no. 10, pp. 1382–1397, 2010.
[174] L. Pastor-Pérez, F. Baibars, E. Le Sache, H. Arellano-García, S. Gu, and T. R. Reina, “CO2 valorisation via Reverse Water-Gas Shift reaction using advanced Cs doped Fe-Cu/Al2O3 catalysts,” *J. CO2 Util.*, vol. 21, pp. 423–428, 2017.
[175] F. Ghodoosi, M. R. Khosravi-Nikou, and A. Shariati, “Mathematical Modeling of Reverse Water-Gas Shift Reaction in a Fixed-Bed Reactor,” *Chem. Eng. Technol.*, vol. 40, no. 3, pp. 598–607, 2017.
[176] Sasol, “Value Chain.” [Online]. Available: http://www.sasol.com/innovation/gas-liquids/value-chain. [Accessed: 05-Jul-2017].
[177] C. B. Clifford, “Fischer-Tropsch Process to Generate Liquid Fuels,” 2017. [Online]. Available: https://www.e-education.psu.edu/egee439/node/679. [Accessed: 21-Sep-2017].
[178] N. H. Leibbrandt, A. O. Aboyade, J. H. Knoetze, and J. F. Görgens, “Process efficiency of biofuel production via gasification and Fischer-Tropsch synthesis,” *Fuel*, vol. 109, pp. 484–492, 2013.
[179] A. de Klerk, *Fischer-Tropsch Refining*. 2011.
[180] I. Hannula, “Co-production of synthetic fuels and district heat from biomass residues, carbon dioxide and electricity: Performance and cost analysis,” *Biomass and Bioenergy*, vol. 74, pp. 26–46, 2015.

[181] Q. Smejkal, U. Rodemerck, E. Wagner, and M. Baerns, “Economic assessment of the hydrogenation of CO2 to liquid fuels and petrochemical feedstock,” *Chemie-Ingenieur-Technik*, vol. 86, no. 5, pp. 679–686, 2014.
[182] A. Franco and C. Casarosa, “Thermodynamic and heat transfer analysis of LNG energy recovery for power production,” *J. Phys. Conf. Ser.*, vol. 547, no. 1, 2014.
[183] Đ. Dobrota, B. Lalić, and I. Komar, “Problem of Boil - off in LNG Supply Chain,” *Trans. Marit. Sci.*, vol. 2, no. 2, pp. 91–100, 2013.
[184] B. Songhurst, “LNG Plant Cost Escalation,” *Oxford Inst. Energy Stud.*, no. February, pp. 8–10, 2014.
[185] U.S. Department of energy, “Natural Gas for Cars Using Natural Gas for Vehicles : Comparing Three Technologies,” 2015.
[186] M. Smith, N. West, and J. G. Nrel, “Costs Associated With Compressed Natural Gas Vehicle Fueling Infrastructure,” *US Dep. Energy*, 2014.
[187] Y. A. Alsultanny and N. N. Al-Shammari, “Oxygen specific power consumption comparison for air separation units,” *Eng. J.*, vol. 18, no. 2, pp. 67–80, 2014.
[188] R. M. Swanson, J. a Satrio, R. C. Brown, and D. D. Hsu, “Techno-Economic Analysis of Biofuels Production Based on Gasification,” *Energy*, vol. 89, 2010.
[189] Danish Energy Agency and Energinet.dk, “Technology data for energy plants - individual heating plants and energy transport,” 2016.
[190] “Technology Data for Energy Plants - aug 2016 upd oct and nov 2017.”
[191] Danish Energy Agency, “Technology Data for Energy Plants, Updated chapters - August 2016,” 2017.
[192] The Danish Energy Agency, “Data sheet - Energy Storage - 2017 July.” 2017.
[193] R. Skagestad *et al.*, “Ship transport of CO2,” no. 3918, pp. 1–52, 2014.
[194] Petroleum Equipment Institute, “Light ends.” [Online]. Available: https://www.pei.org/wiki/light-ends. [Accessed: 12-Mar-2018].
[195] T. S. Jensen, “Sifre course - presentation.” .

14 Appendices

Appendix A – Energy System Demand 2050

Moderate Energy Savings – 2050

Moderate Energy Savings								
Net Consumption, PJ **2050**	Car	Van	Truck Tractor, etc.	Bus	MC Lawn mower	Aviation	Rail	Ship
Residential Households	-	-	-	-	0.18	-	-	-
Trade & Service	-	0.12	-	-	-	-	-	-
Agriculture, Horticulture & Fishing			3.29					2.30
Industry - Manufacturing			0.23					
Industry - Construction			0.98					
Transport	23.15	8.30	10.17	2.26	0.23	16.54	2.68	2.08
Total	23.15	8.43	14.66	2.26	0.41	16.54	2.68	4.37

Moderate Energy Savings											
Net Consumption, PJ **2050**	Process heat <50 °C	50-75 °C	75-100 °C	100-150 °C	150-200 °C	>200 °C	Space heating Individual	District Heating	Electricity		Total
Residential Households	0.04	-	-	-	-	-	50.86	56.60	32.71		140.38
Trade & Service	-	-	0.45	0.60	-	-	7.40	27.91	43.57		80.06
Agriculture, Horticulture & Fishing	0.64	6.07	1.47	0.54	0.11	0.28	0.18	0.00	7.89		22.75
Industry - Manufacturing	1.45	2.72	7.51	16.71	4.61	17.96	7.23	3.00	30.02		91.44
Industry - Construction	-	0.71	0.71	-	-	-	-	-	1.57		3.97
Transport											65.41
Total	2.13	9.51	10.14	17.85	4.72	18.23	65.66	87.51	115.76		404.01

Appendix B – Electrification of Transport Modes

The trajectory of electrifying the transport modes of rail, light and heavy duty road, sea and aviation are briefly analysed below. The five electrification scenarios are based on the estimated probability of electrifying the different transport modes.

Rail

Transportation via rail is one of the few obvious candidates for direct electrification. Since the trains always run on the same routes, it is possible to supply the necessary infrastructure for direct electrification at a reasonable cost. The Danish rail network is at present partly electrified and is in the process of being further electrified [127]. 1756 km of the 3476 km railway in Denmark is currently electrified and an additional 1362 km is in the progress of being electrified towards 2026 [128], [129]. It is expected, that there is a potential to electrify the remaining 358 km in the long run.

Light duty road

Electrification of light road transport is probably the area which has attracted the most attention when it comes to electrification of transport. This is due to the fact that the majority of the distances travelled in this segment are relatively short, and therefore they do not require as high energy content and density from the batteries as some of the other transport modes. Almost all, if not all, major car manufactures have electric vehicles in their assortment, both as plug-in hybrid electric vehicles (PHEVs) and EVs. The range of a single charge for the EVs on the market ranges between 100 km and above 400 km for Tesla's Model S [130]. The technology is still under development, e.g. Volkswagen is going to invest 150 billion DKK towards 2030 to develop batteries with a range of 1000 km [131]. It is therefore a reasonable assumption that the vast majority of the demand for light road transport can be covered by electricity in a 100 % renewable energy system in 2050.

Heavy duty road

Currently, there are no notable electrification of heavy road transport [41]. However, many of the large truck manufactures are developing electric trucks which are expected to enter the market in the coming years [132]. Daimler has already put smaller electric trucks with a range of up to 100 km and a hauling capacity of 3.5 tons to the market in Europe [133]. Especially in the medium duty truck segment, several manufactures are expected to have all-electric trucks on the market by 2020 including Cummins, Daimler, Volvo and the start-up Thor Trucks [134]–[137]. These medium duty trucks are, according to the manufactures, expected to have a range from around 150 km to 450 km [134], [137]. Also in the more challenging heavy-duty truck segment, both Daimler and Tesla have announced plans to put all-electric trucks to the market in the coming years. The E-Fuso Vision from Daimler is claimed to have a range of 350 km and a hauling capacity of 11 tons [138]. Tesla has by far the most ambitious promises for their Semi Truck with a capacity of 36 tons and a range of 800 km [139]. For busses the challenges seems more manageable since busses often travel the same distances and shorter distances between charging possibilities. The Chinese battery manufacture BYD focuses on electric busses and in 2016 they produced 26,000 electric busses. BYD believes the future lies in busses with large batteries that can run the entire day without charging, and in 2017 they presented a bus with a range of 300 km [140]. In Denmark, the transition to electric busses has started as well, e.g. in Roskilde municipality, where the diesel busses will be replaced by electric busses in 2019 [141].

Sea

As with heavy road transport, sea transport faces some challenges regarding electrification. Sea transport often implies transporting heavy cargo for long distances indicating a need for significant battery capacity and energy content. However, pure electric ships have started to be developed in recent years, especially for shorter distances for passenger transport. The first fully electric ferry was implemented in Norway in 2015. The lithium-ion battery powered ferry has a capacity of 360 passengers and 120 cars and makes the 6 km crossing approximately 34 times a day [71], [142]. Also the ferries operating the 4 km route from Helsingør to Helsingborg are being converted to be battery powered [143]. During 2018 an electric ferry is expected to be implemented at the Ærø ferries. The ferry has a capacity of 31 cars and 196 passengers and must be able to sail 40 km between charges [144], [145]. Danish Shipping estimates that more ferries will be running partly or entirely on electricity in the coming years. The Danish Energy Association estimates that if sailing between 45 and 90 minutes could be electrified, it would cover 20-40 % of the energy consumption for ferries in Denmark [146].

Aviation

Aviation is a transport sector with large requirements for power and energy and therefore the sector also faces challenges when it comes to electrification [147]. There is however, a lot of attention to the subject and a lot of the large actors within the aviation industry are looking into electric airplanes. In 2015 Airbus' E-Fan program resulted in a manned electric plane crossing the English Channel as the first battery powered plane. The E-fan can stay airborne for 50 minutes, but the plane only weights 500 kg, where the battery pack constitutes 33% of its weight [148]. Airbus has also entered a partnership with Siemens and Rolls Royce in an effort to construct an electric commercial airplane by gradually replacing the gas turbines with electric engines [149]. The potential of electric airplanes has also gained the attention of start-up companies. The company Wright Electric has a goal of building a battery powered airplane with a capacity of 150 passengers and for distances less than 480 km and having it in the air within ten years [150], [151]. Both Airbus and Boeing are looking to Norway to test their electric solutions, and the chairman of the Norwegian airport operator Avinor, finds it highly realistic that electric planes will fly commercial routes by 2025 [152]. Since significant development is expected within the next ten years it seems reasonable to expect further development in the long run.

Appendix C – Engine Efficiencies

For EVs in light road transport the efficiency is assumed to be 82 % and for methanol in an ICE it is assumed to be 23 % [153]. The electric efficiency is weighted with the mechanical energy demand between the electric efficiency of vans and cars. The use of LNG is not included for light road transport due to high losses from evaporation [76]. For CNG the efficiency is assumed to be 23 % [153]. The electric efficiency of heavy road transport is assumed to be 63 % [153]. This is based on a weighting between the efficiency of electric trucks and electric busses. The electric efficiency for trucks is based on the efficiency of a diesel truck and the relative difference between the efficiency of an electric bus and diesel bus. For the use of methanol and LNG in an ICE the efficiency is assumed to be 24 % based on the assumption that the efficiency is the same as for a diesel truck [13], [153], [154]. LNG is used in trucks and CNG is used in busses. The efficiency of a bus running on CNG is assumed to be 16 % [153]. For electric planes the efficiency is assumed to be 58 % based on an on-board efficiency of 73 % and additional 20 % losses in charging and discharging [155]. The efficiency of airplanes operating on kerosene is assumed to be 19 % [153]. The electric efficiency of ships is assumed to be 68 % [156]. The LNG efficiency of ships is set to 30 % and for methanol it is set to 31 % based on the assumption that the efficiency is the same as for heavy fuel oil [153], [157]. To be conservative, the efficiency of ships is based on the efficiency of container ships instead of ferries which have a higher efficiency. The energy consumption for ships is divided almost equal between national freight and national passenger transport [13]. The electric efficiency of trains is set to 77 % and the methanol efficiency is assumed to be 28 % based on the assumption that the efficiency is the same as for diesel [13], [153]. The efficiencies are based on intercity trains since they are assumed to constitute the largest share of the traffic work in trains.

Appendix D – Technology Data

Based on the fuel production pathways presented in *Fuel Production Pathways*, this appendix describes the processes in more detail. Furthermore, an energy balance for each process is set up, allowing for the processes to be modelled in Sifre. Lastly, CAPEX and OPEX for the technologies is presented as this is needed for the optimisation of the investments in the ADAPT module of Sifre. For all the processes, the CAPEX and OPEX is stated pr. capacity of primary output.

Heat Areas

As Sifre does not work with mass flows, temperatures of heat streams or pressure levels but only energy flows three different heat areas have been defined [91].

- District heating (DH) area for heat streams at 50-110 °C
- Low temperature process heat (LTPH) area for heat streams at 110-300 °C
- High temperature process heat (HTPH) area for heat streams at 300-1000 °C

The general idea of the heat areas is to be able to distinguish between temperature intervals. The different conversion technologies have different operating temperatures and therefore different demands for temperature levels of the input heat streams, resulting in different temperatures of the recoverable heat in the output streams.

Dryer Unit

Before the thermal gasification process the incoming biomass, which is assumed in the form of wood chips, must be dried from a moisture content around 50 % to around 10-15 % [158]. Dryer data is chosen for a Metso belt-drier [91]. The drying process is driven by 2 bar steam to evaporate the water. A small amount of electricity consumed by pumps and LTPH is supplied. The net energy balance and inputs to the investment module in Sifre can be seen in Figure 45 and Table 11 [91].

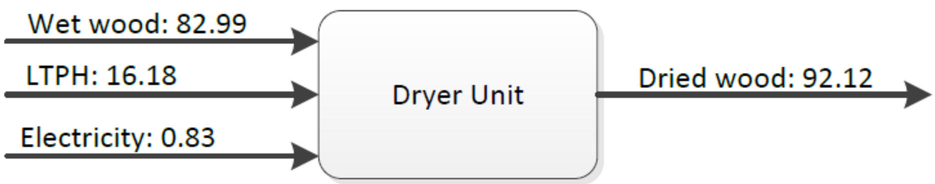


Figure 45 - Net energy balance for the dryer unit [91].

Dryer unit – Sifre	ADAPT
Investment cost [M€/MW]	0.048
O&M cost [€/MW/y]	1,933

Table 11 - Sifre inputs for the dryer unit [91].

Thermal Gasification

Energy processes that use biomass as feed stock are often sensitive to the changes in the biomass input quality. Pre-treatment of the biomass ensures homogeneous input in terms of size, moisture content and density [159]. For syngas production, the moisture content must usually be dried to 10-15 % and virtually any carbonaceous feed stock can be gasified to syngas [159]. In *Appendix E – Technology Overview* the combined thermal gasification and gas cleaning unit can be seen. It includes several processes like the biomass infeeder, thermal gasification reactor, tar reformer, guard bed, catalytic autothermal reformer and rectisol CO_2 removal [91]. For the thermal gasification reactor the biomass, LTPH and pure oxygen is pressurised to 25 bar at around 890 °C. The inputs of LTPH and oxygen is at 25 bar and 230 °C [91]. The steam is required as a reforming agent and the oxygen stream is to achieve the optimal production of syngas, to avoid inert N_2 and to provide heat through combustion to the endothermic reactions [91]. Oxygen is used instead of atmospheric air [160]. The high temperatures reduce the production of small hydrocarbons and tars and optimises the production of H_2 and CO [160]. The optimal ratio between oxygen and steam at temperatures around 890 °C and a pressure of 25 bar is approximately 1:1 on mass basis [91].

The chosen input biomass to the process is dried wood. For 1 MJ of wood (0.063 kg), 0.0184 kg of O_2 must be supplied. Sifre operates with energy flows, therefore the LHV of O_2, which is 0 MJ/kg, is set to 1 MJ/kg [91]. This results in 0.0184 MJ of O_2 input pr. MJ of wood. This result in a net energy balance for thermal gasification as shown in Figure 46, where preheating of the oxygen is included [91]. The composition of the product gas is shown in Table 12 [111].

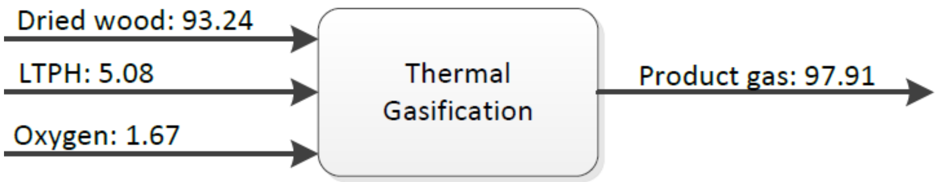


Figure 46 - Net energy balance for thermal gasification[91].

Component	H_2	CO	CO_2	H_2O	CH_4	N_2	H_2S	HCl	Tar
Mol. Frac. (%)	20.1	15.8	21.9	34.1	5.4	0.027	0.003	0.005	2.647

Table 12 – Estimated composition of product gas from an oxygen steam blown gasifier at 890 °C and 25 bar [111].

The tar, particulate matter, alkali materials and sulphur compounds must be removed before synthesis reactions. This is done by a tar reformer, a dust filter and a guard bed. The remaining hydrocarbons are reformed in a catalytic autothermal reformer and the CO_2 is removed through a rectisol process with methanol as a physical absorbent [111].

The tar reformer is a hot gas cleaning technology. It operates at 890 °C and utilises the excess steam from the product gas [158], [159]. Tar compounds from the product gas such as naphthalene, propane, ethane, ethylene and acetylene (from the category "Tar" in Table 12) are reformed to syngas by catalytic cracking in a bubbling fluidized bed [158]. Approximately half of the methane is cracked as well. The heat for the process is circulated as much as possible and further heat is provided by combustion of 10 % the product gas. It results in an efficiency of the process of 90 %, if high temperature process heat (HTPH) recovery is included [91].

The dust filter removes the particulate matter, alkali materials and sulphur compounds after the product gas leaves the tar reformer. Cooling prior to the filter is necessary resulting in HTPH recovery. The guard bed based on metal oxides removes the sulphur, assumed in the form of H_2S. The efficiency of both processes are 100 % [91]. The catalytic autothermal reformer converts the remaining hydrocarbons with the steam present in the product gas. Oxygen and heat is supplied for the cracking [111]. Key figures based on [111] are oxygen supply of 1.98 t/h and heating of the oxygen. Lastly, the rectisol CO_2 removal operates at ambient temperatures and the syngas is cooled before the process, achieving HTPH and LTPH. Methanol is utilised as a physical absorbent, and the final CO_2 concentration is around 3 % in the syngas [111]. Power for pumps and fans is needed. This result in a net energy balance for the total gas cleaning process as shown in Figure 47 [91].

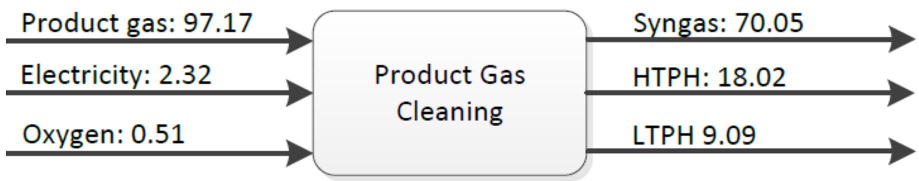


Figure 47 - Net energy balance for the gas cleaning process after thermal gasification [91].

The total net energy balance for the dryer unit, thermal gasification and gas cleaning is shown in Figure 48. In the modelling the two heat streams are grouped because of Sifre only being able to handle two outputs. They are afterwards divided in a heat splitter. The efficiency of the total process is 73.5 %, and 93.4 % with heat recovery. The composition of the output syngas from the total process is a hydrogen to CO ratio of 1.27:1 [91]. It defines the syngas composition for the model. Hence, if a higher ratio is needed for a specific process both a syngas and a hydrogen stream are inputs and similarly for outputs of syngas from other processes. The inputs to the investment module in Sifre are shown in Table 13. All Sifre inputs are shown in *Appendix F – Sifre Input Data*.

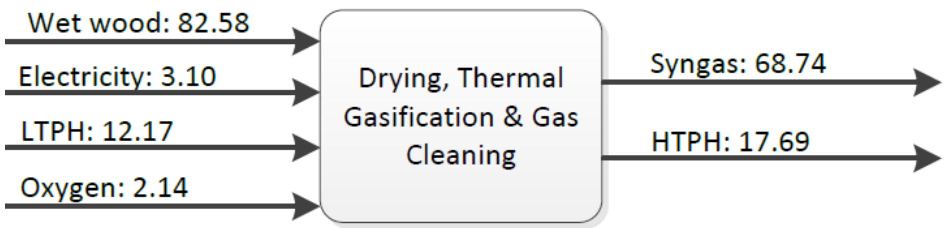


Figure 48 – Net energy balance for the dryer unit, thermal gasification and gas cleaning [91].

Thermal gasification and gas cleaning – Sifre	ADAPT
Investment cost [M€/MW]	0.647
O&M cost [€/MW/y]	25,885

Table 13 - Sifre inputs for thermal the dryer unit, gasification and gas cleaning [91].

Anaerobic Digestion

Biogas plants produce methane rich gas on the basis of biodegradable organic material in an anaerobic process [161]. The typical composition of the biogas is 50-75 % CH_4, 25-50 % CO_2 and smaller fractions of nitrogen, oxygen, hydrogen and hydrogen sulphide [160]. The content of the gas depends on the inputs of biomass which often consists of straw, animal slurry and organic waste. The amount of impurities also varies according to the feed stock. If the feed stock is either solid waste from landfills or dry matter from waste water, the biogas can contain troublesome siloxanes and halides [160]. The scope of this project does not involve the latter. It concerns the removal of hydrogen sulphide and separation of CH_4 and CO_2.

The anaerobic digestion is assumed to be supplying the necessary heat for the process via the exothermic reactions within the digester tank [162]. The content of the tank must, during the complete retention time around three weeks, be heated to 35-40 °C as a mesophilic digestion is assumed. A sketch of a possible system from inputs to treated biogas is shown in *Appendix E – Technology Overview* [161]. The "Technology Data for energy carrier generation and conversion" from the DEA [161] states that it is not practical nor usual to measure the energy content of the input material as a calorific value. However, as Sifre operates with energy balances an effective conversion of input energy to biogas with 65 % content of methane is estimated to 50 % [163]. A small amount of electricity for machinery and a small amount of heating for the input stream are estimated [161], [162]. This gives a net energy balance of the process as shown in Figure 49 and inputs to the investment module in Sifre as shown in Table 14 [161].

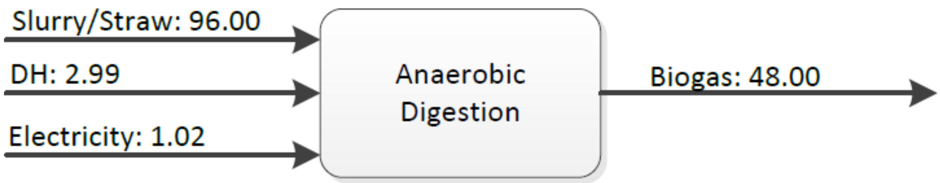


Figure 49 - Net energy balance for anaerobic digestion [162], [163].

Anaerobic digestion – Sifre	ADAPT
Investment cost [M€/MW]	0.372
O&M cost [€/MW/y]	26,009

Table 14 - Sifre inputs for anaerobic digestion [161].

CO_2 stripping

For fuel production, the biogas must be upgraded. There are several opportunities for upgrading the biogas to either methane through hydrogenation or CO_2 removal/stripping, or to syngas through reforming. This project only concerns separation of the CO_2 in a water scrubber and hydrogenation. The stripping of CO_2 is a commercial technology that separates the CH_4 and CO_2 by spraying or bubbling water over the gas since CO_2 is more soluble in water [161]. The pressure necessary for the process is approximately the same as for the gas transmission grid, hence no further compression is needed after. The electricity consumption and net energy balance of the process is shown in Figure 50 [161]. It includes compression and is equal to 3.2 % of the input of biogas. Since the LHV of CO_2 is zero, an arbitrary value for the LHV of CO_2 is chosen to be 1 MJ/kg, as for O_2. The molecular weight of CH_4 is 16.04 g/mole, and for CO_2 it is 44.01 g/mole [164]. The mole ratio of CH_4/CO_2 in the biogas is approximately 1.85:1 with 65 % methane and 35 % CO_2. The output ratio in weight is 1:1.48, and the LHV of methane is 50 MJ/kg. To briefly show the energy balance calculations, the equations beneath are included.

$$CH_4:\ 65\ \% \frac{mole\ CH_4}{mole\ biogas} \cdot 0.01604 \frac{kg\ CH_4}{mole\ CH_4} \cdot 50 \frac{MJ}{kg\ CH_4} = 0.521 \frac{MJ}{mole\ biogas}$$

$$CO_2\text{:}\;\; 35\ \% \,\frac{mole\ CO_2}{mole\ biogas} \cdot 0.04401 \frac{kg\ CO_2}{mole\ CO_2} \cdot\ 1 \frac{MJ}{kg\ CO_2} = 0.015 \frac{MJ}{mole\ biogas}$$

$$Energy\ share\ of\ CH_4\ in\ the\ output\ pr.biogas\ input\text{:}\quad \frac{0.521}{0.521 + 0.023} = 97.13\ \%$$

$$Energy\ share\ of\ CO_2\ in\ the\ output\ pr.biogas\ input\text{:}\quad \frac{0.023}{0.521 + 0.023} = 2.87\ \%$$

Though, the biogas energy output from the anaerobic digestion is only calculated as methane. Hence, for every unit of biogas energy as an input, the same amount of methane in energy should be an output if the leakages are neglected. It is set to 1 %. The total efficiency of the process is distorted by the LHV energy value given to CO_2. It becomes over 100 %. The energy shares therefore change to the following.

$$Energy\ share\ of\ CH_4\ in\ the\ output\ pr.biogas\ input\text{:}\quad \frac{0.521}{0.521} = 100\ \%$$

$$Energy\ share\ of\ CO_2\ in\ the\ output\ pr.biogas\ input\text{:}\quad \frac{0.023}{0.521} = 2.96\ \%$$

If the inputs are to sum to 100 MJ and 3.2 MJ electricity is added for every 100 MJ biogas, then the energy balance for the CO_2 stripping is as shown in Figure 50.

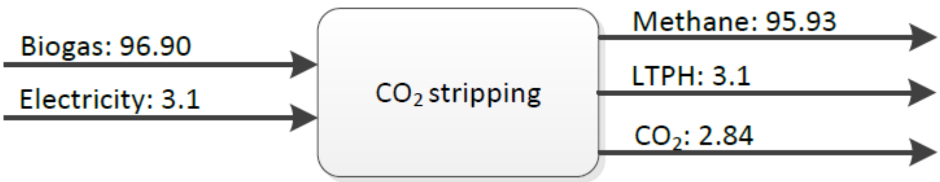


Figure 50 - Net energy balance for CO_2 stripping of biogas [161].

CO_2 stripping – Sifre	ADAPT
Investment cost [M€/MW]	0.246
O&M cost [€/MW/y]	6,711

Table 15 - Sifre inputs for CO_2 stripping of biogas [161].

Methanation

As mentioned the biogas can be upgraded to methane instead of stripping the CO_2 from the gas. There are two types of upgrading, biological and catalytic. This project only concerns the catalytic type due to the readiness of the technology [93]. Here, hydrogen is reacting with the CO_2 content in the biogas and forms methane and water, called methanation or hydrogenation [3]. The reaction is exothermic and can be run at moderate pressures around 10 bar and temperatures ranging from 250-400 °C in a Sabatier reactor [165], [166]. Many different reactor designs can be used both fixed and fluidized bed, tube or slurry bubble reactors. Common for most is the use of nickel as the catalyst which is commercially available [165]–[167].

$$CO_2\ +\ 4H_2\ \rightarrow\ CH_4\ +\ 2H_2O\qquad (-165\ kJ/mol)$$

The process has a high conversion factor of CO_2 to methane. Experimentally shown to be above 98 % [165]. Approximately 4 % of the input energy is for compression of the gas [168], giving an energy balance as shown in Figure 51 based on LHV and a loss in the form of heat of 10 %. The inputs to the Sifre investment module are shown in Table 16 [168].

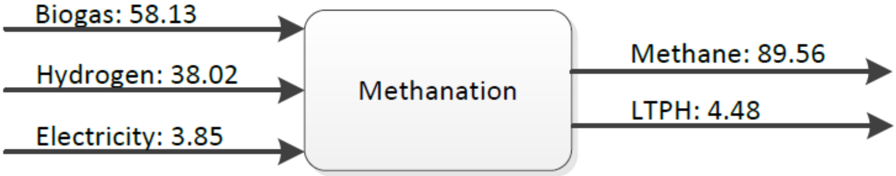


Figure 51 - Net energy balance for methanation of biogas [165]–[167].

Methanation – Sifre	ADAPT
Investment cost [M€/MW]	0.12
O&M cost [€/MW/y]	2,400

Table 16 – Sifre inputs for methanation of biogas [168].

Steam Reforming of Methane

Steam reforming of methane is presently a commercial technology. It is a highly endothermic reaction operating in a temperature range of 800-880 °C and at 20-30 bar [110], [169]. The heat is supplied through steam directly for the process.

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (+206\ kJ/mol)$$

The conversion efficiency of methane is a function of the temperature. Higher temperatures give a higher conversion rate of methane. For temperatures around 900 °C the conversion of methane is almost 100 % [94]. From the lower heating values and an assumed efficiency of the process of 95 % the net energy balance of the steam reforming of methane is as shown in Figure 52 [94], [164]. Due to the fixed syngas composition of the model, an additional hydrogen stream is added. The inputs to the investment module in Sifre are shown in Table 17 [170].

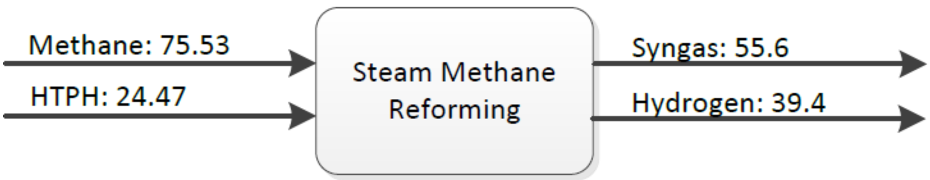


Figure 52 - Net energy balance for steam methane reforming [94], [164].

Steam methane reforming – Sifre	ADAPT
Investment cost [M€/MW]	0.283
O&M cost [€/MW/y]	5,654

Table 17 - Sifre inputs for steam methane reforming.

Direct Air Capture

The production of electro fuels for transportation is relying on a carbon source. The common sources are different types of biomass, e.g. through thermal gasification or anaerobic digestion. Though, it is not the only possible carbon source. DAC can also provide a carbon feedstock. This project implements two methods to the Sifre model. Scrubbing and calcination, and temperature swing adsorption (TSA) [101].

Scrubbing and Calcination

The scrubbing process is carried out with either a sodium- or calcium hydroxide solution, $Na(OH)_2/Ca(OH)_2$, as a scrubbing agent [101], [171]. The CO_2 is captured by blowing ambient air through the scrubbing towers, where the CO_2 reacts with the scrubbing agent forming $Na_2CO_3/CaCO_3$. The sodium cycle is chosen for this project because more data was available for it. In the sodium cycle, Na_2CO_3 reacts with $Ca(OH)_2$ giving 2 NaOH and $CaCO_3$. The calcium carbonate precipitates and is easily collected. The calcium is regenerated in a calcination process. It requires very high temperatures of more than 800 °C [101]. The processes of the CO_2 capture with Na as the scrubbing agent are shown beneath [171].

$$Absorption: \quad 2\,NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O \quad (-109.4\ kJ/mole)$$

$$Causticization: \quad Na_2CO_3 + Ca(OH)_2 \rightarrow 2\,NaOH + CaCO_3 \quad (-5.3\ kJ/mole)$$

$$Calcination: \quad CaCO_3 \rightarrow CaO + CO_2 \quad (+179.2\ kJ/mole)$$

$$Hydration: \quad CaO + H_2O \rightarrow Ca(OH)_2 \quad (-64.5\ kJ/mole)$$

As seen the absorption and hydration are exothermic and the calcination is strongly endothermic. One would suggest recirculation of heat between the processes. The heat from the absorption process is mostly lost to the ambient air that is funnelled through the scrubber. Some of the heat is recycled in the sodium carbonate and water [171]. The total energy supply required for the process is calculated in [171], and it is equal to 442 kJ/mole of stored CO_2 at 80 bar. It is equal to 10.04 MJ/kg CO_2. It includes 107 kJ/mole CO_2 of electricity for compressors, pumps and fans and 335 kJ/mole CO_2 of HTPH for the calcination process and drying of $CaCO_3$. 105 kJ/mole CO_2 of heat can be recycled at the hydration process at temperatures up to 400 °C as LTPH. An overview of the process can be seen in *Appendix E – Technology Overview*, and the net energy balance and inputs to the investment module in Sifre can be seen in Figure 53 and Table 18 [101], [171]. The amount of CO_2 in the output is calculated from the assumed arbitrary LHV of 1 MJ/kg and the molecular weight of 44.01 g/mole CO_2.

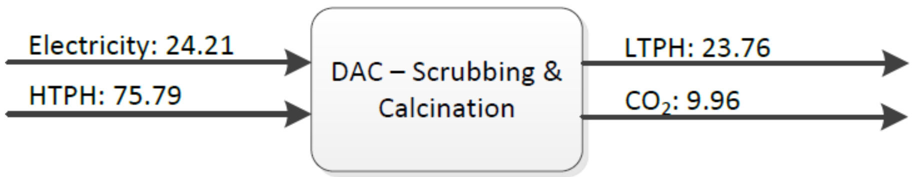


Figure 53 - Net energy balance for scrubbing and calcination of direct air capture of CO_2 [171].

DAC, scrubbing and calcination – Sifre	ADAPT
Investment cost [M€/MW]	0.826
O&M cost [€/MW/y]	16,527

Table 18 - Sifre inputs for scrubbing and calcination of direct air capture of CO_2 [101].

Temperature Swing Adsorption

The Swiss company Climeworks is currently developing a promising technology that performs an adsorption/desorption cycle, temperature swing adsorption (TSA), to extract CO_2 from ambient air [73], [101]. Information regarding the investment and operation costs have been found by contacting the company [172]. The energy balance of the process is found from a literature review. Only few valid sources were found, since it is a new and emerging technology only included in updated or new reports [73], [101]. Ambient air is blown through filters that bind the CO_2 chemically. The saturated filters must be heated to release the almost 100 % pure CO_2. The filters are reusable [172]. The operating temperature of the TSA process is only around 95 °C for the separation process of the CO_2 from the filters, and the net energy input pr. kg CO_2 is lower than that for the scrubbing and calcination process [101]. It is estimated to 7.2 MJ/kg CO_2 stored at 80 bar. The net energy balance and inputs to the investment module in Sifre can be seen in Figure 54 and Table 19. Recovery of 25 % of the input energy as heat is assumed in the range of district heating temperatures. No sources were available on the matter.

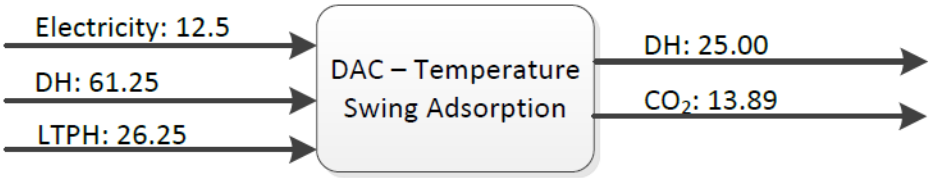


Figure 54 - Net energy balance for temperature swing adsorption of direct air capture of CO_2 [101].

DAC, temperature swing adsorption – Sifre	ADAPT
Investment cost [M€/MW]	0.638
O&M cost [€/MW/y]	15,944

Table 19 - Sifre inputs for temperature swing adsorption of direct air capture of CO_2 [172].

Electrolysis

Electrolysis is a process where electricity is used to electrochemically reduce or oxidise a reactant [14]. The water electrolysis unit converts water and electricity to hydrogen and oxygen. An input heat stream is also utilised to lower the need for electricity. As earlier mentioned this project only works with the solid oxide electrolyser cells (SOEC) technology. It is currently still under development, but it is expected to become commercial due to a large R&D focus of the technology [14]. The SOEC operates at high temperatures from 800-1000 °C and has the advantage over the other electrolyser technologies that more of the energy needed for dissociation can be supplied by heat, hence reducing the need for electricity [14]. The thermoneutral voltage decreases from 1.48 to 1.34 V for a temperature increase from 25 – 800 °C [25]. The SOEC has a further advantage when the outputs are used for production of synfuels. SOEC has the possibility of electrolysing mixtures of steam and CO_2 to CO, H_2 and O_2 because it conducts oxygen ions [9], [14]. It is called co-electrolysis. Both steam dissociation and a mixture of steam and CO_2 are included in the model. The investment costs for a SOEC plant are estimated to potentially become low compared to other electrolyser technologies because of the materials and high power density [160]. The SOEC technology has potential to operate under high pressures, up to 100 bar, because of the solid electrolyte. The principle of the SOEC is schematically shown in *Appendix E – Technology Overview* [25]. At the cathode, H_2O and CO_2 are reduced to H_2 and CO respectively. At the anode the oxygen ions are oxidised to oxygen [25].

$$Cathode: \quad H_2O + 2e^- \rightarrow H_2 + O^{2-}$$

$$Cathode: \quad CO_2 + 2e^- \rightarrow CO + O^{2-}$$

$$Anode: \quad 2O^{2-} \rightarrow O_2 + 2e^-$$

The overall reaction of the SOEC is based on the input, steam to hydrogen and oxygen or steam and CO_2 to CO, hydrogen and oxygen [25].

$$2H_2O \rightarrow 2H_2 + O_2$$

$$CO_2 + 2H_2O \rightarrow CO + 2H_2 + 3/2\,O_2$$

For the model, the co-electrolysis input ratio between H_2O and CO_2 is fixed at 1:1. The ratio of the output gas for H_2 and CO then becomes 2:1. The heat from the outlet streams are recovered through heat exchange to the inlet streams [78]. The model operates with steam inputs to the SOEC only a little above 100 °C because of the durability of the cell and difficulties handling the HTPH outside the cell. Operating at thermoneutral voltage the total efficiency of the SOEC is found to be 81.7 % [14], [78], [173]. The net energy balance for hydrogen production can be seen in Figure 55 and the inputs to the investment module in Table 20 [14]. The net energy balance for the syngas production can be seen in Figure 56. The syngas output has a H_2 to CO ratio of 1.27 because of the composition of the syngas from other processes in the model. Hence, an independent H_2 stream is also apparent. The investment costs for the two types of SOEC are assumed to be identical. Though, the arbitrary LHV of the input CO_2 for the co-electrolysis distorts the values slightly because the investment costs are pr. MW input, as shown in Table 20 and Table 21.

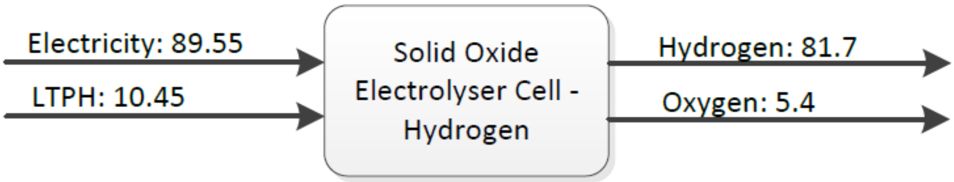


Figure 55 - Net energy balance for solid oxide electrolyser cell for production of hydrogen [14].

Solid Oxide Electrolyser Cell, H_2 – Sifre	ADAPT
Investment cost [M€/MW]	0.591
O&M cost [€/MW/y]	14,754

Table 20 - Sifre inputs for solid oxide electrolyser cell – Hydrogen [14].

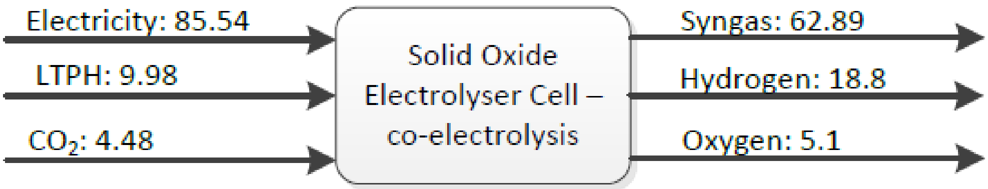


Figure 56 - Net energy balance for solid oxide electrolyser cell for production of syngas [14].

Solid Oxide Co-Electrolyser Cell – Sifre	ADAPT
Investment cost [M€/MW]	0.565
O&M cost [€/MW/y]	14,903

Table 21 - Sifre inputs for solid oxide co-electrolyser cell [14].

In Sifre the outputs from the co-electrolysis are modelled as two streams: a syngas stream and a gas stream which is a mix of hydrogen and oxygen. This gas stream is separated in a gas splitter to a hydrogen and an oxygen stream. The gas splitter is not a physical unit, it is only necessary because the maximum number of outputs in Sifre is two streams. The input data to Sifre can be found in *Appendix F – Sifre Input Data*.

Synthesis

Methanol Synthesis and Purification

Methanol synthesis has been a commercial process for almost 90 years using coal as feed stock in the beginning [160]. This project focuses on syngas and methane as feed stocks. The total process of the synthesis and purification consists of numerous processes. Two examples of the complete process are shown in *Appendix E – Technology Overview*. A process with syngas as the feed stock [91] and a process with methane as the feed stock that is converted to syngas in a steam reformer in the first step [160]. In Sifre all the processes will be handled as one conversion unit. If methane is the feed stock, it will first be converted to syngas through steam reforming and afterwards be treated as syngas to the methanol synthesis unit. This is a fair simplification since the energy flows, efficiencies and outputs are directly related to the inflow of syngas and the H_2/CO ratio, which is fixed to an optimal mixture by adjusting the hydrogen inflow [91], [160].

The methanol synthesis operates with highest efficiency if the M-ratio by mole fraction is 2.05 [111] and the CO_2/CO ratio is also low [160]. The M-ratio is defined as:

$$M = \frac{H_2 - CO_2}{CO + CO_2}$$

The level of hydrogen has to be raised compared to the syngas M-ratio chosen in the model which is 1.27. Some hydrogen is recirculated from the purge gas, raising the M-ratio 0.13. The M-ratio must be raised 0.65 additionally. It is achieved by adding 45.6 mole of H_2 per 100 mole of raw syngas [91]. The input streams to the methanol synthesis are fixed to 69 % cleaned syngas and 31 % H_2.

The syngas is compressed to 90 bar in the synthesis reactor, hence a large power consumption for the compression is needed [111]. Smaller compressors, pumps, blowers and refrigeration are also included. Furthermore, there are a lot of processes that demand heat or must have heat removed. This result in a net energy balance for the methanol synthesis and purification shown in Figure 57 [91].

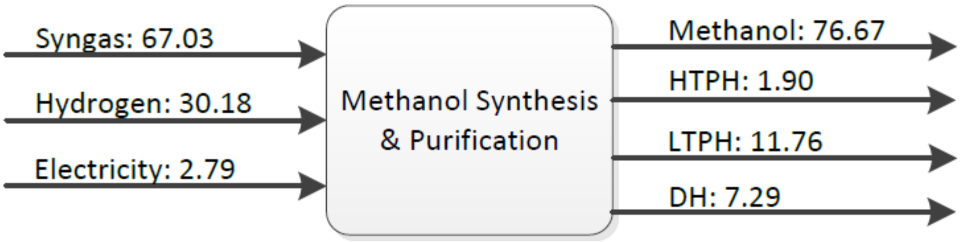


Figure 57 – Net energy balance for methanol synthesis and purification [91].

In the modelling the heat streams are grouped because of Sifre only being able to handle two outputs. They are afterwards divided in heat splitters. Without utilisation of the waste heat, the total efficiency of the process is 76.67 %. With heat utilisation the efficiency increases to 97.6 %. The investment and O&M costs are shown in Table 22. All inputs for Sifre can be found *Appendix F – Sifre Input Data*.

Methanol synthesis and purification – Sifre	ADAPT
Investment cost [M€/MW]	0.177
O&M cost [€/MW/y]	5,317

Table 22 – Sifre inputs for methanol synthesis and purification unit [91].

Water Gas Shift Reactor

The hydrogen supply necessary for optimal operation of the different processes can come from electrolysis or water gas shift reaction. In periods with high electricity prices it can be more feasible to supply hydrogen from the latter. The water gas shift reaction process is to convert CO in the raw syngas to hydrogen and CO_2 [77].

$$CO + H_2O \rightarrow H_2 + CO_2 \quad (-41.4\ kJ/mol)$$

The water is added as high pressure high temperature steam (HTPH) to the exothermic process. The outputs are H_2, CO_2 and LTPH [111]. This gives a net energy balance for the process and inputs to Sifre as seen in Figure 58 and Table 23. All inputs for Sifre can be found in *Appendix F – Sifre Input Data*.

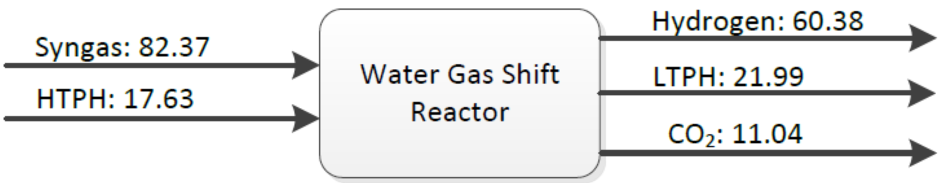


Figure 58 - Net energy balance for water gas shift reactor [91].

Water gas shift reactor – Sifre	ADAPT
Investment cost [M€/MW]	0.073
O&M cost [€/MW/y]	3,518

Table 23 - Sifre inputs for water gas shift reactor [91].

The reverse water gas shift (RWGS) reaction is utilised if there is an excess amount of hydrogen compared to CO or simply to convert CO_2 to CO. It is the opposite of the water gas shift reaction. Hence, it is endothermic and heat must be supplied. The operating temperature is around 750 °C to increase the reaction rate [174], [175]. The reaction takes place in a fixed-bed catalytic reactor. The heat is assumed to be recovered internally through heat exchangers to reduce the HTPH demand, hence decreasing the heat output to zero. A cold trap at the outlet is used to condense the water and separate it from the CO_2 [175]. The net energy balance of the process with 10 % heat losses included is shown in Figure 59. The investment costs are assumed identical to that of the water gas shift reactor, though the arbitrary LHV of the input CO_2 distorts the values slightly, as shown in Table 24.

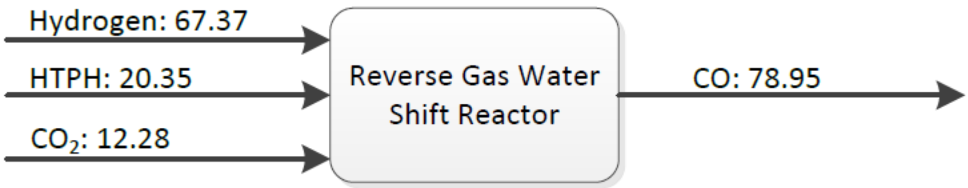


Figure 59 - Net energy balance for reverse water gas shift reactor [174], [175].

RWGS – Sifre	ADAPT
Investment cost [M€/MW]	0.064
O&M cost [€/MW/y]	3,086

Table 24 - Sifre inputs for RWGS [91].

The CO output stream is mixed with hydrogen to obtain the chosen syngas ratio for the model.

Fischer-Tropsch synthesis

Fischer-Tropsch (FT) synthesis was discovered in 1923 and it has been a commercial process for more than 60 years [176]. The Fischer-Tropsch synthesis is the conversion of syngas to hydrocarbons. The feed stock for syngas can be both coal, natural gas, biomass and others. The South African company Sasol has large experience with the first two [176]. It is assumed, that as long as the input to the FT synthesis is syngas, the origin of the syngas is of less significance. The simplified process is represented as in [77] and [101].

$$CO + 2H_2 \rightarrow -[CH_2]_n - + H_2O \quad (-165\ kJ/mol)$$

$$n\,CO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + n\,H_2O$$

The process is exothermal. As the reactions imply the outputs from the FT synthesis can vary. The syngas can be converted to alkanes containing up to at least 20 carbon atoms [177]. By adjusting pressure, temperature, residence and addition of catalysts the output share of the desired hydrocarbons can be increased. The intent in this project is to maximise the liquid jet fuel production, since the FT pathway is the only option included to produce jet fuel. Jet fuel consist of hydrocarbons with typically C8/C9 to C15/C16 carbon molecules, approximately around that of kerosene [6], [27], [177]. Jet fuel from FT synthesis is low in aromatic and sulphur content [177]. The lack of aromatics can be problematic due to lower viscosity and density [27]. It is presently certified by the ASTM for a 50 % blend. By adding aromatics a 100 % blend is certified by the ASTM [86].

The total process consists of FT synthesis, hydrotreating, cracking/isomerising and separation [6]. The total process is shown in *Appendix E – Technology Overview* with gasification of biomass as the syngas source. The products of the FT synthesis are upgraded in the hydrotreating process into lighter hydrocarbons. Documented outputs for syngas-to-liquids range from 5-30 % naphtha, up to 5 % liquefied petroleum gas (LPG) and 65-85 % diesel and kerosene with up to 50 % of the output volume as jet fuel corresponding to 50-60 % by energy [100]. The high energy output of jet fuel is achieved through oligomerisation of smaller hydrocarbons, typically of C3 and C4, and hydrocracking of longer hydrocarbons [70]. The two upgrading processes are well known and widespread in the fossil fuel industry.

Inputs and outputs used in Sifre can be seen on Figure 60. As evident from the processes the ratio of H_2/CO is approximately 2 or a little above. Hence, like for the methanol synthesis the hydrogen level has to be raised depending on the catalyst. For cobalt catalysts with low intrinsic water gas shift activity, the hydrogen must be supplied as an input. Iron catalysts possess water gas shift activity and both water gas shift and the FT synthesis can be carried out in the same reactor [77]. This project works with hydrogen as an input, hence a cobalt catalyst for the FT synthesis is used. The hydrogen can still be supplied by a water gas shift reaction or from electrolysis as an input separated from the FT reactor. Furthermore, cobalt generally outperforms iron in terms of exhibiting lower light product selectivity [77]. At the University of Kentucky Center for Applied Energy Research, low-temperature FT synthesis is carried out at 20 bar over cobalt catalysts at a temperature range of 200–230 °C with a H_2/CO ratio of 2 [77]. Low temperature and high pressure in the reactor reduces the output of smaller hydrocarbons, C1 to C4, and favours the production of longer chains that can be directly used or converted to jet fuel [77]. The FT synthesis in Sifre is modelled at a pressure of 20 bar at 220 °C. The efficiency of the FT synthesis is 83.7 % compared to the LHV from syngas to FT liquids (fuels) [25], [78], [101], [178], [179]. The specific value for the outputs of jet fuel and gasoline is taken from [179], which is a book on FT refining by Arno De Klerk. The remaining 16.3 % is heat from the exothermal reaction giving an output of LTPH. Recirculation of the heat from outlet to inlet is assumed possible, though some is lost. Based on [78], the total internal power consumption for compressors, pumps, blowers, etc. is 2 % of the input energy compared to LHV. This result in a net energy balance for the FT synthesis is shown in Figure 60. The most important inputs to Sifre for the FT synthesis can be seen in Table 25 an all inputs for Sifre can be found in *Appendix F – Sifre Input Data*.

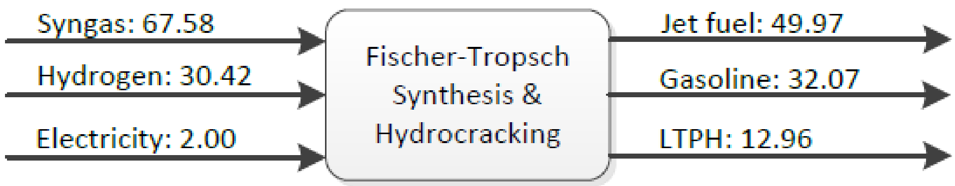


Figure 60 - Net energy balance for FT synthesis with H_2 from water gas shift reaction.

FT synthesis – Sifre	ADAPT
Investment cost [M€/MW]	0.505
O&M cost [€/MW/y]	9,857

Table 25 - Sifre inputs for FT synthesis [21], [23], [25], [78], [96], [101], [180], [181].

LNG plant

LNG is produced by cryogenic refrigeration of methane to about -162 °C at atmospheric pressure [182]. The estimated electricity input is, based on the source, varying from 1.9 – 3.0 MJ/kg LNG [182]. An average of 2.5 MJ/kg is assumed for this project. The energy density for LNG is 55.2 MJ/kg and for methane 55.5 MJ/kg [164]. Because of heating of the LNG from the ambient when stored the total losses of the process increases. If not cooled during the storage period then boil-off gas is created due to continuous evaporation of the LNG [183]. It lowers the quality of the LNG. The total loss of the process is assumed to results in 10 % [183]. The net energy balance for the LNG plant is shown in Figure 61, and the inputs to Sifre in Table 26.

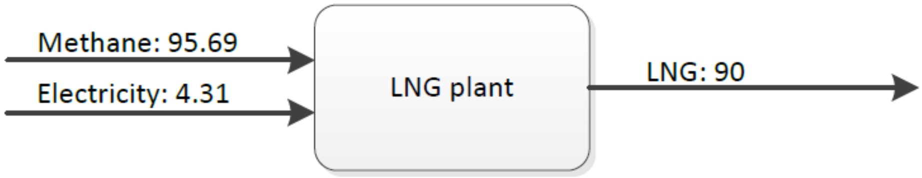


Figure 61 – Net energy balance for liquefaction of methane to LNG [182].

LNG plant – Sifre	ADAPT
Investment cost [M€/MW]	0.265
O&M cost [€/MW/y]	5,306

Table 26 - Sifre inputs for liquefaction of methane to LNG [184].

CNG Compression

The compression of methane/natural gas to compressed natural gas (CNG) is a broadly used technology for fuelling of light duty vehicles with over 10 million vehicles worldwide [3]. The pressure of the steel tank is typically around 200-300 bar achieving energy to volume ratio of 35 % of that of LNG [103]. The energy consumption of the compression is in the range of 2.0-2.7 % [3], [185]. 2.5 % is assumed in this project, hence the net energy balance for the CNG compression is shown in Figure 62 and the inputs to the investment module in Sifre is shown in Table 27.

Figure 62 - Net energy balance for compression of methane to CNG [3], [185].

CNG compression – Sifre	ADAPT
Investment cost [M€/MW]	0.152
O&M cost [€/MW/y]	3,046

Table 27 - Sifre inputs for compression of methane to CNG [186].

Air Separation Unit

The air separation unit (ASU) produces high pressure oxygen from ambient air. The input is electricity and the output is oxygen. Based on [187], the specific power consumption for an ASU type 31 is 0.608 kWh/Nm^3 O_2. Recalculated to energy streams with the arbitrary set LHV of oxygen to 1 MJ/kg, it becomes 1.53 GJ of electricity pr. GJ of O_2 [91]. The investment and O&M costs are based on data from [188]. The costs are calculated pr. MW of output oxygen, hence they seem high because of the low arbitrary LHV. The net energy balance for the ASU can be seen in Figure 63 and the investment data for Sifre can be seen in Table 28 [91].

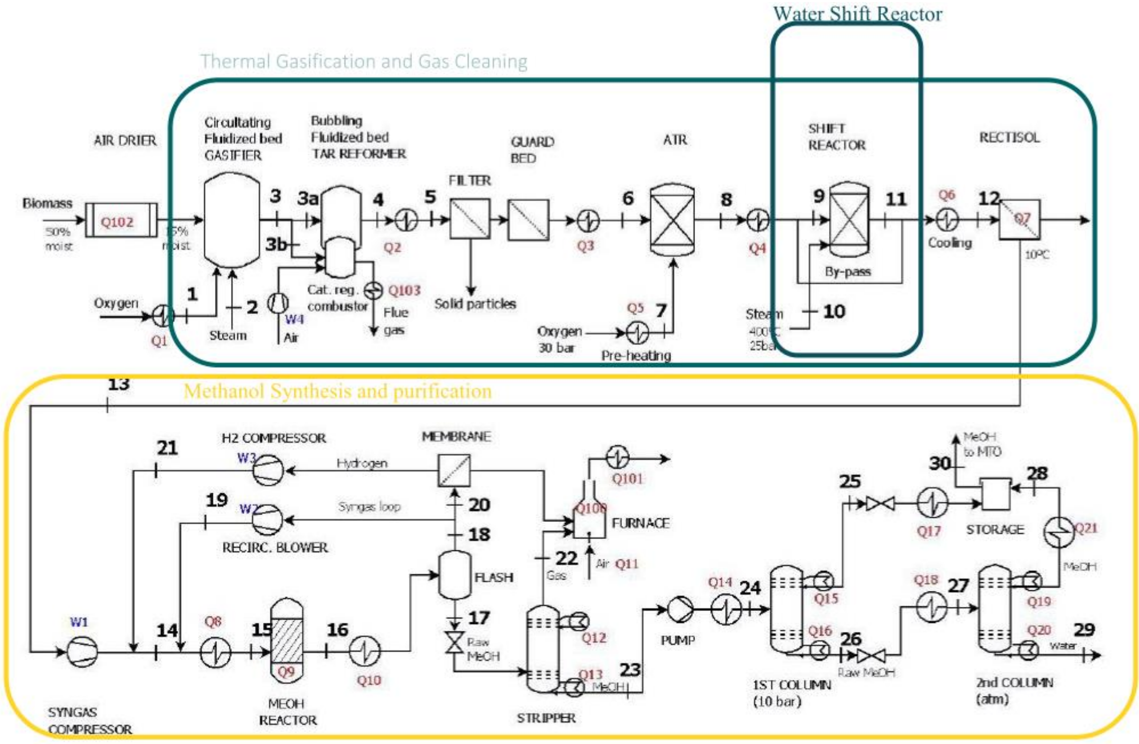
Figure 63 – Net energy balance for the air separation unit [91].

Air separation unit – Sifre	ADAPT
Investment cost [M€/MW]	2.157
O&M cost [€/MW/y]	64,447

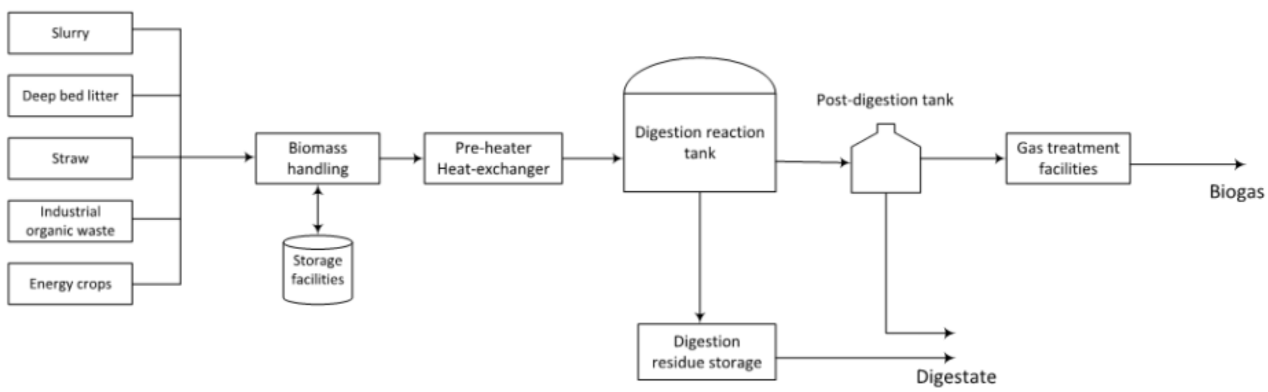
Table 28 – Sifre inputs for the air separation unit [91].

Appendix E – Technology Overview

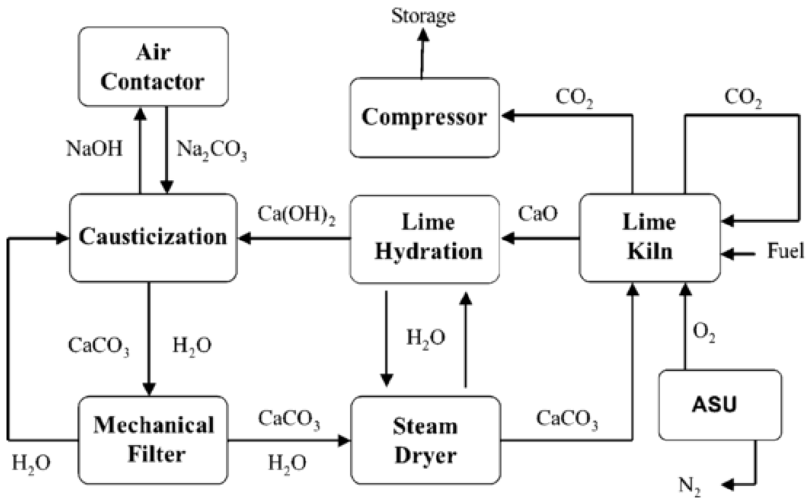
Overview of the thermal gasification process [91].



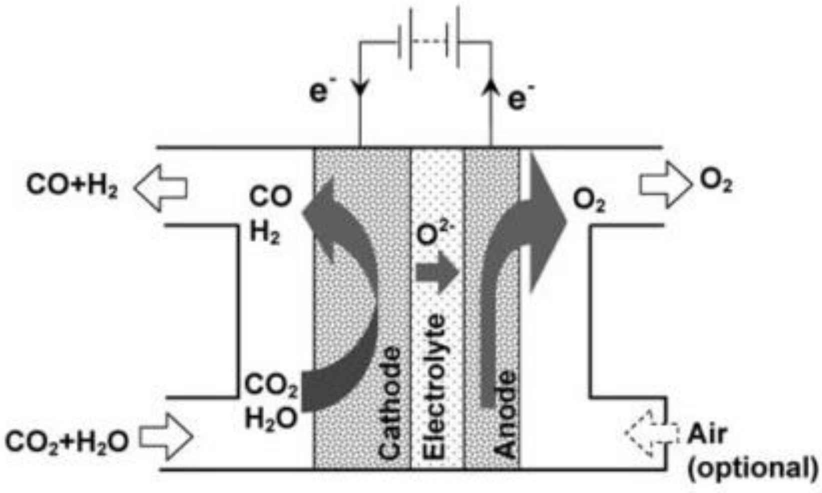
Overview of the anaerobic digestion process [161].



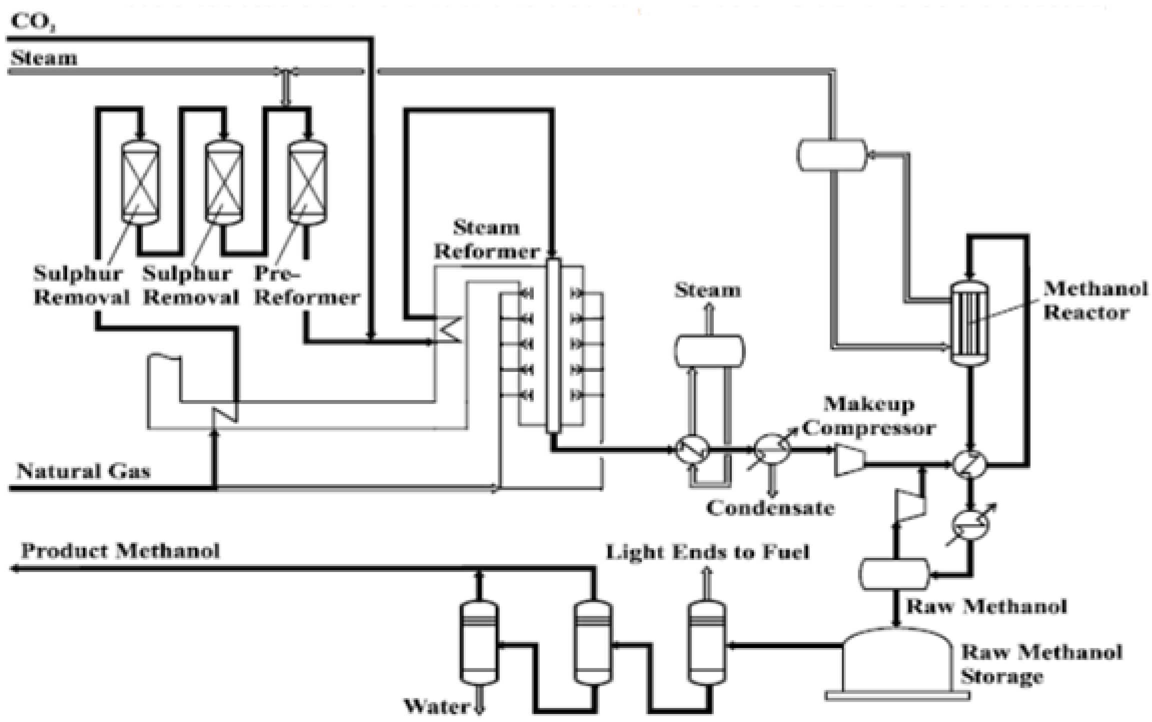
Overview of the DAC – scrubbing and calcination process [171].



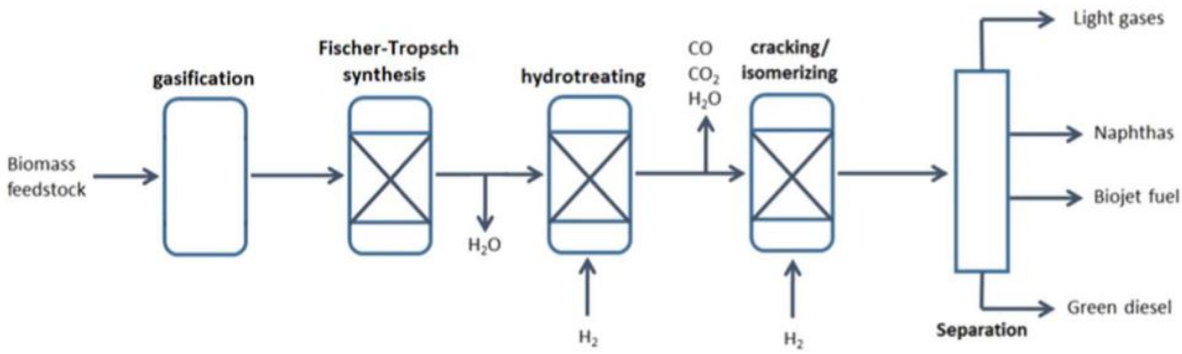
Overview of the SOEC co-electrolysis of steam and CO_2 [25].



Overview of the methanol synthesis by one-step reforming [160].



Overview of the FT synthesis and hydrocracking process [6].



Appendix F – Sifre Input Data

Fuel production pathways

The Sifre input data for the units utilised in the fuel production pathways are listed below. The references are not included in the list since they are included in *Appendix D – Technology Data*.

Sifre input (Drying, Thermal Gasification and Gas Cleaning Unit):
- Type: Backpressure (Syngas and HTPH)
- Cb: 3.89
- Production efficiency: B: 5.12 (Of primary output)
- Fuel Consumption: Wet wood: 84.39 %, Oxygen: 0.00219 %, El: 3.17 %, LTPH: 12.44 %
- ADAPT: Investment cost: 0.661 M€/MW
- ADAPT: O&M cost: 26,454 €/MW/y
- ADAPT: Life time: 20 y
- Operating Cost: 2.40 €/MWh (only for gasification unit)(modelled in Sifre as a tax)
- Ramping up/down: 5 MW/min
- Min production: 15 %

Sifre input (Anaerobic Digestion):
- Type: Condensation
- Production efficiency: B: 7.5
- Fuel Consumption: Slurry: 50-95 %, Straw: 5-50 %
- ADAPT: Investment cost: 0.372 M€/MW
- ADAPT: O&M cost: 26,009 €/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 0.5 MW/min
- Min production: 25 %

Sifre input (CO_2 stripping):
- Type: Backpressure (GasMix1, LTPH)
- Cb: 30.94 (for GasMix1 vs. LTPH)
- Production efficiency: B: 3.75 (Of primary output)
- Fuel Consumption: Biogas: 96.9 %, Power: 3.1 %
- ADAPT: Investment cost: 0.246 M€/MW
- ADAPT: O&M cost: 6,711 €/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 100 %/min
- Min production: 15 %

Sifre input (GasSplitter1):
- Type: Backpressure (Methane, CO_2)
- Cb: 33659
- Production efficiency: B: 3.6 (Of primary output)
- Fuel Consumption: GasMix1: 100 %

Sifre input (Methanation):
- Type: Backpressure (Methane, LTPH)

- Cb: 19.99 (for Methane vs. LTPH)
- Production efficiency: B: 4.02 (Of primary output)
- Fuel Consumption: Biogas: 58.13 %, Hydrogen: 38.02 %, Power: 3.85 %
- ADAPT: Investment cost: 0.120 M€/MW
- ADAPT: O&M cost: 2,400 €/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 100 %/min
- Min production: 15 %

Sifre input (Steam methane reformer):
- Type: Backpressure (Syngas, hydrogen)
- Cb: 1.411 (for syngas vs. H2)
- Production efficiency: B: 6.475 (Of primary output)
- Fuel Consumption: Methane 75.53%, HTPH 24.47%
- ADAPT: Investment cost: 0.283 M€/MW
- ADAPT: O&M cost: 5,654 €/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 100 %/min

Sifre input (Direct Air Capture – CO_2 – Scrubbing and calcination):
- Type: Backpressure (CO_2, LTPH)
- Cb: 0.419 (for CO_2 vs. LTPH)
- Production efficiency: B: 36.14 (Of primary output)
- Fuel Consumption: HTPH 75.79%, Electricity 24.21%
- ADAPT: Investment cost: 0.826 M€/MW
- ADAPT: O&M cost: 16,527 €/MW/y
- ADAPT: Life time: 20 y
- Min production: 15 %
- Ramping up/down: 100 %/min

Sifre input (Direct Air Capture – CO_2 – Temperature swing adsorption):
- Type: Backpressure (CO_2, DH)
- Cb: 0.556 (for CO_2 vs. DH)
- Production efficiency: B: 25.92 (Of primary output)
- Fuel Consumption: DH 87.5 %, Electricity 12.5 %
- ADAPT: Investment cost: 0.638 M€/MW
- ADAPT: O&M cost: 15,944 €/MW/y
- ADAPT: Life time: 20 y
- Min production: 15 %
- Ramping up/down: 100 %/min

Sifre input (Solid Oxide Electrolyser Cell - Hydrogen):
- Type: Backpressure (Hydrogen, Oxygen)
- Cb: 15.13 (for Hydrogen vs. Oxygen)
- Production efficiency: B: 4.13 (Of primary output)
- Fuel Consumption: Electricity: 89.55 %, LTPH 10.45 %
- ADAPT: Investment cost: 0.591 M€/MW

- ADAPT: O&M cost: 14,754 €/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 100 %/min
- Min production: 15 %

Sifre input (Solid Oxide Electrolyser Cell - Syngas):
- Type: Backpressure (GasMix2, Oxygen)
- Cb: 15.15 (GasMix2 vs. Oxygen)
- Production efficiency: B: 4.33 (Of primary output)
- Fuel Consumption: Electricity: 89.55 %, LTPH 10.45 %, CO_2: 0.00469 %
- ADAPT: Investment cost: 0.591 M€/MW
- ADAPT: O&M cost: 14,754 €/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 100 %/min
- Min production: 15 %

Sifre input (GasSplitter2):
- Type: Backpressure (Syngas, Hydrogen)
- Cb: 3.34
- Production efficiency: B: 3.6 (Of primary output)
- Fuel Consumption: GasMix2: 100 %

Sifre input (Methanol synthesis and purification unit):
- Type: Backpressure (Methanol and HeatMix1)
- Cb: 3.66
- Production efficiency: B: 4.696 (Of primary output)
- Fuel Consumption: Syngas: 67 %, H2: 30.18 %, El: 2.787 %
- ADAPT: Investment cost: 0.177 M€/MW
- ADAPT: O&M cost: 5,317 €/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 100 %/min
- Min production: 15 %

Sifre input (HeatSplitter1):
- Type: Backpressure (HeatMix2 and DH)
- Cb: 1.873
- Production efficiency: B: 5.522 (Of primary output)
- Fuel Consumption: HeatMix1: 100 %

Sifre input (HeatSplitter2):
- Type: Backpressure (HTPH and LTPH)
- Cb: 0.162
- Production efficiency: B: 25.88 (Of primary output)
- Fuel Consumption: HeatMix2: 100 %

Sifre input (Water gas shift reaction unit)
- Type: Backpressure (GasMix3 and LTPH)

- Cb: 2.745
- Production efficiency: B: 5.96 (Of primary output)
- Fuel Consumption: Syngas: 82.37 %, HTPH: 17.63 %
- ADAPT: Investment cost: 0.073 M€/MW
- ADAPT: O&M cost: 3,518 €/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 100 %/min
- Min production: 15 %

Sifre input (GasSplitter3):
- Type: Backpressure (Hydrogen and CO_2)
- Cb: 5470.15
- Production efficiency: B: 3.6 (Of primary output)
- Fuel Consumption: GasMix3: 100 %

Sifre input (Reverse water gas shift reaction unit)
- Type: Condensation (pure CO)
- Production efficiency: B: 4
- Fuel Consumption: Hydrogen: 76.8 %, HTPH: 23.2 %, CO_2: 0.00014 %.
- ADAPT: Investment cost: 0.073 M€/MW
- ADAPT: O&M cost: 3,518 €/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 100 %/min
- Min production: 15 %

Sifre input (SyngasMixer):
- Type: Condensation (Syngas)
- Production efficiency: B: 3.6
- Fuel Consumption: CO: 48.0 %, Hydrogen: 52.0 %

Sifre input (FT synthesis & Hydrocracking unit)
- Type: Backpressure (FuelMix1 and LTPH)
- Cb: 6.33 (FuelMix1, LTPH)
- Production efficiency: B: 4.39 (Inputs to FT liquids = primary output)
- Fuel Consumption: Syngas: 67.5 %, H2: 30.5 %, El: 2.0 %
- ADAPT: Investment cost: 0.505 M€/MW
- ADAPT: O&M cost: 9,857 €/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 100 %/min
- Min production: 15 %

Sifre input (FuelSplitter1):
- Type: Backpressure (Jet Fuel, Gasoline)
- Cb: 1.56
- Production efficiency: B: 5.91 (Of primary output)
- Fuel Consumption: FuelMix1: 100 %

Sifre input (LNG plant)
- Type: Condensation (LNG)
- Production efficiency: B: 4.0
- Fuel Consumption: Electricity: 4.31 %; Methane: 95.69 %
- ADAPT: Investment cost: 0.556 M€/MW
- ADAPT: O&M cost: 11,119 €/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 100 %/min
- Min production: 15 %

Sifre input (CNG compression)
- Type: Condensation (CNG)
- Production efficiency: B: 3.69
- Fuel Consumption: Electricity: 2.5 %; Methane: 97.5 %
- ADAPT: Investment cost: 0.152 M€/MW
- ADAPT: O&M cost: 3,046 €/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 100 %/min
- Min production: 15 %

Sifre input (Air Separation unit)
- Type: Condensation (Oxygen)
- Production efficiency: B: 5.5
- Fuel Consumption: Electricity: 100 %
- ADAPT: Investment cost: 2.147 M€/MW
- ADAPT: O&M cost: 64,446,831 €/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 100 %/min
- Min production: 15 %

The Surrounding Energy System

The Sifre input data for the surrounding energy system is listed below.

Sifre input (Onshore wind - large) [20]
- Maximum capacity: 9 GW
- Price: 2.1 EUR/MWh corresponding to variable O&M
- ADAPT: Investment cost: 0.83 MEUR/MW
- ADAPT: O&M cost: 21,200 EUR/MW/y
- ADAPT: Life time: 30 y

Sifre input (Offshore wind) [20]
- Maximum capacity: 30 GW
- Price: 2.2 EUR/MWh corresponding to variable O&M
- ADAPT: Investment cost: 1.71 MEUR/MW
- ADAPT: O&M cost: 32,100 EUR/MW/y
- ADAPT: Life time: 30 y

Sifre input (PV – large utility) [161]
- Maximum capacity: 12 GW
- Price: 1 EUR/MWh
- ADAPT: Investment cost: 0.56 MEUR/MW_p
- ADAPT: O&M cost: 7,400 EUR/MW/y
- ADAPT: Life time: 30 y

Sifre input (PV – small residential) [161]
- Maximum capacity: 12 GW
- Price: 1 EUR/MWh
- ADAPT: Investment cost: 0.85 MEUR/MW
- ADAPT: O&M cost: 8,500 EUR/MW/y
- ADAPT: Life time: 40 y

Sifre input (Solar district heating) [14], [105]
- Maximum production: 12 GW
- Price: 0.57 EUR/MWh corresponding to variable O&M
- ADAPT: Investment cost: 0.2957 MEUR/MW
- ADAPT: O&M cost: 1185 EUR/MW/y
- ADAPT: Life time: 20 y

Sifre input (HP – large, DH) [20]
- COP: 4.1 (Ambient heat source, no development in supply temp.)
- Variable O&M: 1.6 EUR/MWh (excl. electricity)
- ADAPT: Investment cost: 0.53 MEUR/MW_{heat}
- ADAPT: O&M cost: 2000 EUR/ MW_{heat} /y
- ADAPT: Life time: 25 y

Sifre input (HP – individual) [189]
Air to water existing one family house
- COP: 4.4 (Total efficiency, floor heating)
- Variable O&M: 1.6 EUR/MWh (excl. electricity)
- ADAPT: Investment cost: 7,600 EUR/unit = 760 EUR/ kW_{heat} = 7.6 MEUR/MW_{heat} (1 unit = 10 kW_{heat})
- ADAPT: O&M cost: 239 EUR/unit/y = 23.9 EUR/kW/y = 23,900 EUR/MW/y
- ADAPT: Life time: 18 y

Is only used to convert individual heat demand to electricity consumption in heat pumps.

Sifre input (Wood chips boiler) [20]
- Type: Heat boiler (DH)
- Production efficiency: 3.78
- Fuel Consumption: Wood chips
- Variable O&M: 5.4 EUR/MWh
- ADAPT: Investment cost: 0.8 M€/MW
- ADAPT: O&M cost: 16,000 EUR/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 15 MW/min

- Min production: 15 %

Sifre input (Gas boiler) [14]
- Type: Heat boiler (HTPH)
- Production efficiency: 3.64
- Fuel Consumption: Methane, Syngas and/or Hydrogen
- Variable O&M: 1.1 EUR/MWh
- ADAPT: Investment cost: 0.05 M€/MW
- ADAPT: O&M: 1700 EUR/MW/y
- ADAPT: Life time: 25 y
- Ramping up/down: 15 MW/min
- Min production: 15 %

Sifre input (Wood chips CHP) [20]
- Type: Backpressure (Electricity and DH)
- Production efficiency: 15 (Of primary input)
- Cb: 0.34
- Fuel Consumption: Wood chips
- Variable O&M: 4 EUR/MWh
- ADAPT: Investment cost: 2.62 MEUR/MW
- ADAPT: O&M cost: 41,028 EUR/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 40 MW/min
- Min production: 15 %

Sifre input (Gas turbine - HTPH) [20]
- Type: Backpressure (Electricity and HTPH)
- Production efficiency: 8.37 (Of primary input)
- Cb: 1.5
- Fuel Consumption: Methane, syngas and hydrogen
- Variable O&M: 4 EUR/MWh
- ADAPT: Investment cost: 0.52 MEUR/MW
- ADAPT: O&M cost: 18,000 EUR/MW/y
- ADAPT: Life time: 25 y
- Ramping up/down: 40 MW/min
- Min production: 20 %

Sifre input (Gas CHP NG) [190]
- Type: Backpressure (Electricity and DH)
- Production efficiency: 8.37 (Of primary input)
- Cb: 1.5
- Fuel Consumption: Methane
- Variable O&M: 4 EUR/MWh
- ADAPT: Investment cost: 0.52 MEUR/MW
- ADAPT: O&M cost: 18,000 EUR/MW/y
- ADAPT: Life time: 25 y
- Ramping up/down: 40 MW/min

- Min production: 15 %

Sifre input (Gas CHP NG/BG) [190]
- Type: Backpressure (Electricity and DH)
- Production efficiency: 8.37 (Of primary input)
- Cb: 1.5
- Fuel Consumption: Methane and/or Biogas
- Variable O&M: 4 EUR/MWh
- ADAPT: Investment cost: 0.52 MEUR/MW
- ADAPT: O&M cost: 18,000 EUR/MW/y
- ADAPT: Life time: 25 y
- Ramping up/down: 40 MW/min
- Min production: 15 %

Sifre input (Electric boiler - HTPH) [191]
- Type: Condensation (HTPH)
- Production efficiency: 3.79
- Fuel Consumption: Electricity
- Variable O&M: 1.2 EUR/MWh
- ADAPT: Investment cost: 0.06 MEUR/MW
- ADAPT: O&M cost: 920 EUR/MW/y
- ADAPT: Life time: 20 y
- Ramping up/down: 60 MW/min
- Min production: 15 %

Sifre input (Oxygen storage) [105]
- ADAPT: Investment cost: 0.38 MEUR/MWh
- ADAPT: Life time: 30 y
- Charge efficiency: 99 %
- Discharge efficiency: 99 %
- Loss pr. hour: 0.1 %

Sifre input (Biogas storage) [105]
- ADAPT: Investment cost: 0.00067 MEUR/MWh
- ADAPT: Life time: 20 y
- Charge efficiency: 99 %
- Discharge efficiency: 99 %
- Loss pr. hour: 0.1 %

Sifre input (Methane storage) [105]
- Charge efficiency: 99 %
- Discharge efficiency: 99 %
- Loss pr. hour: 0.01 %

Sifre input (Syngas storage) [105]
- ADAPT: Investment cost: 0.080 MEUR/MWh
- ADAPT: Life time: 30 y

- Charge efficiency: 99 %
- Discharge efficiency: 99 %
- Loss pr. hour: 0.1 %

Sifre input (Hydrogen storage) [192]
- ADAPT: Investment cost: 0.0033 MEUR/MWh
- ADAPT: Life time: 30 y
- Charge efficiency: 98 %
- Discharge efficiency: 98 %
- Loss pr. hour: 0.1 %

Based on a small existing cavern.

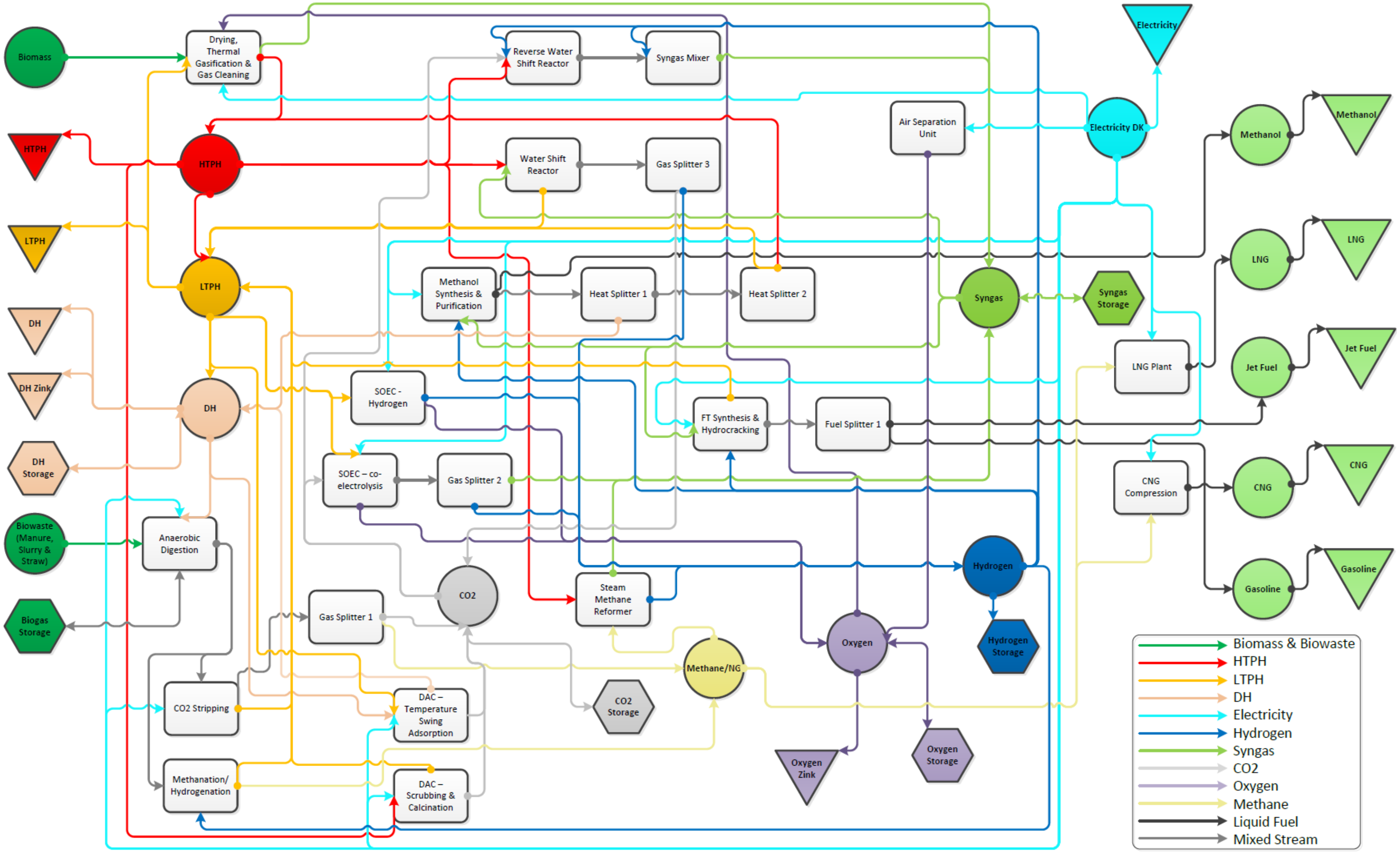
Sifre input (CO_2 storage) [193]
- ADAPT: Investment cost: 0.000132 MEUR/MWh
- ADAPT: O&M cost: 21.6 EUR/MWh/year
- ADAPT: Life time: 20 y
- Charge efficiency: 99 %
- Discharge efficiency: 99 %
- Loss pr. hour: 0.1 %

Sifre input (Battery storage) [105]
- ADAPT: Investment cost: 0.1008 MEUR/MWh
- ADAPT: Life time: 12 y
- Charge efficiency: 95 %
- Discharge efficiency: 95 %
- Loss pr. hour: 0.1 %

Sifre input (HTPH storage) [105]
- ADAPT: Investment cost: 0.00269 MEUR/MW
- ADAPT: Life time: 25 y
- Charge efficiency: 90 %
- Discharge efficiency: 90 %
- Loss pr. hour: 1.0 %

Sifre input (DH storage) [105]
- ADAPT: Investment cost: 0.0023 MEUR/MW
- ADAPT: Life time: 30 y
- Charge efficiency: 99 %
- Discharge efficiency: 99 %
- Loss pr. hour: 0.1 %

Appendix G – Sifre Modelling of Fuel Production Pathways



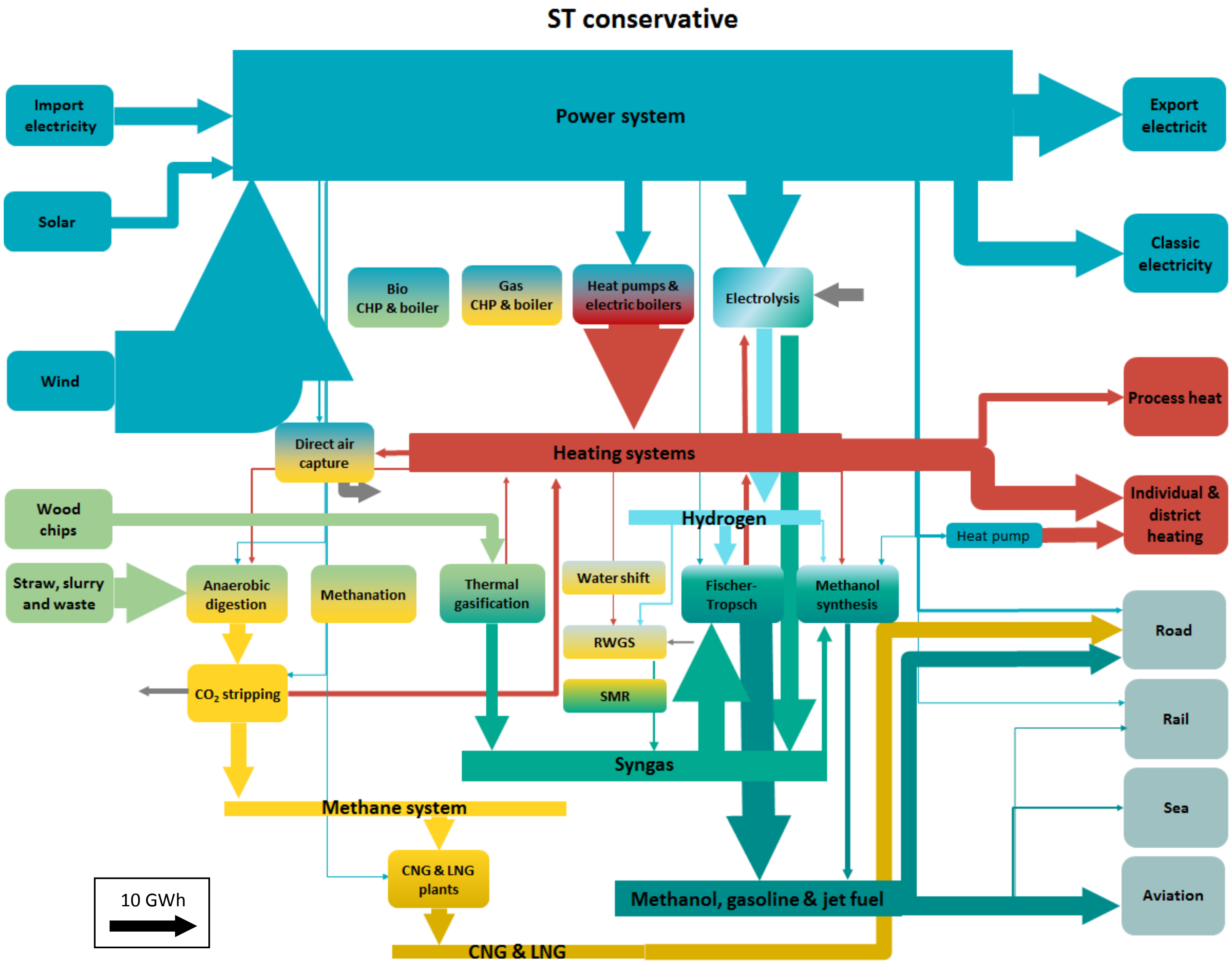
Appendix H – Sankey Diagrams

This appendix includes Sankey diagrams illustrating the energy flows in all 15 base simulations. Table 29 illustrates the colour codes used in the Sankey diagrams.

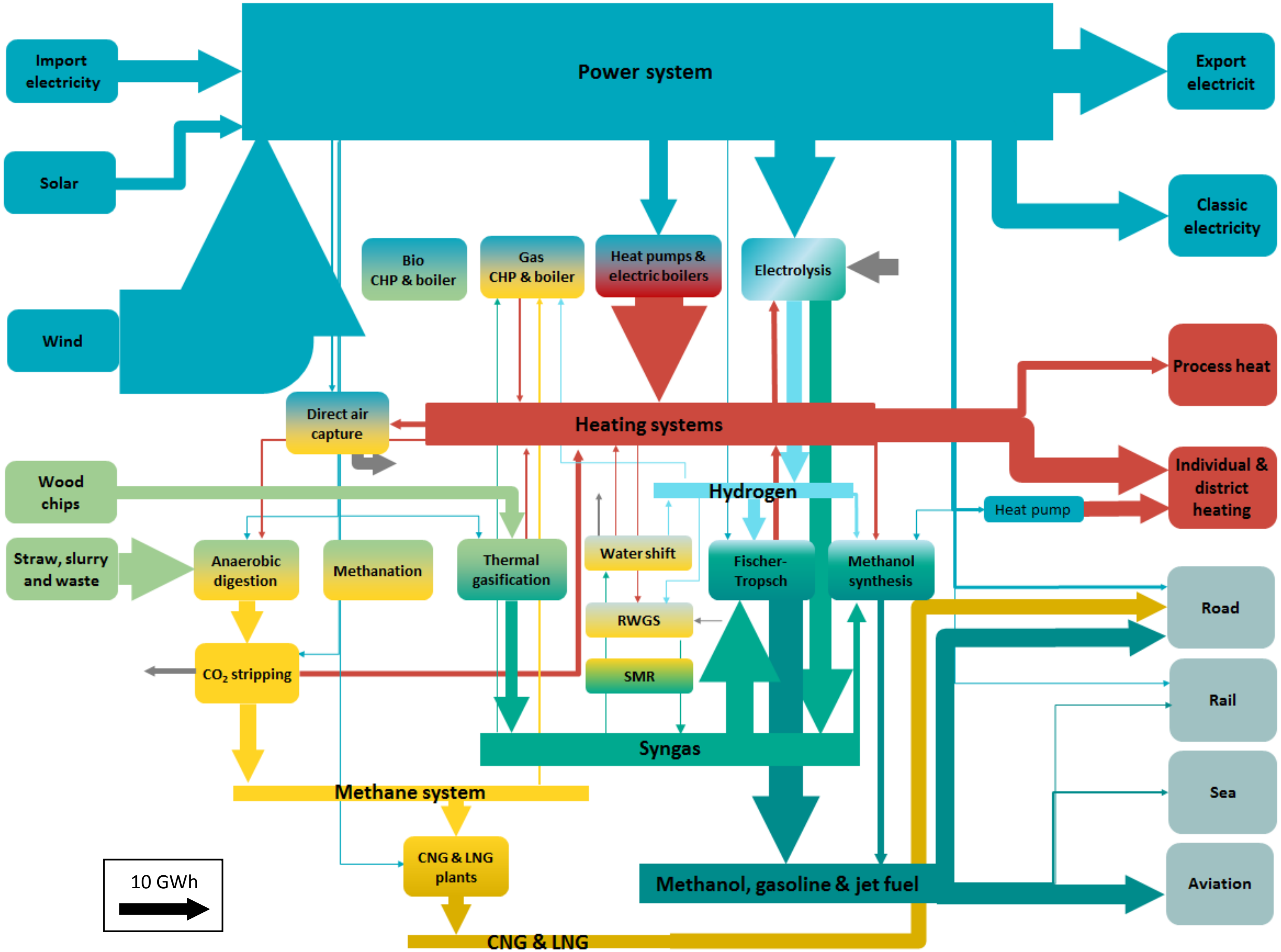
	Bio input
	Methane and biogas
	Syngas
	Methanol, gasoline & jet fuel
	Hydrogen
	Electricity
	Heat
	CNG & LNG
	CO2

Table 29 - colour codes used in the Sankey diagrams.

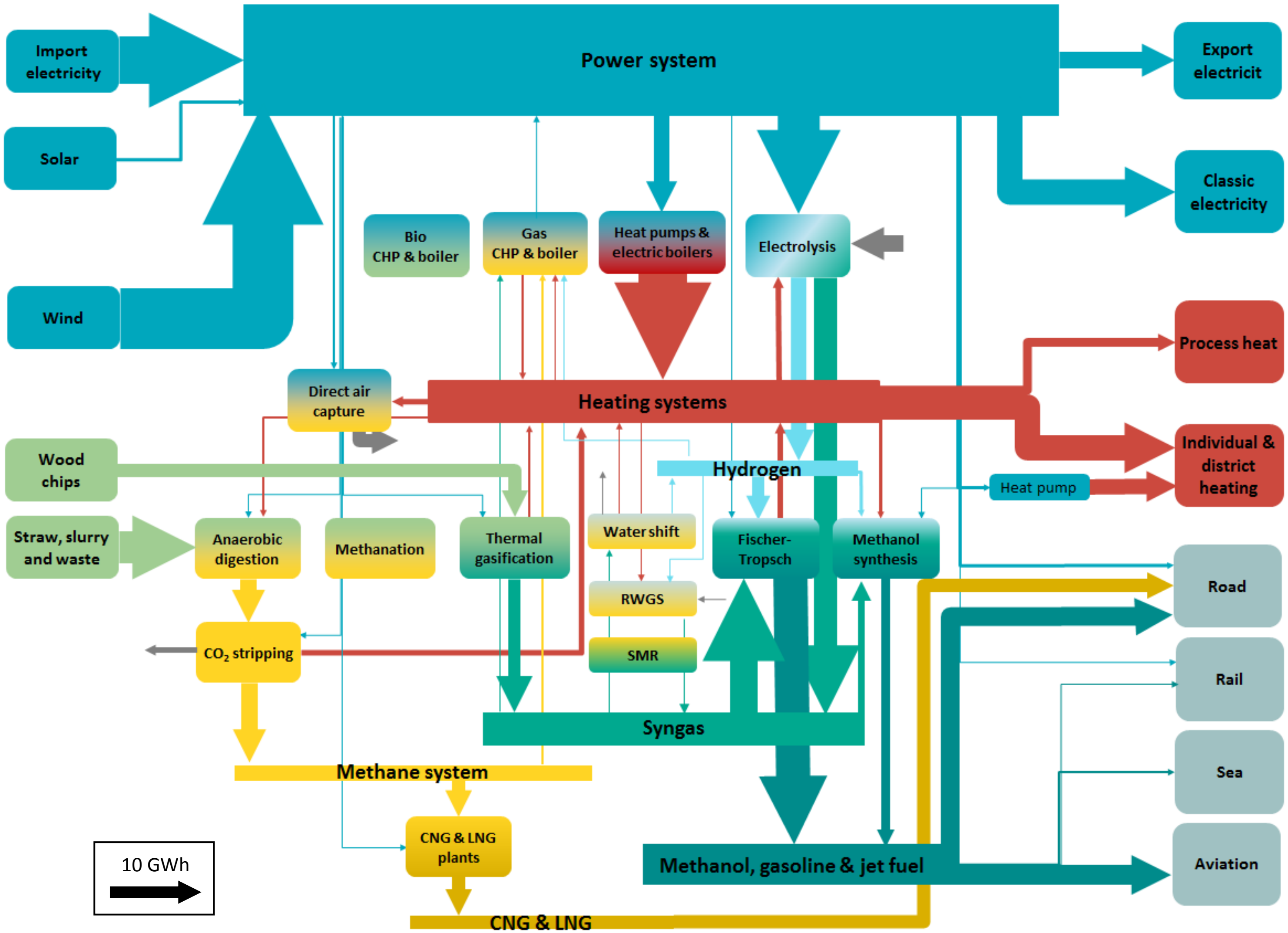
"Conservative"



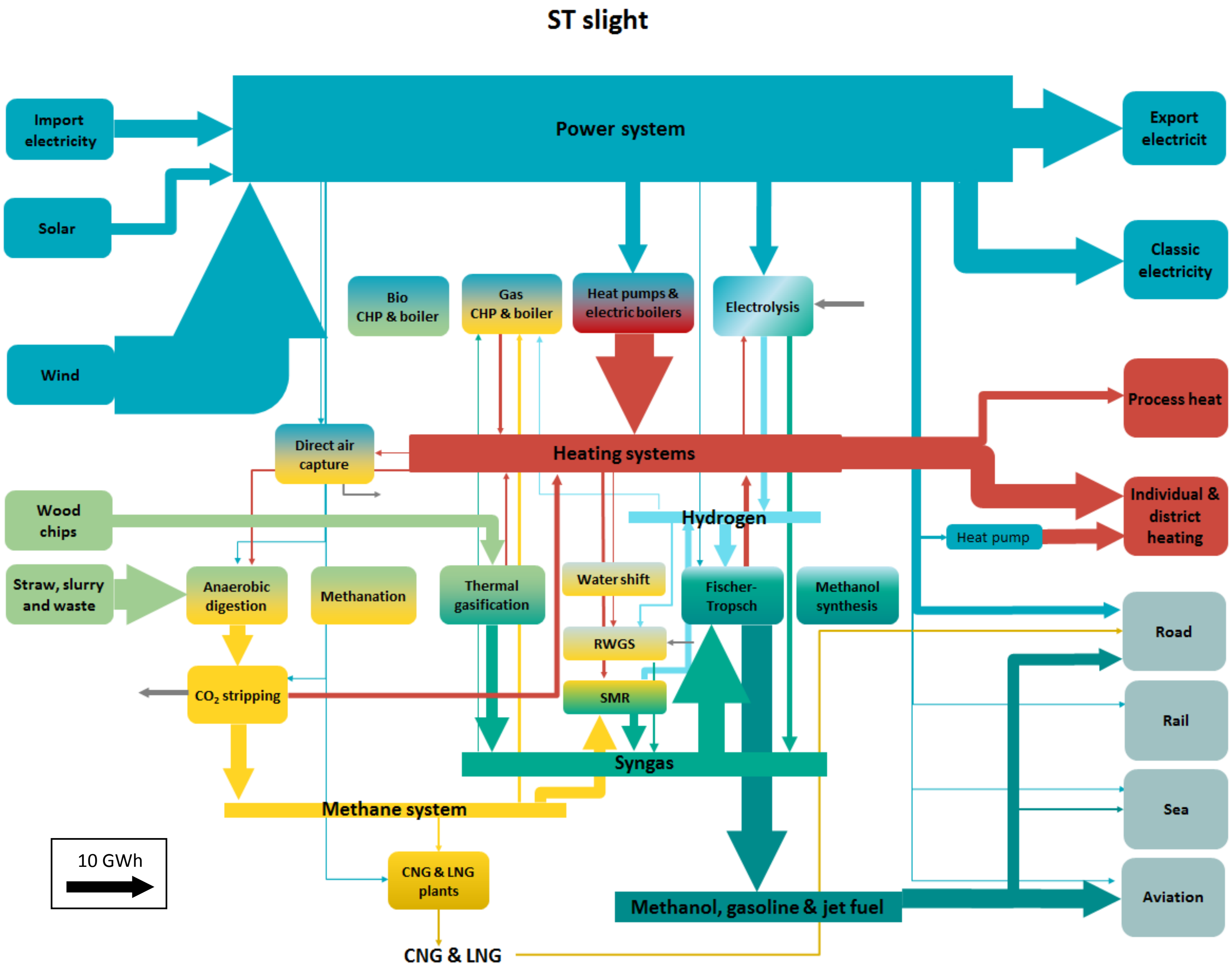
DG conservative



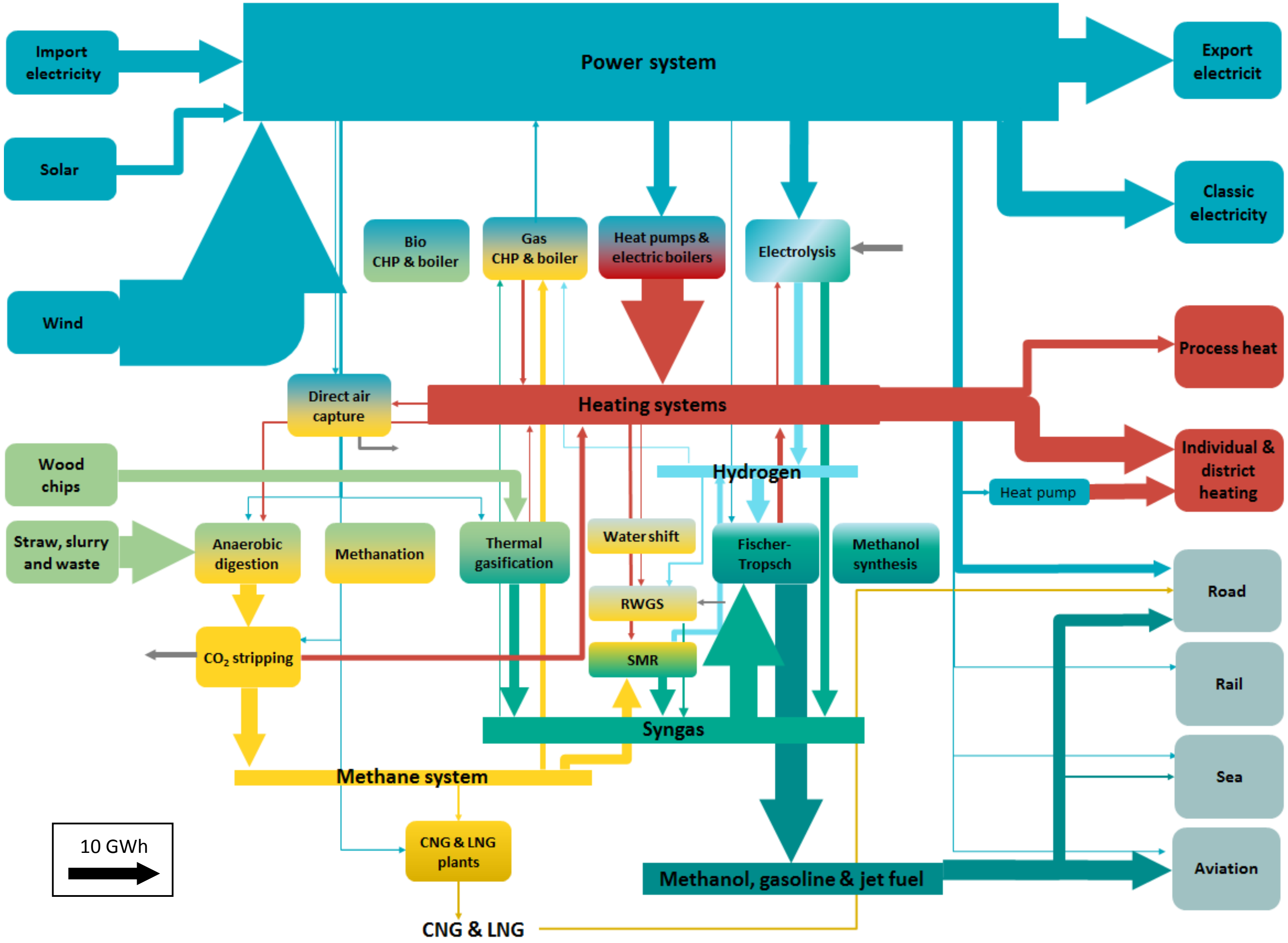
GCA conservative



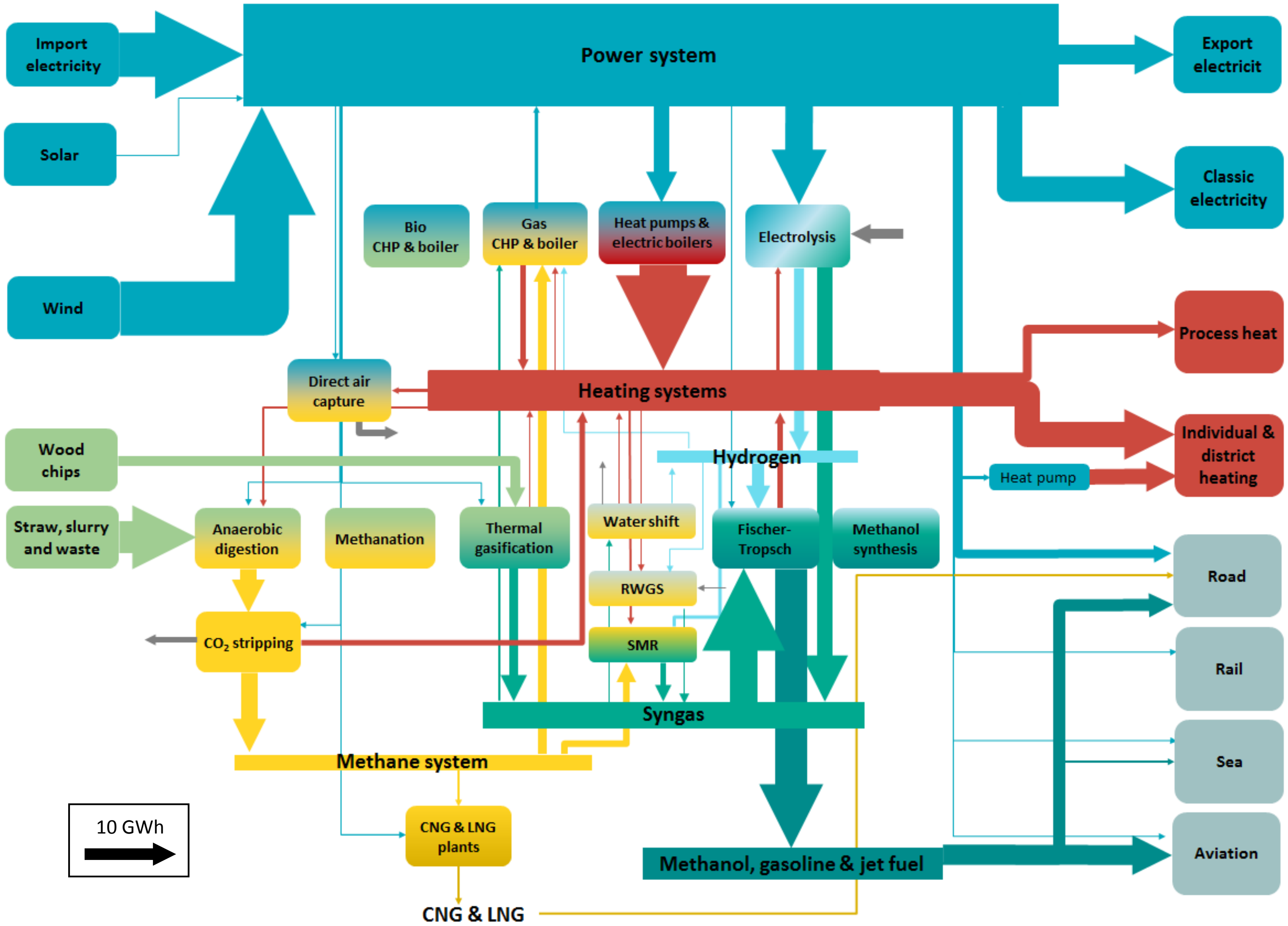
"Slight"


ST slight
Power system
Import electricity
Solar
Wind
Export electricit
Classic electricity
Bio CHP & boiler
Gas CHP & boiler
Heat pumps & electric boilers
Electrolysis
Process heat
Direct air capture
Heating systems
Individual & district heating
Heat pump
Wood chips
Hydrogen
Straw, slurry and waste
Anaerobic digestion
Methanation
Thermal gasification
Water shift
Fischer-Tropsch
Methanol synthesis
Road
RWGS
CO_2 stripping
SMR
Rail
Syngas
Sea
Methane system
10 GWh
CNG & LNG plants
Methanol, gasoline & jet fuel
Aviation
CNG & LNG

DG slight

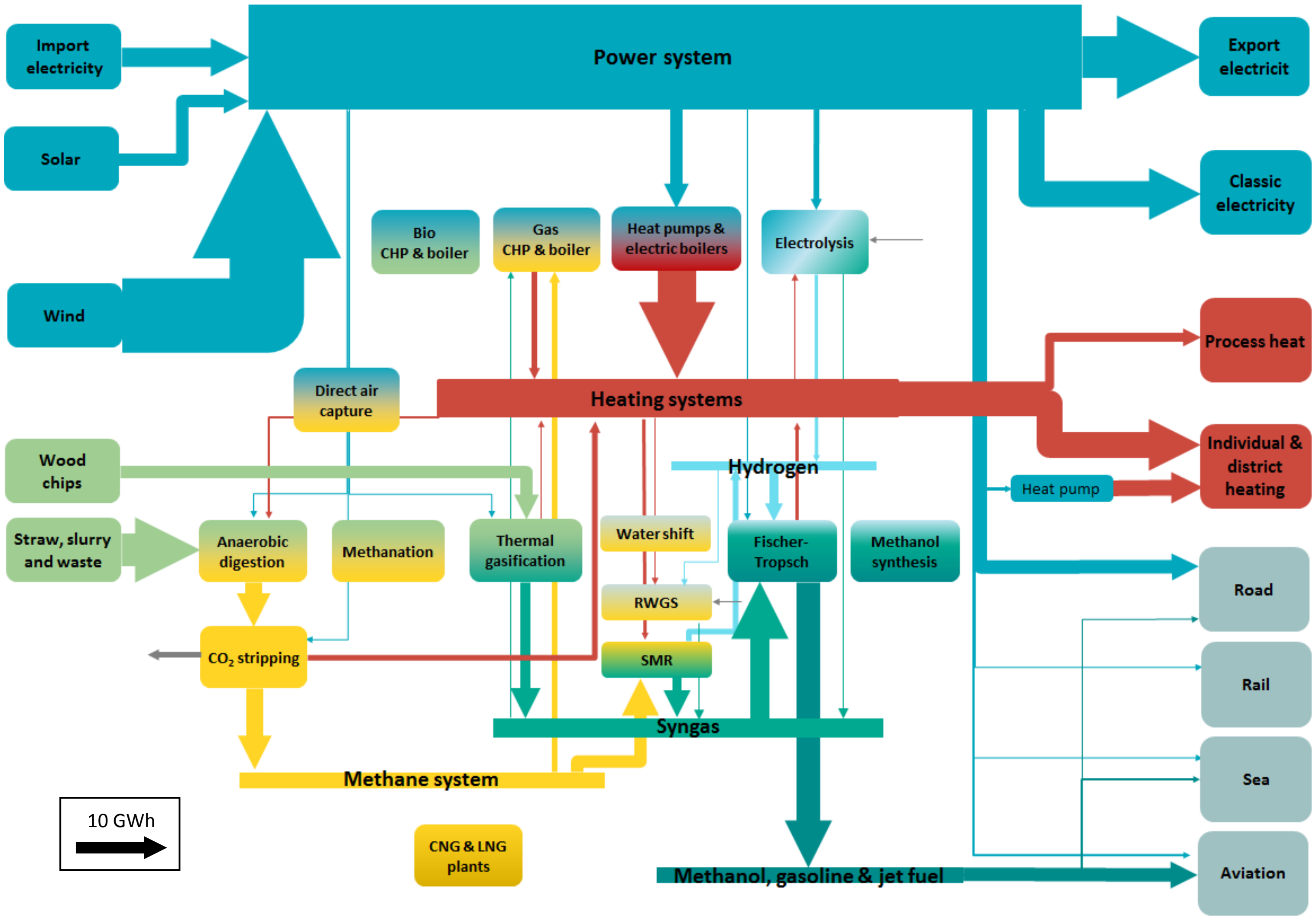

Import electricity
Solar
Wind
Power system
Export electricit
Classic electricity
Bio CHP & boiler
Gas CHP & boiler
Heat pumps & electric boilers
Electrolysis
Process heat
Direct air capture
Heating systems
Individual & district heating
Heat pump
Wood chips
Hydrogen
Straw, slurry and waste
Anaerobic digestion
Methanation
Thermal gasification
Water shift
Fischer-Tropsch
Methanol synthesis
Road
RWGS
CO2 stripping
SMR
Rail
Syngas
Sea
Methane system
10 GWh
CNG & LNG plants
Aviation
Methanol, gasoline & jet fuel
CNG & LNG

GCA slight

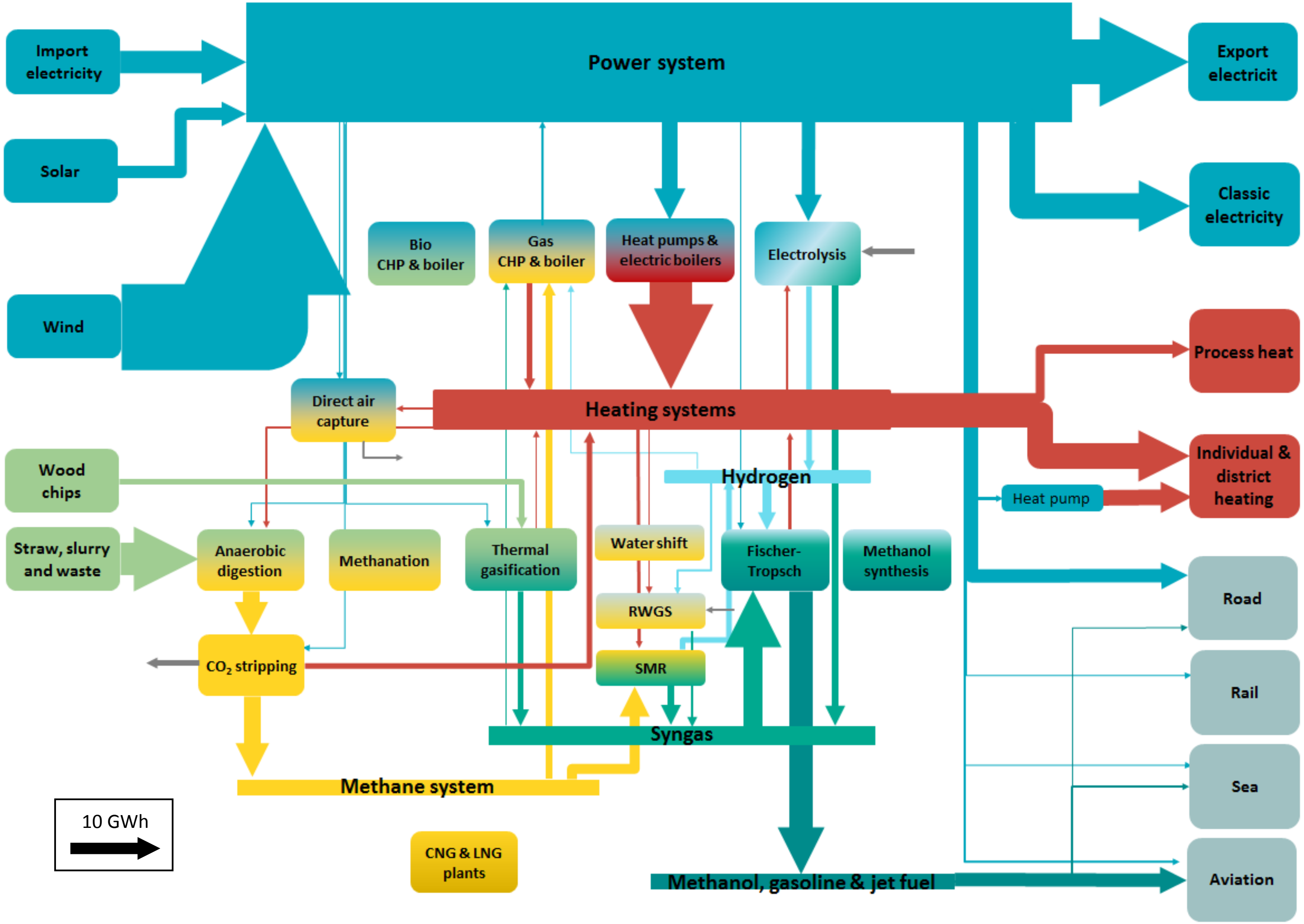

Import electricity
Solar
Wind
Power system
Export electricit
Classic electricity
Bio CHP & boiler
Gas CHP & boiler
Heat pumps & electric boilers
Electrolysis
Process heat
Direct air capture
Heating systems
Individual & district heating
Wood chips
Hydrogen
Heat pump
Straw, slurry and waste
Anaerobic digestion
Methanation
Thermal gasification
Water shift
Fischer-Tropsch
Methanol synthesis
Road
RWGS
CO_2 stripping
SMR
Rail
Syngas
Sea
Methane system
10 GWh
CNG & LNG plants
Methanol, gasoline & jet fuel
Aviation
CNG & LNG

"Moderate"

ST moderate

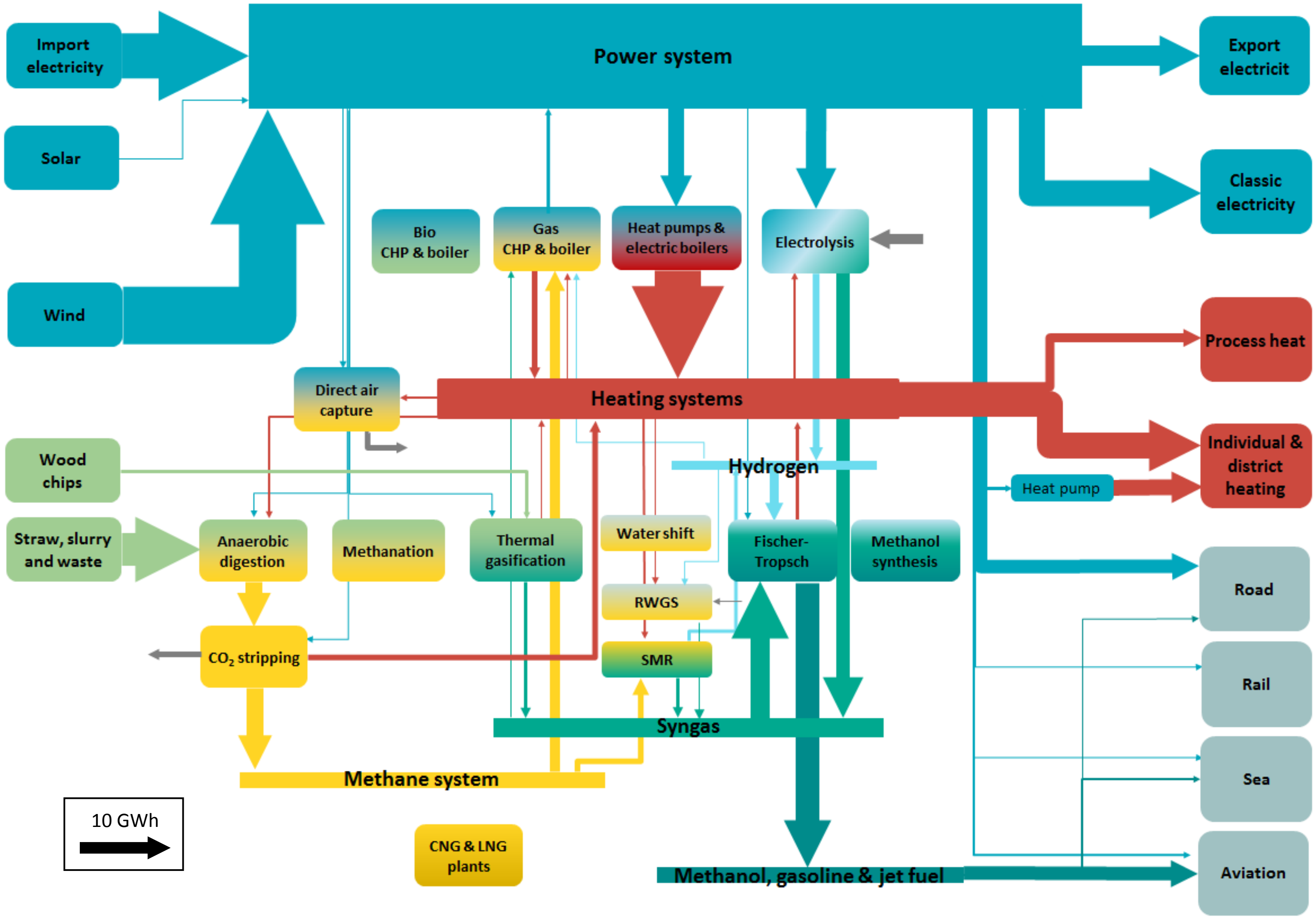


DG moderate

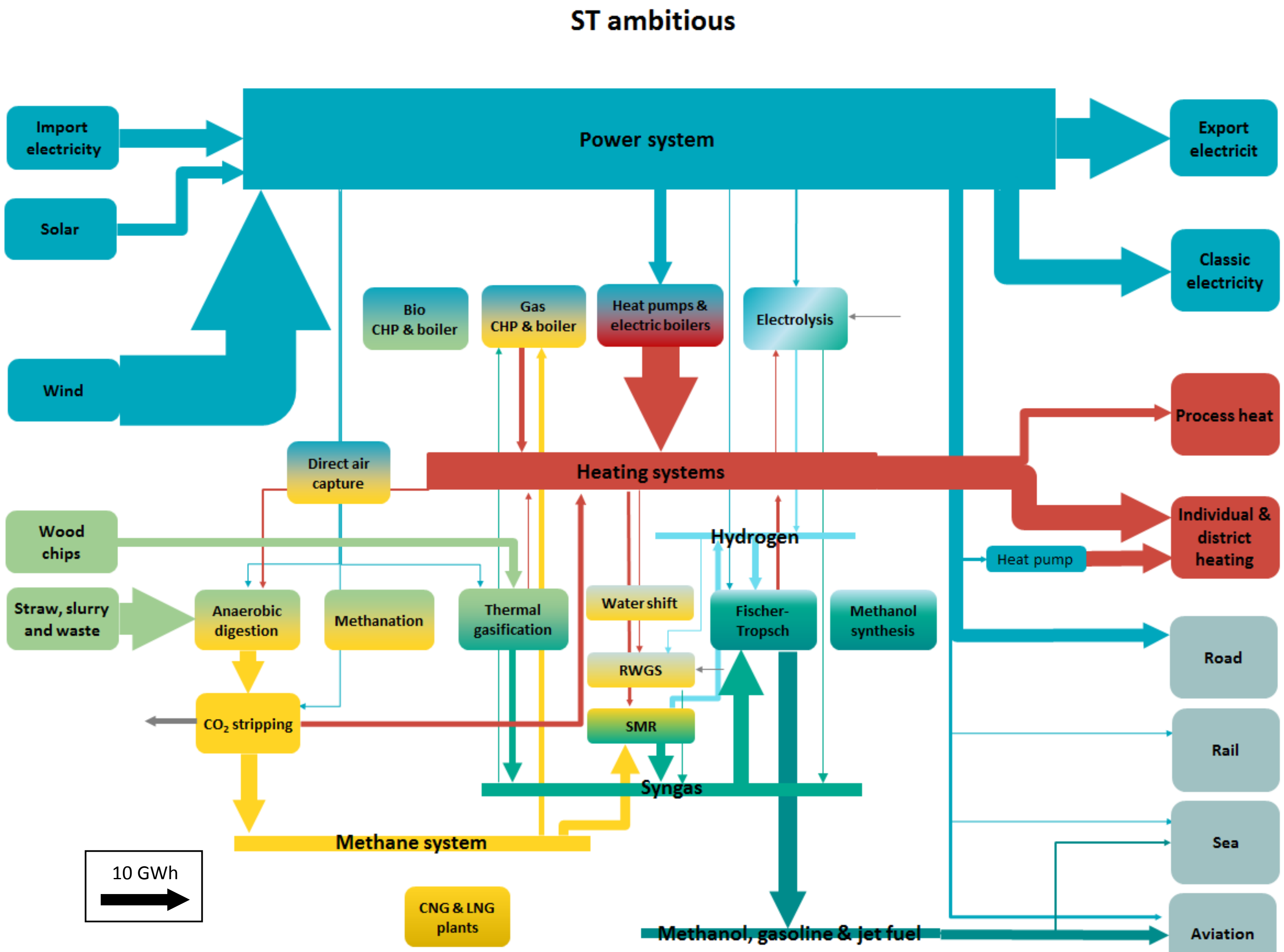


Power system
Import electricity
Solar
Wind
Export electricit
Classic electricity
Bio CHP & boiler
Gas CHP & boiler
Heat pumps & electric boilers
Electrolysis
Process heat
Direct air capture
Heating systems
Individual & district heating
Heat pump
Wood chips
Hydrogen
Straw, slurry and waste
Anaerobic digestion
Methanation
Thermal gasification
Water shift
Fischer-Tropsch
Methanol synthesis
Road
RWGS
CO2 stripping
SMR
Rail
Syngas
Sea
Methane system
10 GWh
CNG & LNG plants
Methanol, gasoline & jet fuel
Aviation

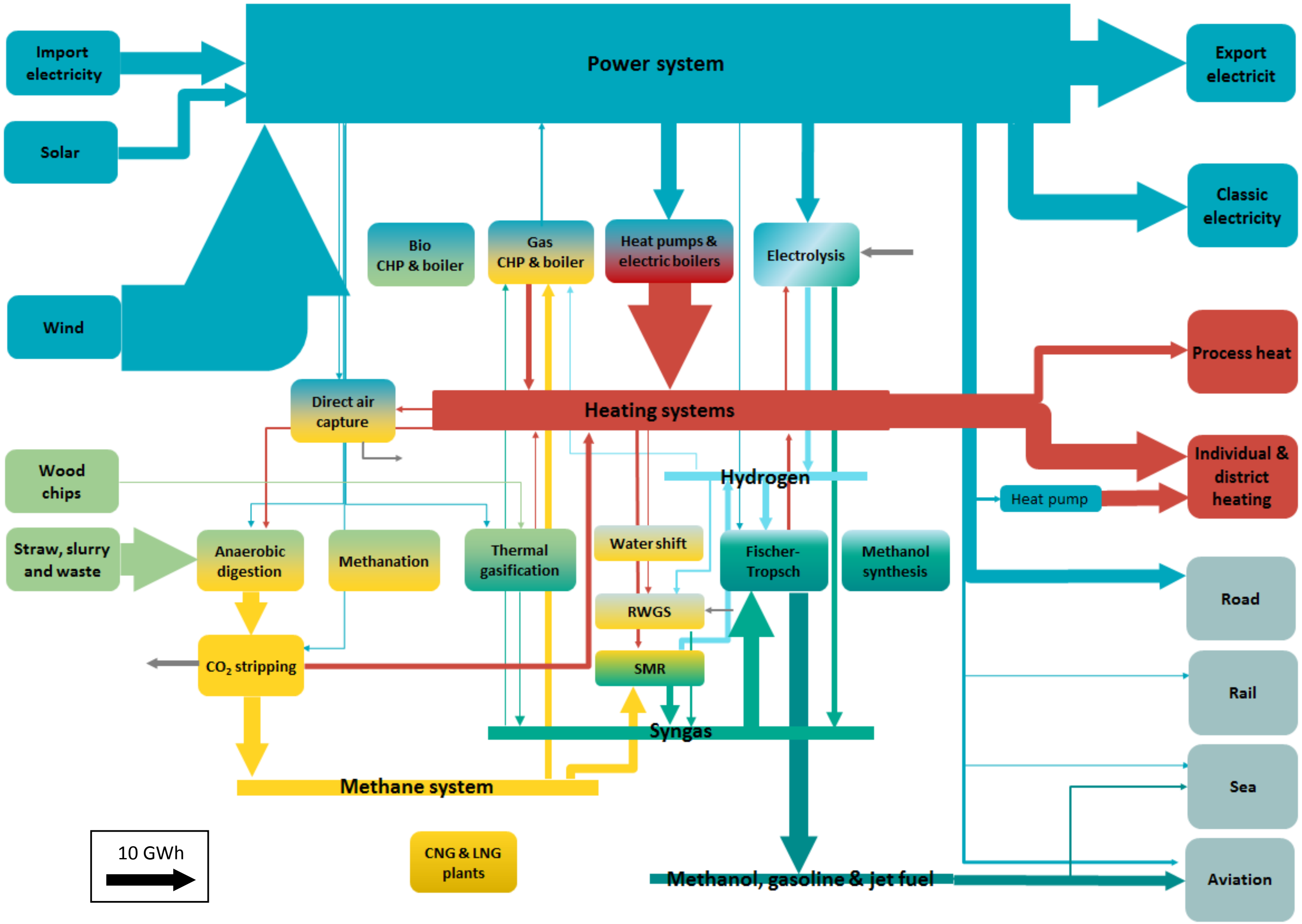
GCA moderate



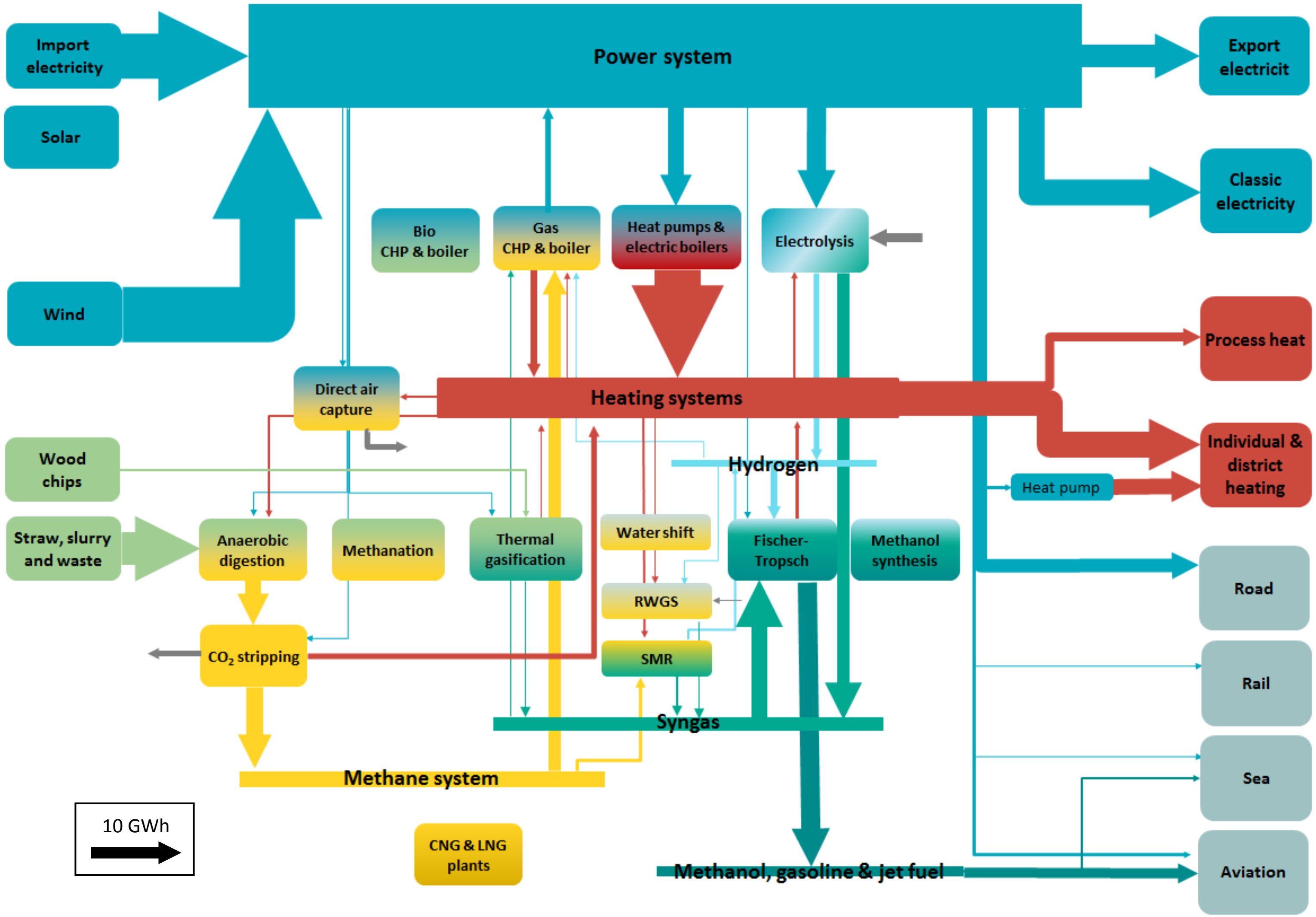
14.1.1 "Ambitious"



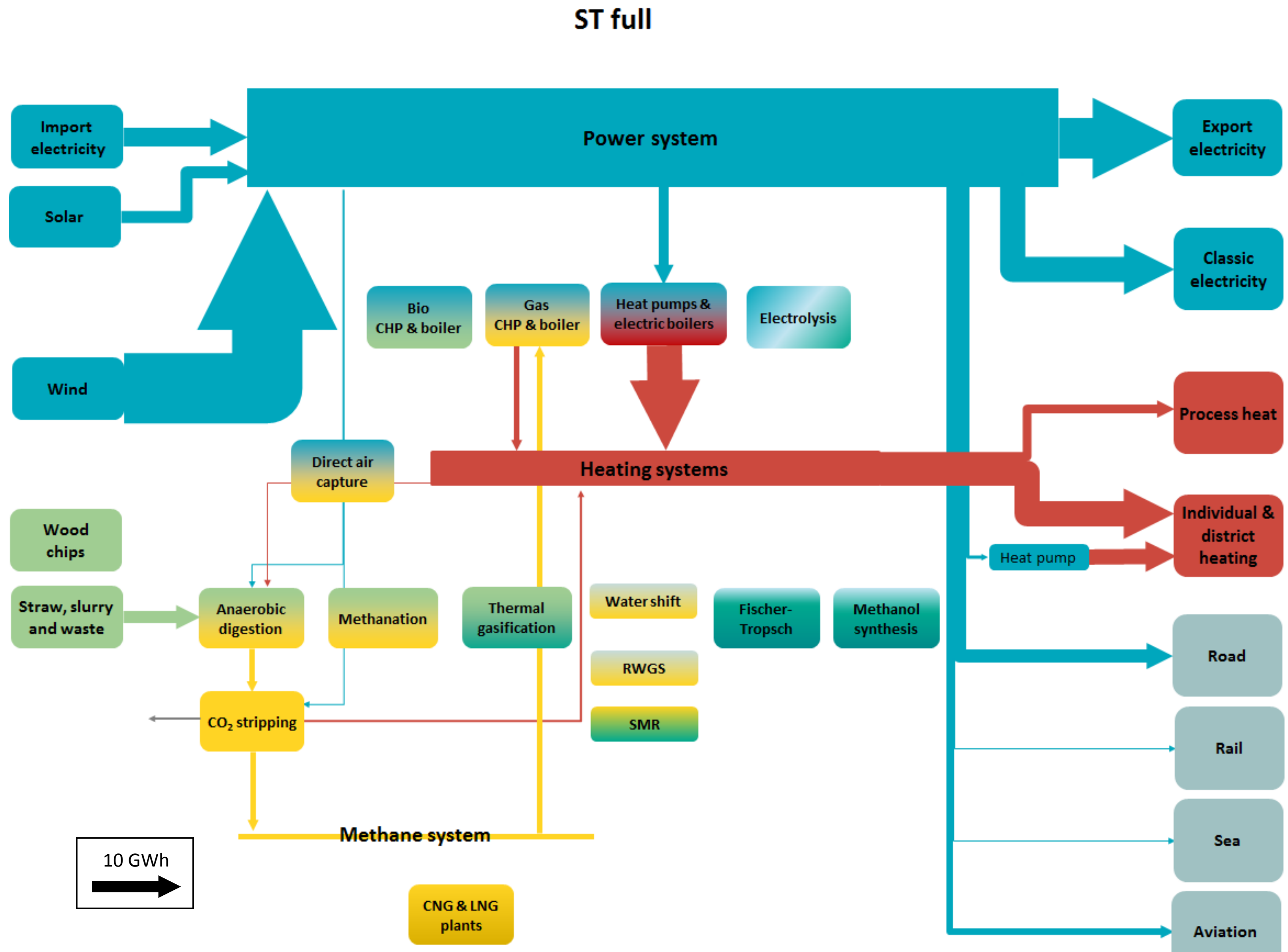
DG ambitious



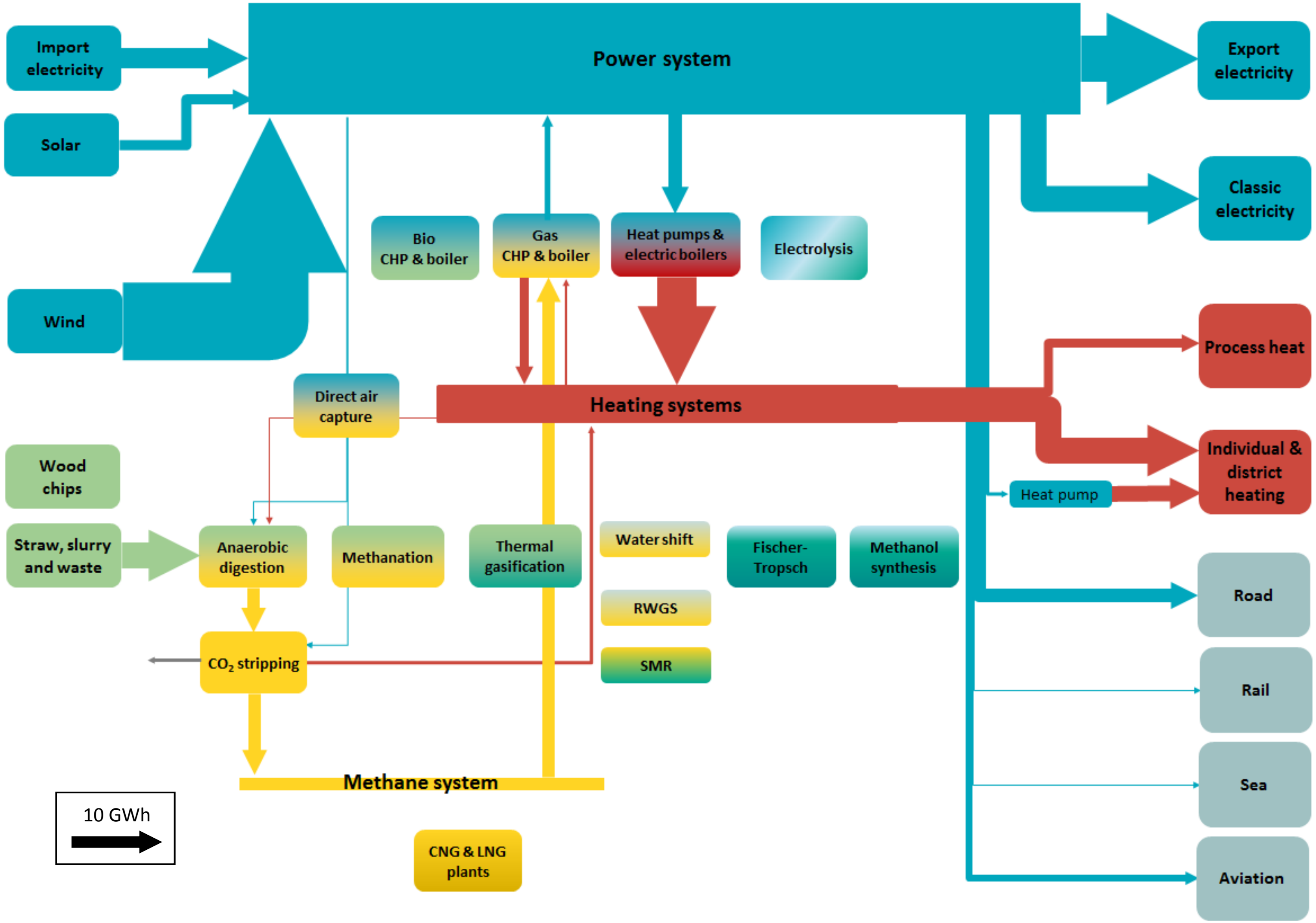
GCA ambitious



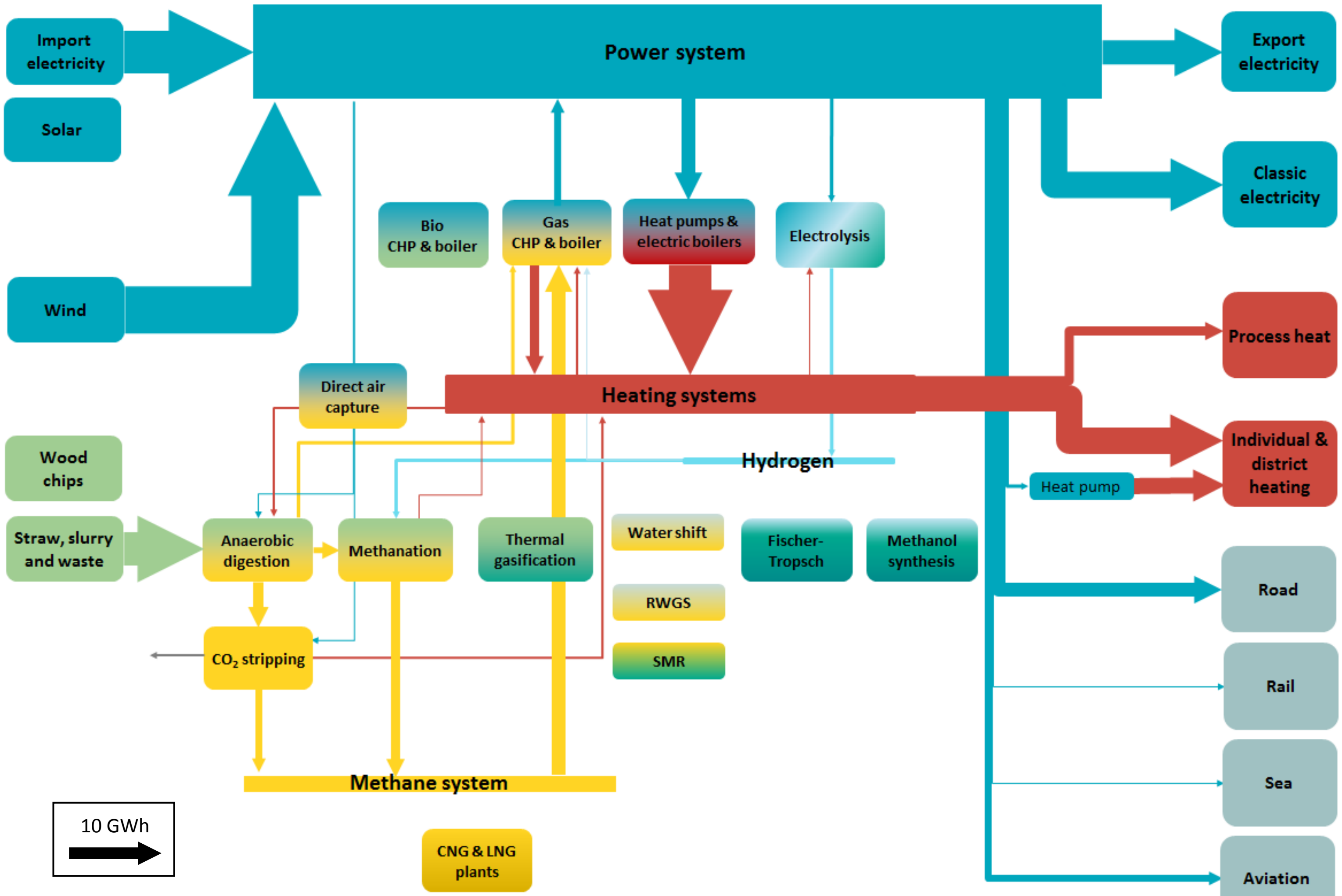
14.1.2 "Full"


ST full
Power system
Import electricity
Solar
Wind
Export electricity
Classic electricity
Bio CHP & boiler
Gas CHP & boiler
Heat pumps & electric boilers
Electrolysis
Process heat
Direct air capture
Heating systems
Individual & district heating
Heat pump
Wood chips
Straw, slurry and waste
Anaerobic digestion
Methanation
Thermal gasification
Water shift
RWGS
SMR
Fischer-Tropsch
Methanol synthesis
Road
Rail
Sea
Aviation
CO_2 stripping
Methane system
10 GWh
CNG & LNG plants

DG full


Import electricity
Solar
Wind
Power system
Export electricity
Classic electricity
Bio CHP & boiler
Gas CHP & boiler
Heat pumps & electric boilers
Electrolysis
Direct air capture
Heating systems
Process heat
Individual & district heating
Heat pump
Wood chips
Straw, slurry and waste
Anaerobic digestion
Methanation
Thermal gasification
Water shift
RWGS
SMR
Fischer-Tropsch
Methanol synthesis
CO2 stripping
Methane system
CNG & LNG plants
Road
Rail
Sea
Aviation
10 GWh

GCA full


Import electricity
Solar
Wind
Power system
Export electricity
Classic electricity
Bio CHP & boiler
Gas CHP & boiler
Heat pumps & electric boilers
Electrolysis
Process heat
Direct air capture
Heating systems
Individual & district heating
Wood chips
Hydrogen
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Anaerobic digestion
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Thermal gasification
Water shift
Fischer-Tropsch
Methanol synthesis
Road
RWGS
CO_2 stripping
SMR
Rail
Sea
Methane system
10 GWh
CNG & LNG plants
Aviation

Appendix I – Merit Order Curve for Fuels for Transportation with Tariffs

Figure 64 shows the merit order curve for fuels for transportation for the 15 original simulations with tariffs included on inputs of electricity, heat and gas for the production units. The value of the tariffs is the same as used in the "back of an envelope" calculation for the total cost of infrastructure in the *Discussion*.

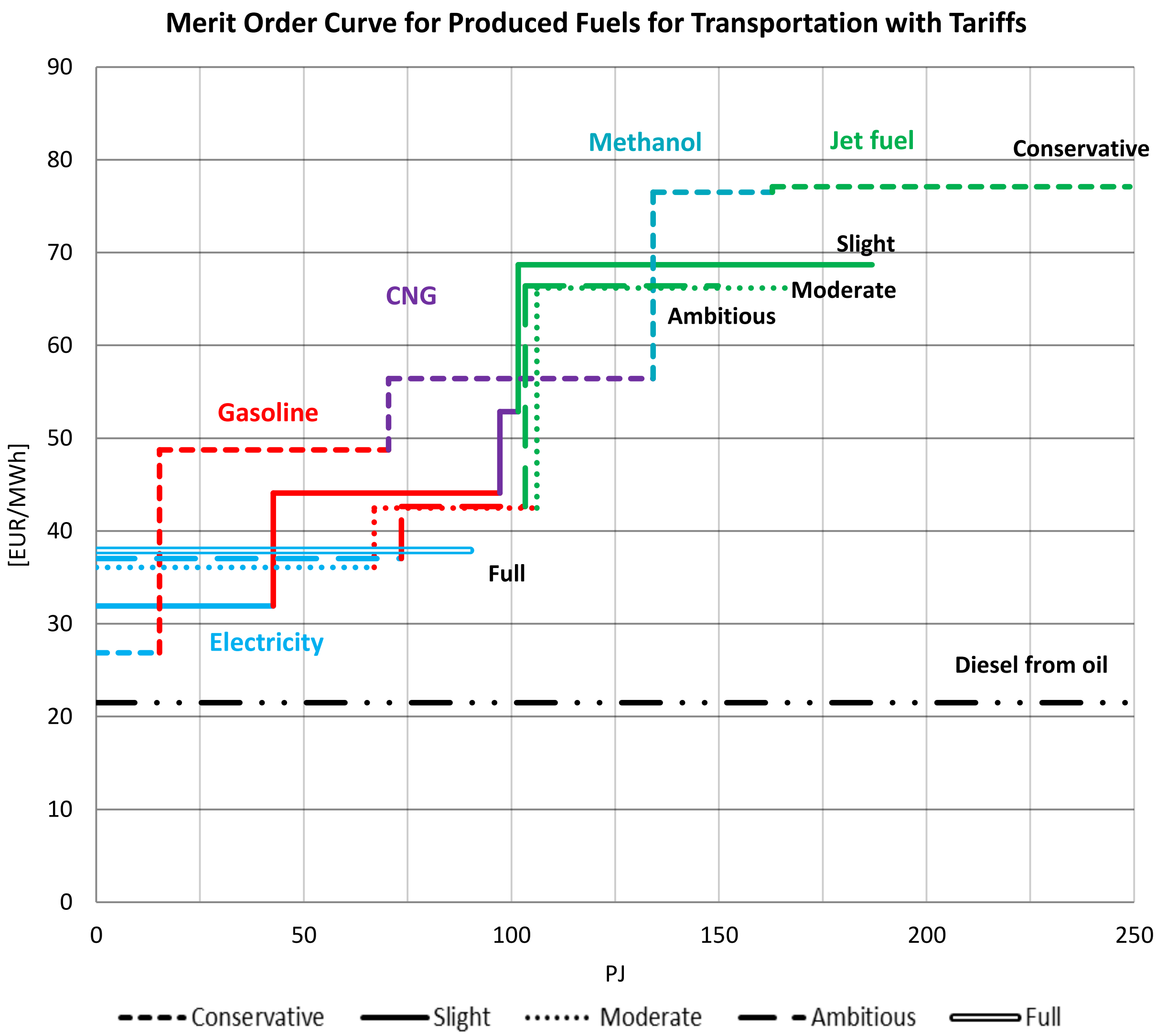

Figure 64 - Merit order curve for fuels for transportation with tariffs for the five electrification scenarios based on the weighted average production cost pr. primary output for all produced fuels. The specific fuels are represented by different colours shown as the colour of the text. The different scenarios are also represented with text. Diesel from fossil oil reserves without externality costs is shown as a reference.