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Method for comparing efficiency and system integration potential for biomass-based fuels production pathways

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ABSTRACT

Biomass are seen as an important resource for fuel production in the maritime and aviation sectors. Sustainable biomass, however, is a limited resource and it is therefore important to utilize it as efficiently as possible. This study developed a modelling frame to compare the performance of various fuel production pathways from lignocellulosic biomass. It considers both the energy efficiencies of the processes and their potential to be integrated into future fossil free energy systems. The model provides a general framework for converting experimental results and process simulation to higher level techno-economic- and life-cycle analysis in a comparable manner. In this study the performance of six technology pathways from three different categories; direct liquefaction, power-to-X, and gas-to-liquid, were evaluated. The results showed that from a socio-economic perspective investment into renewable electricity and hydrogen production were the dominating factors. This resulted in the direct liquefaction options being both the cheapest and most energy efficient while the power-to-X options were the most expensive and less efficient. On the other hand, the extensive use of hydrogen in power-to-X and gas-to-liquid pathways allows for a high utilization of the carbon content in the biomass.

1. Introduction

The EU aims to reduce the greenhouse gas emissions with 55% by 2030 and achieve climate neutrality by 2050 (European Commission, 2021a). One of the biggest challenges in reaching that goal is the transportation sector which has the largest reliance on fossil fuels of any sector and accounts for 37% of total CO_2 emissions in 2020 worldwide (International Energy Agency, 2021). The transport sector has seen the fastest growth in CO_2 emissions of any sector due to increasing demand and limited uptake of renewable alternatives. In Europe the Renewable Energy Directive (REDII) defined a target of 14% renewable energy in the transport sector by 2030. Within this target there is also a dedicated target of 3.5% for advanced biofuels produced from sustainable feedstocks specified as part of RED II. These are waste biomass feedstocks that does not compete with food production (European Commission, 2030).

As part of the European Green Deal, EU is working on revision of the energy and transport related legislation that aim to align current laws with the 2030 and 2050 ambitions. The proposal includes blending obligations for aviation fuel suppliers. From 2025 aviation fuel made available in EU airports must contain 2% sustainable aviation fuel (SAF), increasing to 5% by 2030, 32% by 2040, and 63% by 2050 (European Commission, 2021b). The maritime sector can utilize a wide variety of different fuels including hydrogen or electricity on shorter travel distances, biomass-based liquid fuels, methanol, ammonia etc. Therefore, the proposed legislation from EU is not defined as blending obligations, but instead as a reduction in CO_2 emission relative to 2020 values. The ‘FuelEU Maritime’ proposal defines reductions of 6% by 2030, 26% by 2040, and 75% by 2050 (Comission, 2021). Similar initiatives are made around the world. In the US it is called the Low Carbon Fuel Standard and in Africa strategy for reducing CO_2 emission from transport are discussed in the Africa Transport Policy Program (SSATP). All these initiatives for both aviation and maritime should provide the necessary incentives for industries to start investing in the new technology.

There are various technologies for producing sustainable transportation fuels. Common for all of them is that they are all still under

Abbreviations: SAF, sustainable aviation fuel; LCA, Life Cycle Analysis; GHG, Greenhouse Gas; P2X, Power to X; G2L, Gas to Liquid; eRWGS, electric Reverse Water Gas Shift; HTL, Hydrothermal Liquefaction; FT, Fischer Tropsch; LPG, Liquified Petroleum Gas; PSA, Pressure Swing Absorption.

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development as none of them has been implemented on large scale compared to the existing fossil-based fuels. Comparison and analysis of these technology pathways are important to evaluate their feasibility and potential. In a study by Tanzer et al. (2019) the performance of three technologies for producing maritime quality fuels, Hydrothermal Liquefaction, fast pyrolysis, and gasification and Fischer Tropsch, were evaluated using an interlinked spreadsheet modelling approach. The work included both mass and energy balances, CAPEX/OPEX for a single plant and greenhouse gas (GHG) reductions compared to fossil-based fuels. Another study investigating marine fuel production is Korberg et al. (2021a). Here a total of 18 different production routes are considered including biofuels, bio-electrofuels, electrofuels, liquefied hydrogen, and electricity. The study was focusing on the total cost of ownership which is a summation of fuel-, propulsion-, and storage costs. For sustainable jet fuel production, a study by de Jong et al. (de Jong et al., 2015) investigated both the short- and long-term feasibility of six production pathways. The study was based on a techno-economic framework from existing process modelling data and the focus was on minimum fuel selling price estimations and different implementation strategies. A similar study by Cervi et al. (2020) also investigated the techno economic potential for sustainable jet fuel. Here the focus was specifically on production in Brazil and the study had a larger focus on biomass availability and cost.

To evaluate the performance and the applicability of different production pathways, several different methods can be used including experimental work, process simulations, techno-economic assessment, life cycle analysis (LCA), and energy system and integration analysis. All these different methods are required in the development and commercialisation of sustainable transportation fuels.

Experimental work has been carried out over the years for many different processes (Jensen et al., 2017) (Snowden-Swan et al., 2020) (Jones et al., 2013) (Christensen et al., 2021). Comprehensive experimental work is the foundation for further analysis and is thereby essential to both validate the process and provide important performance characteristics. To translate the experimental results to full scale feasibility studies, process simulations can be conducted. These are often directly linked to experimental data and by using commercial modelling software, provides the scaled-up performance of the technology. This also allows for combining different processes to benefit from potential synergies (Hannula, 2015) (Lozabo et al., 2020).

Techno-economic assessment and LCA are used to evaluate the economic perspective and environmental impact of various technology pathways (de Jong et al., 2017) (de Jong et al., 2018) (Tanzer et al., 2019) (da Silva et al., 2016). The results usually boil down to an estimation of the minimum fuel selling price or greenhouse gas emission (GHG) reduction. These studies often seek to compare different technologies or process configurations. They are therefore dependent on valid and comparable data to be provided by experimental work and process simulations. Another method for evaluating the performance and impact of various technologies is energy system analysis. Here the performance of specific technologies is analysed by integrating them into an existing energy system or future energy system scenario (Skov et al., 2021) (Korberg et al., 2020) (Korberg et al., 2021b). This allows for analysis of not only the performance of the process itself but also how it affects the rest of the energy system. This kind of studies also rely on data from experimental work or process simulations to produce feasible and trustworthy results.

Given the many different methods found in the literature for evaluating various technology pathways, the link between experimental data and process simulation to higher level techno-economic analysis, LCA and energy system analysis, is essential in obtaining feasible results. This link was often found lacking and non-transparent in the literature, which makes is difficult to understand the underlying data of the analysis. The purpose of this study is to strengthen this link, by providing a general modelling framework that can objectively compare the outcome from different experimental- or process simulation studies. A lot of parameters are of interest when analyzing the performance of fuel production pathways. The parameters include conversion efficiencies, additional inputs required, and utilization/handling of by-products. Most of the technologies are still in development meaning that new knowledge is obtained every year, which changes the parameters mentioned above. Furthermore, this study compares the impact of integrating various technologies for fuel production into an energy system. This was generally not considered in the studies found in the literature when comparing multiple different technologies.

The objective of this work is thereby to develop a modelling framework that can objectively compare the performance of different technology pathways for converting biomass into fuels. When new process data becomes available or if another biomass feedstock are to be considered, the model will allow for easy alteration in the input data to reflect the new findings. It combines both the performance of the process itself and its performance in an energy system up to national scale. More specifically, the aim of this work is to evaluate:

- How does different routes for producing biomass-based fuels compare in terms of energy conversion?
- What are the potentials/barriers in implementing biomass-based fuel production on large scale in an energy system?

The contribution from this study to the research field, is a modelling framework to compare data from various technologies as they are being developed. This will serve as a bridge from experimental data and process simulations to techno-economic analysis and life cycle assessments, by providing the necessary input in a comparable manner for the further analysis.

This study analyses various production pathways for producing sustainable fuels for the aviation and maritime sector. The focus is limited to carbon-based liquid fuels as that is what is required for the blending obligations as specified by the European Union in the aviation sector. This excludes other options such as direct electrification, hydrogen, and ammonia. The carbon source for the fuel production is biomass, which can be converted to liquid fuels in several different ways. Direct liquefaction technologies such as pyrolysis and hydrothermal liquefaction can convert the biomass directly to a biocrude which is then refined to meet target fuel specifications. An alternative to direct liquefaction is "gas-to-liquid" processes where the biomass is first converted to a synthesis gas in e.g., a gasifier and then processed to desired hydrocarbon products. Alternatively, by combusting the biomass in a combined heat and power or heat recovery only plant, the carbon can be captured as CO_2 and then be used as the carbon source for synthetic fuel production. This is often referred to as Power-to-X as the process requires significant amount of external hydrogen. In this study the biomass is limited to lignocellulosic due to it being the most widely used in the literature. Other potential biomass feedstock for fuel production includes agricultural waste, sewage sludge, animal manure, and the biogenic fraction of collected waste. These are not considered in this study, but the general methodology can be applied to these alternative feedstocks.

The results and discussion section is separated into two parts. First the modelling framework is applied to six different technology pathways for producing sustainable fuels. Here the performance in terms of energy efficiency is analysed and discussed. Secondly the technology pathways are integrated into an energy system where their impact is compared and discussed.

2. Methodology

A modelling framework has been developed and is illustrated in Fig. 1. It consists of three parts, model inputs, the modelling framework, and model outputs. Obtaining validated input parameters is crucial to produce trustworthy outputs. The model is set up in such a way that the input parameters are easily changeable when new data becomes

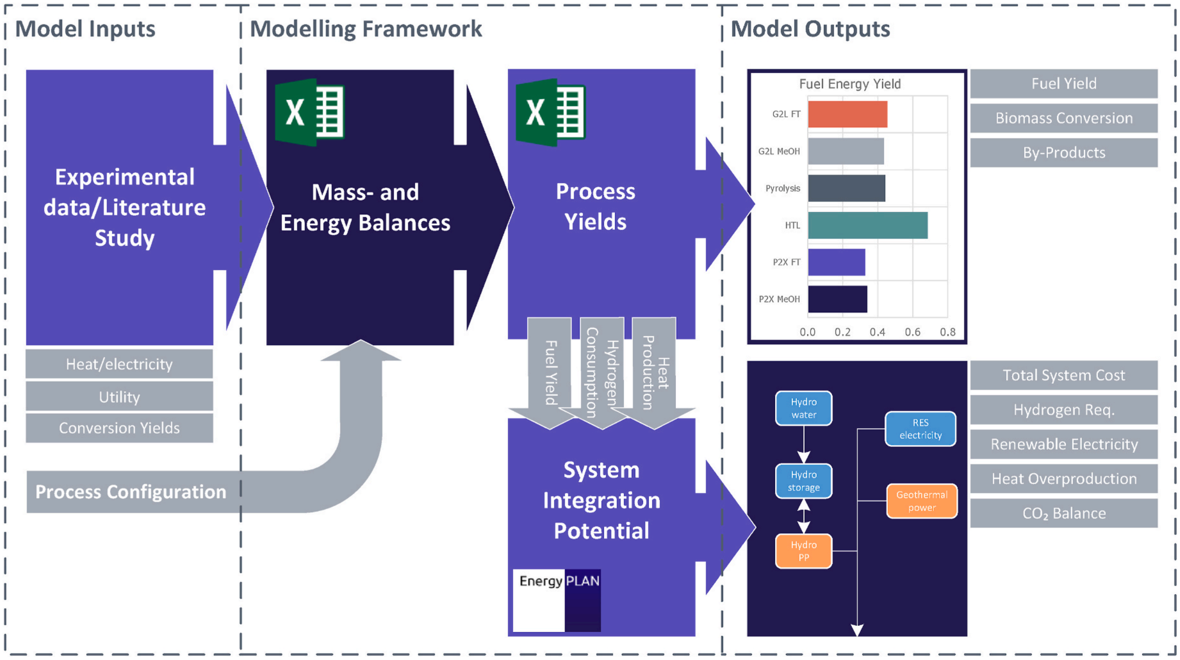

Fig. 1. Overview of the model design.

available. This allows for quick analysis of how the changes are reflected in the overall performance of the process and its integration into an energy system.

2.1. Conversion processes

In this study six promising pathways for converting lignocellulosic biomass to liquid fuels were chosen. The processes were chosen based on what was found in the literature, these are shown in Fig. 2. The input for all the pathways is lignocellulosic biomass in the form of forestry residue and the produced fuel can be used in both the maritime and aviation sector. As shown in Fig. 2 all the pathways utilize external hydrogen. This is assumed to be supplied via electrolysis using renewable electricity at an efficiency of 75% based on higher heating value (Green Hydrogen Systems, 2022). This means that the energy input to all the pathways is limited to biomass and electricity. In the following sections, the six technology pathways are briefly described.

2.1.1. Power-to-methanol

In this pathway the biomass is combusted, producing heat that can be utilized as process heat or for district heating. Flue gas condensation is used after the combustion to increase the overall thermal efficiency where the flue gas is cooled down to 40 °C, which is the required temperature for the downstream carbon capture unit. From the flue gas, CO_2 is captured in a carbon capture unit and utilized, in combination with external hydrogen, to produce methanol. Hydrogen is supplied

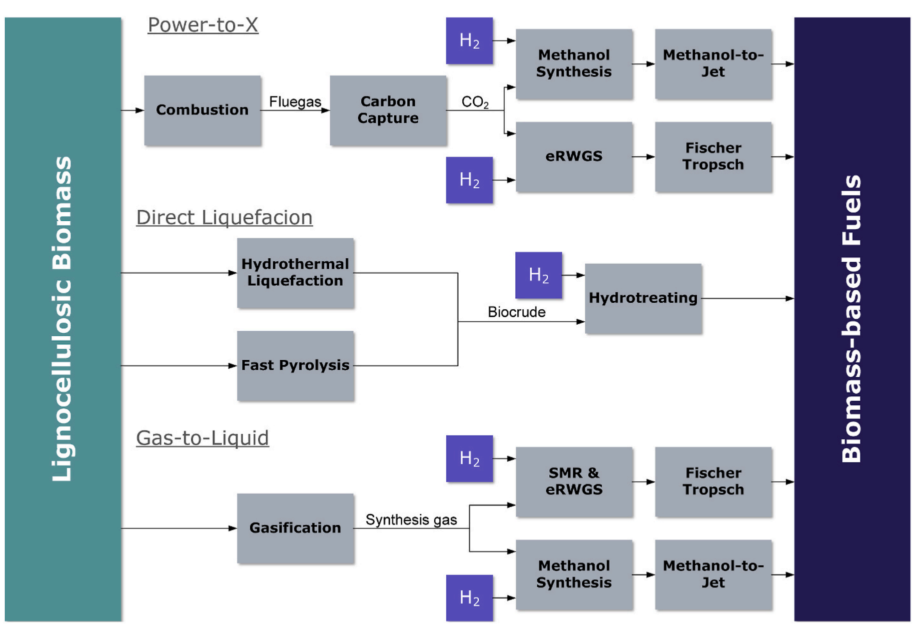

Fig. 2. The six chosen technology pathways for converting lignocellulosic biomass to biomass-based fuels, which were analysed using the modelling framework presented in this study.

following the ratio $H2/CO_2 = 3$ on molar basis (Valmet, 2017) (Xue et al., 2017).

The produced methanol can be used directly as a fuel in the maritime sector, but since it is not compatible with today's fossil-based fuels in the aviation sector an upgrading step is required. Here the methanol is upgraded to a combination of diesel, gasoline, kerosene, and some light components via a three-step process. First is a dehydration step that removes oxygen in the form of water, turning the methanol to alkenes. Second is an oligomerization step where the short-chained molecules are combined to form long-chained alkenes. Finally, the hydrogenation step where the long-chained alkenes are converted to saturated hydrocarbons by adding hydrogen (Tabak and Yurchak, 1990).

2.1.2. Power-to-Fischer Tropsch

Here biomass is combusted and CO_2 from the flue gas is captured as in the previous pathway. The captured CO_2 will serve as the carbon source for the Fischer Tropsch process, but as it requires a CO input to operate, the CO_2 is converted to a syngas containing CO and H_2 via the Reverse Water Gas Shift reaction (RWGS). External hydrogen is supplied to the RWGS reactor in the ratio $H_2/CO_2 \approx 3$. This ratio provides enough hydrogen to convert the CO_2 to CO in RWGS and results in the produced syngas with a $H_2/CO \approx 2$ ratio which is required for the downstream Fischer Tropsch process. The type of reactor in this case is electric (eRWGS), where the endothermic reaction is powered purely by electricity. This allows for high carbon efficiency and lower carbon emission compared to the traditional thermal RWGS process (Christensen et al., 2021).

The produced syngas is then converted directly to hydrocarbons via Fischer Tropsch process at low temperatures. To be compatible with existing fuels the Fischer Tropsch syncrude is hydrocracked using 1 g of hydrogen per 100 g of biocrude (Hannula, 2015). The overall carbon efficiency from the captured CO_2 to hydrocarbons are >95% (Christensen et al., 2021). The final fuel product consists of primarily diesel and kerosene with small fractions of naphtha and LPG. The process can be designed to favour either diesel or kerosene depending on the fuel demand.

2.1.3. Hydrothermal liquefaction (HTL)

HTL converts the biomass directly to biocrude, gas and solids using critical pressure and temperatures, 300–350 bar and 390–420 °C (Jensen et al., 2017). As no phase change is taking place in the process, the thermal efficiency loss is low. Biomass can be utilized without drying due to water being used as the reactor medium. The produced aqueous phase from the process is partly recirculated to ensure the required dry matter content in the inlet stream. The gas product is rich in CO_2 content with >85% by weigh, other components include hydrogen and hydrocarbons (Lozabo et al., 2020). In this study the gas product is used to produce process heat.

The crude oil contains oxygen which has to be removed via hydrotreating to produce a compatible fuel product. A hydrogen consumption of 3% by weight to the biocrude input is required for this process (Jensen, 2018). As hydrogen is added in over-stoichiometry the unreacted hydrogen is recovered by pressure swing absorption (PSA) to reduce the hydrogen loss.

2.1.4. Fast pyrolysis

In the fast pyrolysis the biomass is dried to a moisture content of 10% by weight prior to entering the reactor (Jones et al., 2013). Process temperature is typically in the range 500–600 °C and the products are crude oil, gas, biochar/ash and some process water. The produced biochar is combusted to provide the process heat required to for the process (Jones et al., 2013).

The pyrolysis oil contains both water and oxygen. Similar to HTL oil it requires hydrotreating before it can be used as transportation fuels. For this process 5.8% by weight hydrogen to pyrolysis oil input is required. The unreacted hydrogen is recovered using a PSA (Jones et al., 2013).

2.1.5. Gas-to-liquid Fischer Tropsch

Prior to the gasification process the biomass is dried to a moisture content of 10%. Oxygen and steam are supplied to the gasifier which converts the biomass to a synthetic gas, containing mainly hydrogen, CO, CO_2, CH_4, water and some other hydrocarbons at temperatures around 200 °C (Hannula, 2015).

To ensure the desired H_2:CO ratio of 2 in the Fischer Tropsch process, the methane is converted to CO and hydrogen via steam methane reforming. Then hydrogen is added in an eRWGS, similar to the carbon capture and Fischer Tropsch case, to convert the CO_2 to CO and water. In the Fischer Tropsch process the cleaned synthetic gas is converted to hydrocarbons in the diesel, gasoline, kerosene, and heavy fuel range. As mentioned previously the FT-crude oil requires upgrading in a hydrocracker which consumes 1% by weight of hydrogen per fuel input (Silva, 2016).

2.1.6. Gas-to-Liquid Methanol

Here the synthesis gas from the gasifier is first cleaned from water, ash, and char content before it enters the methanol synthesis loop. To satisfy the stoichiometry of $(H_2–CO)/(CO_2+CO) = 2.05$ on molar basis, external hydrogen is added to the process. Since the synthesis gas already contains some hydrogen and some of the carbon is CO rather than CO_2, the requirement for external hydrogen is lower compared to the carbon capture and methanol case described previously. The methane from the synthesis gas is purged from the methanol loop together with other impurities.

The methanol must undergo a series of upgrading steps, which converts the methanol to longer chained hydrocarbons to obtain a fuel product that is also compatible with existing aviation fuels. For this process additional hydrogen is added to the processes (Tabak and Yurchak, 1990).

2.2. Model inputs

The model inputs consist of operating conditions, conversion yields, by-products, product compositions, and utility requirement for all the major processes within each technology pathway. These are based on state-of-the-art data from experimental work and process simulations found in the literature. The level of detail and uncertainty in the modelling are directly dependent on these input data. All the input data used throughout the analysis can be found in the supplementary material.

To ensure a comparable comparison it is important that the biomass input is consistent. Table 1 shows the lignocellulosic biomass input data used throughout the analysis.

It is also important that the produced fuels are comparable. In all six pathways analysed in this study the produced fuel is a hydrocarbon fuel which can be distilled into various fuel cuts, as shown in Table 2. It is assumed that the kerosene fraction of the fuels is used as aviation fuels and all the remaining fractions can be utilized in the maritime sector.

A higher flexibility is reported for both the Fischer Tropsch and methanol to fuel pathways compared to the direct liquefaction options (fast pyrolysis and HTL). Here it is reported that up to 80% of the fuel can be made into the desired boiling point range (Christensen et al., 2021). These processes can thereby target the most desirable product which will typically be the kerosene (jet fuel) fraction. This flexibility

Table 1
Forestry residue biomass input data.

Parameter	Unit	Value	Ref.
Moisture	% wt	50	Tanzer et al. (2019)
Ash	% wt of dm	3.8	Jensen et al. (2017)
Higher Heating Value (HHV)	MJ/kg dm	20.2	Jensen et al. (2017)

Table 2
Estimated fuel distillation cuts for the produced fuels.

	Fuel distribution (wt %)				
	Maritime fuel			Jet fuel	
	Gasoline <193 °C	Diesel 272–425 °C	Heavy >426 °C	Kerosene 193–271 °C	Ref.
P2MeOH	21	55		24	Kaltschmitt and Neuling (2018)
P2FT	16	60		24	Christensen et al. (2021)
HTL	25	45	8	22	Snowden-Swan et al. (2020)
Pyrolysis	44	41	1	14	Ringsred et al. (2021)
G2L MeOH	21	55		24	Kaltschmitt and Neuling (2018)
G2L FT	21	43	15	21	Bahri et al. (2021)

can become a significant advantage if the processes are implemented on larger scale.

2.3. Modelling framework

The modelling framework converts input data to mass- and energy balances for the given process configuration. Input data are used to produce input/output models of all major processes within a given technology pathway. The models are made in an interlinked spreadsheet and used to estimate total process yields and by-product production. The level of detail for this part of the analysis is illustrated in Fig. 3, which shows the energy balance for the Gas to Liquid Methanol pathway. This is a graphical representation of the input/output models of the major processes within this pathway. All energy inputs are represented as biomass and renewable electricity and the system consists of five major units: gasification, solid combustion, electrolysis, methanol synthesis, and methanol to fuel conversion.

2.3.1. System integration potential

The overall energy balances are also used to evaluate and compare the performance of each technology pathway within a full energy system. For this the EnergyPLAN software was used which is an open-source energy system analysis tool that allows the user to conduct simulation of the entire energy system, electricity, heating, cooling, transport, and industry on an hourly basis (Lund et al., 2021). This is done deterministically meaning the same inputs will result in the same outputs. EnergyPLAN requires energy demands, conversion yields, and costs as inputs, in turn it will simulate the operation of the energy system based on the chosen simulation strategy to provide hourly, monthly, and annual energy balances as well as total costs for operating the energy system. These energy inputs are provided by the input/output modelling of each technology pathway. The benefit of EnergyPLAN is that by simulating the entire energy system, it allows for an assessment of how a single technology impacts the entire energy system, thus allowing for the assessment of benefits and costs across all sectors. The impact of the technologies can thereby, be assessed in the context of the entire energy system. EnergyPLAN has been used in many cases, including national energy strategies for countries, e.g., Denmark, Ireland, and Chile and local regions, such as Beijing and Utrecht (Lund et al., 2021) (Thellufsen et al., 2019) (Paardekooper et al., 2020) (Yuan et al., 2020) (Liu et al., 2021).

For the study carried out in this paper, EnergyPLAN is operated in technical simulation balancing both heat and electricity demand. The technical simulation strategy first utilizes renewable energy to its full potential, as well as waste heat. The goal is to achieve an energy efficient system with a focus on utilization of variable renewable energy within the modelled energy system (Lund et al., 2021).

2.3.2. Danish fossil free 2045 scenario

To investigate the six technology paths, the Smart Energy Denmark scenario, IDA's Climate Response 2045, is used as a test bed (Lund et al., 2022). It provides a scenario for 100% renewable energy transition in Denmark utilizing system integration and system benefits to achieve a cost-efficient decarbonized Denmark. The model was built in EnergyPLAN. Fig. 4 show the primary energy consumption in IDA 2045 across all sectors in the form of a Sankey Diagram.

For the analyses in this paper, the focus is on the transport sector, meaning the demands and technologies in the other sectors are kept constant. For the transport sector, it is assumed in this scenario that personal transportation is fully electrified by 2045, with heavy goods transport operating on a mix between electricity, hydrogen, and e-fuels. Shipping and aviation are almost entirely supplied by e-fuels and biofuels. It is these fuel demands that the 6 technologies investigated can supply.

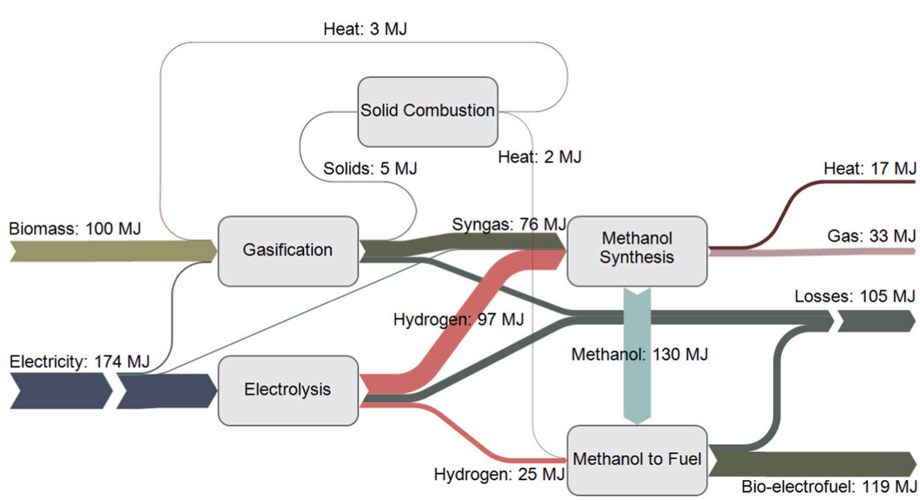

Fig. 3. Energy balance of the gasification followed by methanol synthesis and methanol to fuel pathway.

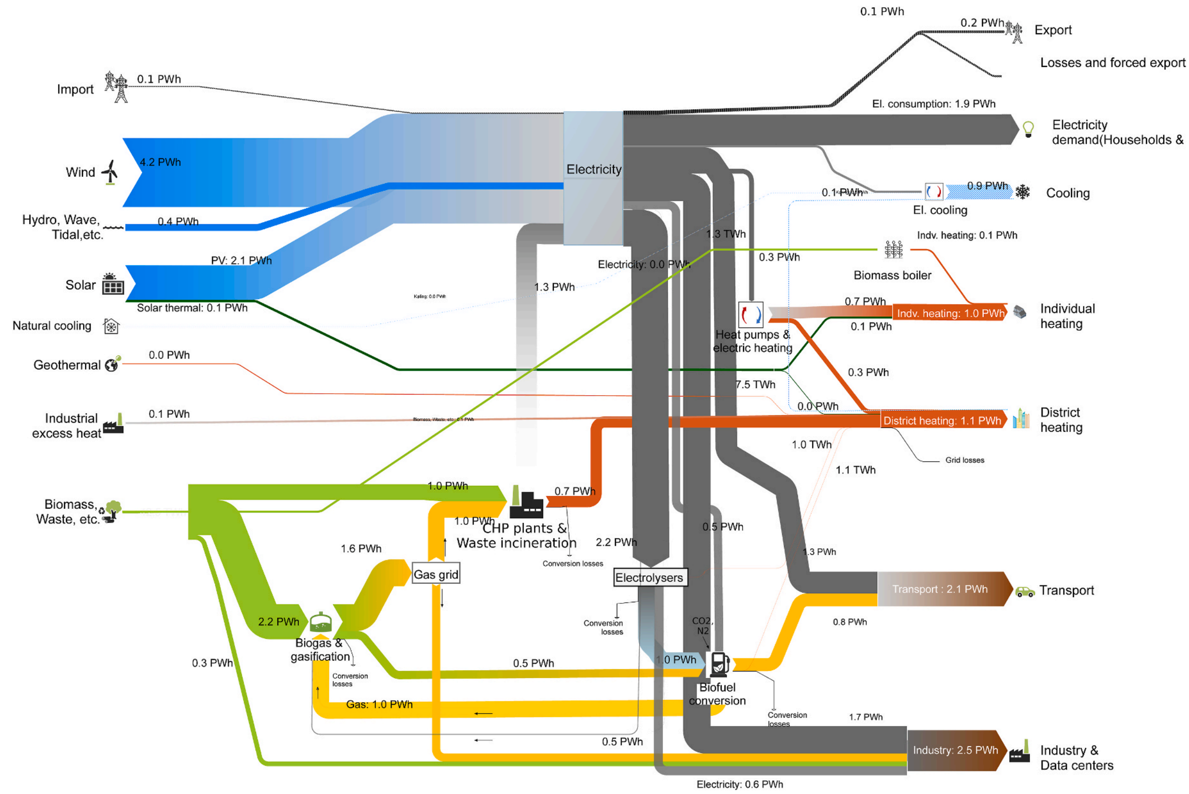

Fig. 4. Primary energy consumption in the IDA 2045 fossil free Danish energy system scenario. This is used as the baseline throughout the energy system analysis (Lund et al., 2022).

2.4. Model outputs

The model output includes various parameters which are of importance when deciding the optimal solution for a given energy system. First are the fuel yield, biomass conversion and by-products produced which are all outputs from the spreadsheet input/output calculations. In this study, fuel efficiency is defined in two ways. First the total energy to fuel efficiency, which is the fuel energy produced divided by the total energy input in terms of biomass and electricity. Secondly, since sustainable biomass is a limited resource, an alternative definition, referred to as biomass to fuel conversion was calculated and compared. It is defined as the fuel produced divided by biomass input. This is a measure for how effectively the limited amount of sustainable biomass is converted to fuels. When evaluating the potential of a conversion pathway it is important to consider both efficiencies.

For the energy system integration model, the outputs include overall hydrogen and renewable electricity requirement, heat production/overproduction, biogenic CO_2 balance within the system, process investment cost, and total system cost. These results heavily depend on the specific energy system analysed and conclusion on the implementation potential are thereby location dependent.

3. Results and discussion

In this section the results from both the mass- and energy balances and the system integration analysis are presented and discussed. Throughout the paper efficiencies are calculated based on higher heating values of the various streams.

3.1. Energy efficiencies

In Fig. 5 overall energy balances for the six technology pathways are shown with a biomass input of 100 MJ. Here all the energy inputs and outputs for each major process are summed up to provide the overall energy balance for the given technology pathway. In Fig. 5 the energy input is condensed as biomass and electricity used for both the process itself and in electrolysis. Energy outputs include the produced fuel, excess heat, gas, and aqueous phase. The losses here represent cooling losses, conversion losses occurring when converting one energy carrier into another, and electrolyzer losses. The electrolyzer is assumed to have a 75% efficiency from power to hydrogen based on higher heating value and is thereby a major part of the total losses for the pathways that heavily utilizes hydrogen. Some of this energy loss could potentially be recovered as heat, but that is not included in this study.

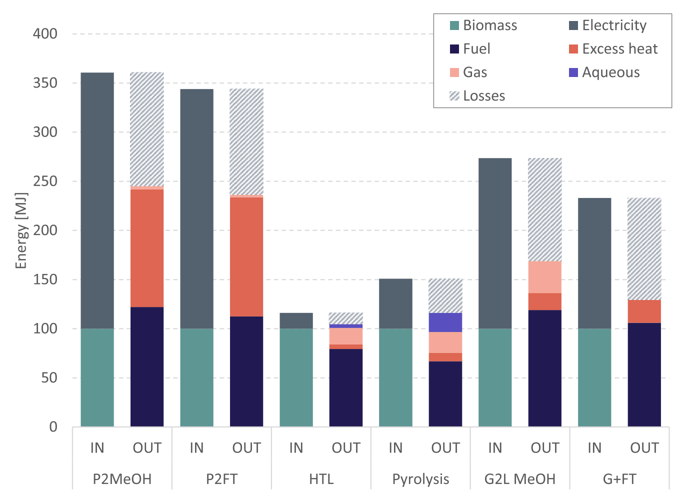

Fig. 5. Overall energy balances for 100 MJ of biomass input. Losses represents the difference between energy output and input. These are mainly cooling and conversion losses.

Fig. 6 provides a more detailed overview of the efficiency in the major processes in each pathway. The efficiencies and energy outputs in each step are shown based on biomass, electricity, and intermediate product inputs. From the figure it is observed that the highest efficiency from energy to fuel is obtained via HTL (68.4%), due to a relatively low requirement for hydrogen and thereby electricity while maintaining a high total fuel output. All the P2X and G2L routes produce higher amounts of fuel, but with a much higher electricity input requirement. This results in a lower energy to fuel efficiency (42.8%–43.8% and 32.7%–33.8% respectively) compared to HTL. Fast pyrolysis produces less fuel compared to the other options but with an electricity requirement on the lower end. The total energy to fuel efficiency for fast pyrolysis at 44.3% puts it slightly higher than the G2L options.

3.2. Biomass to fuel conversion

In addition to the total energy efficiency from energy input to fuel, the biomass conversion efficiency is also of interest. Sustainable biomass is a limited resource, and it is therefore important to maximize the fuel output per biomass used. This is defined as the amount of fuel produced per biomass input on energy basis. A high biomass conversion means that the limited available biomass is converted into as much fuel as possible. For the total fuel energy yield the theoretical maximum is 100% whereas the biomass conversion can exceed that, however this requires additional energy inputs. In Fig. 7 both the fuel energy yield and biomass conversion are plotted for the six pathways.

In terms of biomass conversion all the P2X and G2L pathways obtain high efficiencies (100%–122%). This is higher than what is observed for HTL and pyrolysis, but it comes at a cost in overall energy conversion due to the much higher requirement for renewable electricity in the form of hydrogen.

3.3. System implementation

In this section results from system operations in EnergyPLAN are presented for the six pathways. The demands which are to be fulfilled are based on the IDA 2045 fossil free scenario and the conversion yields for the processes are from the energy balances presented above.

3.3.1. Fuel production and demand

In the 2045 fossil free scenario it is assumed that all light transport is converted to electric vehicles. The remaining need for liquid fuel is thereby only for aviation, maritime and partly heavy trucks with roughly 50% of the total demand being aviation fuel. In Fig. 8 both the total fuel demand and fuels produced from processing 16.7 TWh biomass in the processes are shown. The gap between the produced fuel and the demand is fulfilled by additional electrofuel produced by biogenic CO_2 from other sources.

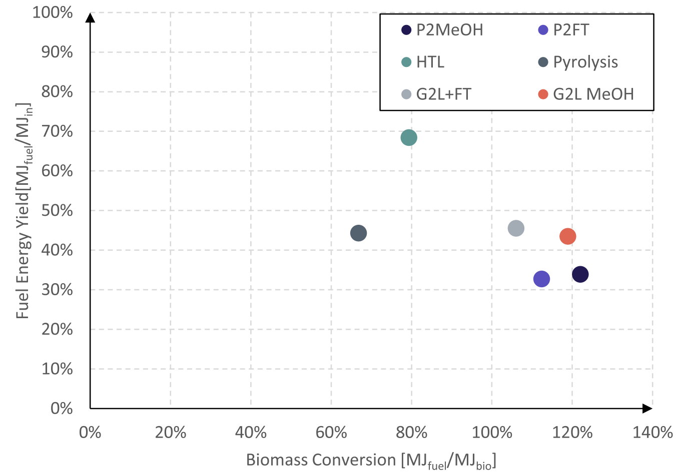

Fig. 7. Fuel energy yield vs. biomass conversion. An ideal production pathway will have a high efficiency in both.

It is observed that for all the processes the aviation fuel demand is the biggest challenge in terms of compliancy. This favours the P2X and G2L routes over direct liquefaction since they are believed to be more flexible when it comes to targeting specific fuel distillation cuts.

3.3.2. Electricity and hydrogen requirement

A dominant factor in the system performance is the use of hydrogen and renewable electricity. These are shown in Fig. 9 and Fig. 10 for the entire system.

Hydrogen in this scenario is only used for fuel production. Fig. 9 indicates how much is required in both the given process and to produce the additional electrofuel to fulfill the demand. The P2X routes followed by G2L has the highest utilization of hydrogen. HTL and pyrolysis uses less hydrogen, but they also produce less fuel per biomass input. This means that more additional electro fuel production is required in the

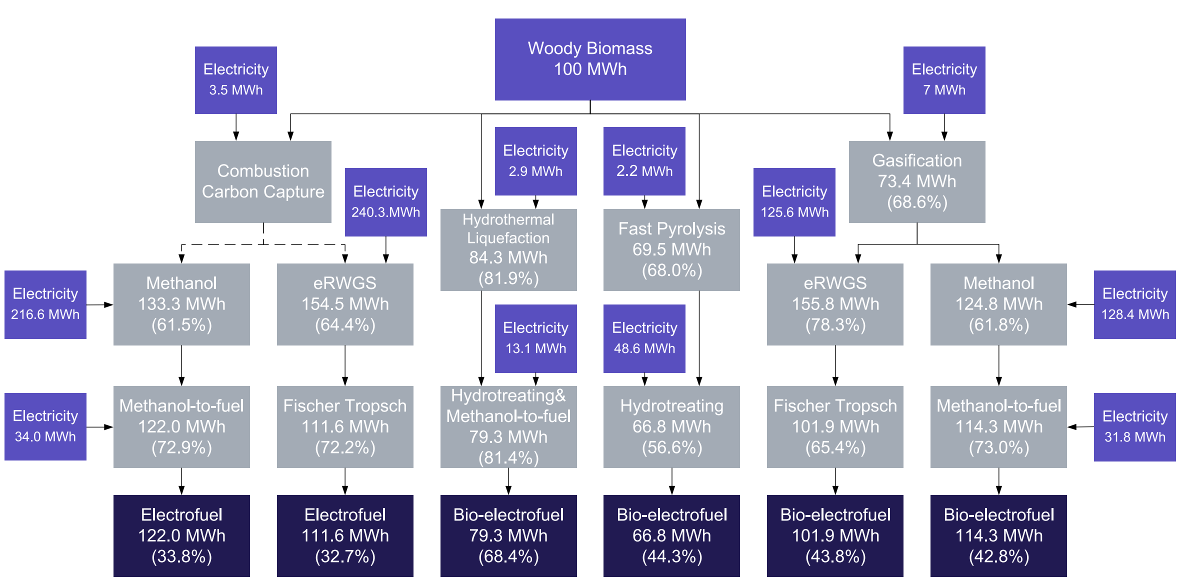

Fig. 6. Conversion efficiency from 100 MWh of biomass input. The efficiency and energy output in each process step is shown based on biomass, electricity, and intermediate product inputs. Electricity inputs represent both electricity required to run the process and produce the necessary hydrogen required via electrolysis.

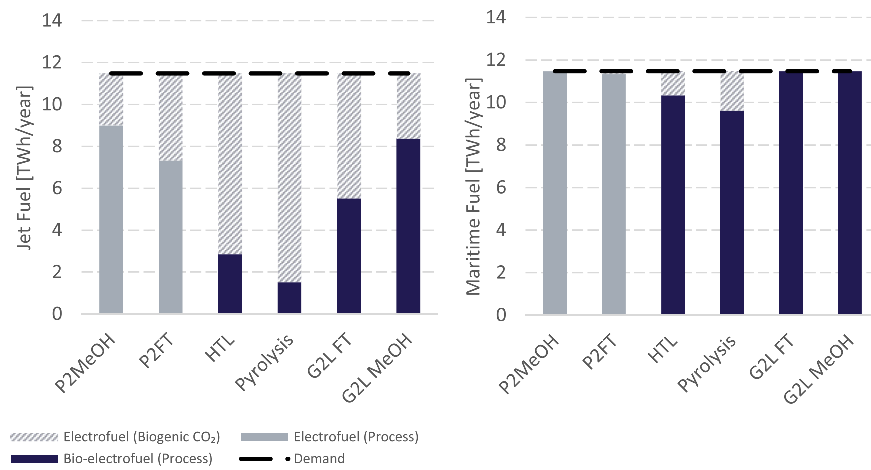

Fig. 8. Liquid fuel production and demand for the six pathways. Electrofuels produced from other biogenic CO_2 are used to fulfil the total fuel demand.

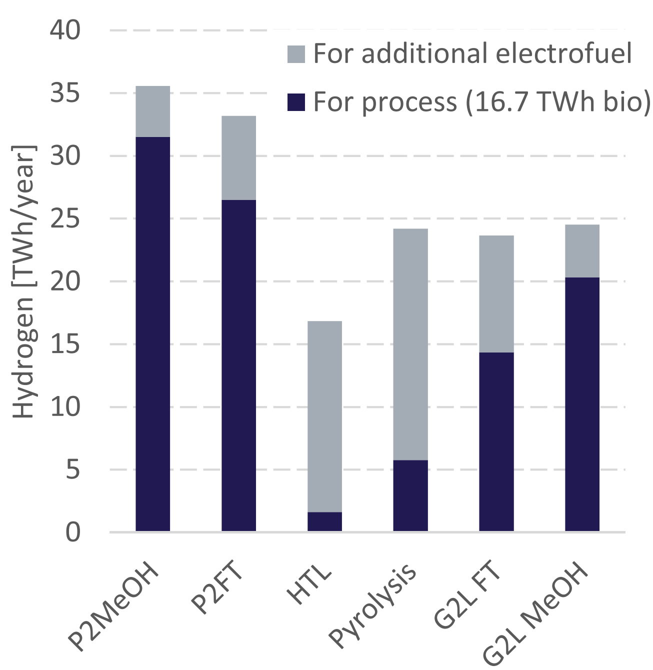

Fig. 9. Total system requirement for hydrogen. These figures include the requirement from all sectors in the energy system.

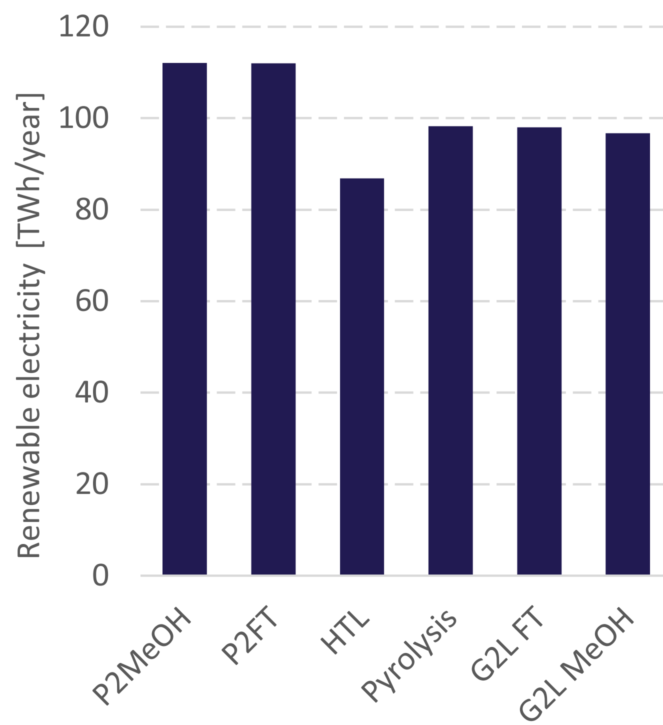

Fig. 10. Total system requirement for renewable electricity. These figures include the requirement from all sectors in the energy system.

system which requires a significant amount of hydrogen. Thereby, the total hydrogen consumption for the pyrolysis route is similar to G2L with HTL being slightly lower. The total requirement for renewable electricity, shown in Fig. 10, follows the same tendency as hydrogen consumptions as most of the electricity in the processes are used for electrolysis. Note, that the hydrogen consumption solely depends on the fuel production method whereas for the total system electricity consumption, the fuel production is only a small part of the total amount.

3.3.3. Heat production

One of the main energy by-products for especially the P2X routes is heat. The energy to fuel conversion for these pathways is relatively low, primarily due to a large production of heat in the process. From a system perspective is it desirable to utilize that heat to obtain a higher energy efficiency. This, however, can prove to be a challenge due to the large quantities. Fig. 11 shows the heat demand over one year alongside the heat produced by the given process and all other sectors.

As the heat produced from the remaining sectors are already primarily waste heat is it difficult from a system perspective to integrate all the excess heat into the system. From Fig. 11 it is observed that the heat from other sectors is slightly lower for the P2X and G2L MeOH routes, which indicate that some of the heat can be integrated rather easily. In the model this is obtained by not having to operate heat pumps and other backup system in peak hours due to the high waste heat production.

A way to tackle this challenge is to convert the biomass combustion plants in the P2X routes from heat only to a combined heat and power plant. This will lower the energy output as heat and simultaneously produce part of the electricity for electrolysis. In this specific case, however, this will require new plants to be built instead of retrofitting existing heat only boilers with carbon capture.

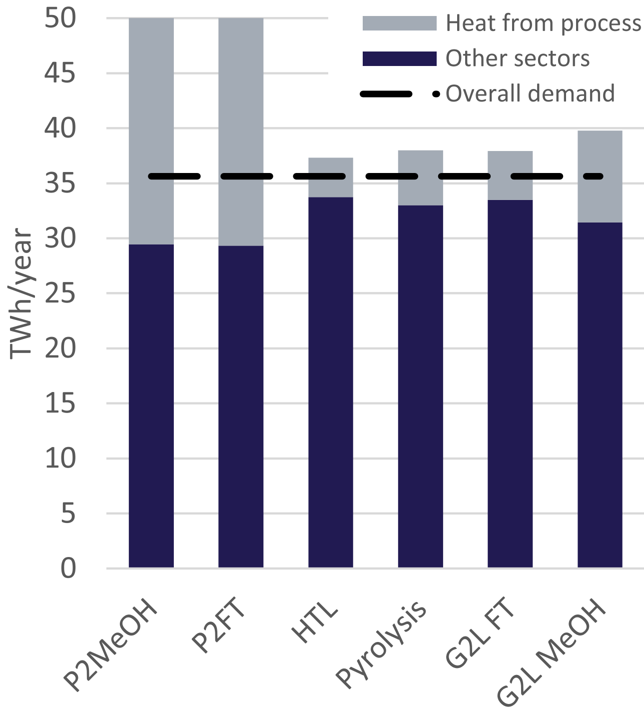

Fig. 11. System heat production and demand.

3.3.4. Biogenic CO2 availability

For electrofuels to be considered renewable, they must rely on renewable hydrogen from electrolysis, and the carbon source should come from renewable sources, so-called biogenic CO_2. This is potentially a limited resource within the energy system. The amount of electrofuels required in the six pathways was shown in Fig. 8 and the corresponding CO_2 requirement for producing those fuels is shown in Fig. 12.

In addition to the required amount of biogenic CO_2, the figure shows the available potential. This is a summation of the CO_2 available within the processes and the potential to capture CO_2 from other point sources.

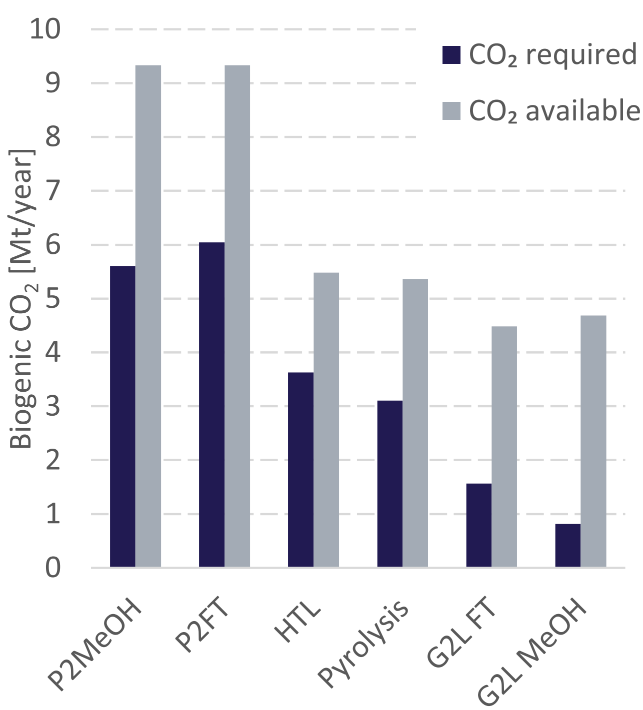

Fig. 12. Total system CO_2 requirement and CO_2 availability to be captured.

These includes other sectors that utilize biomass which are waste incineration, biogas plants, and the industry. All these sectors have the potential to capture parts of the carbon as CO_2 and thereby contributes to the CO_2 available in Fig. 12.

In all these scenarios there is biogenic CO_2 enough to fulfil the demand for electrofuels. However, Fig. 12 also shows the extent to which carbon capture is required within the energy system. Some of the CO_2 point sources will be in low quantities and thereby be expensive to collect.

3.4. Socioeconomic system costs

The EnergyPLAN model also estimates the total annual cost of building the energy system. This is calculated based on investment costs, expected lifetime, as well as operation and maintenance costs. In Table 3 the cost parameters for the six pathways, taken from the Danish Energy Agency (Danish Energy Agency, 2022), are shown in addition to costs for renewable electricity and hydrogen production, which are the sectors most affected by the variations in fuel production technology. Cost parameters for these and all other sectors in the energy system are based on projections from the EnergyPLAN model.

Based on the fuel yield presented earlier and the cost parameters in Table 3 the socioeconomic investment cost per energy produced can be estimated. This is shown in Fig. 13 where the annual investment cost is separated into; the process itself, electrolysis, hydrogen storage, renewable electricity, and potential heat savings in the system.

From Fig. 13 the P2X routes proves to be the most expensive options in terms of investment cost per fuel produced, whereas HTL and fast pyrolysis are the cheapest. The variations in investment cost between the pathways are more observed in the connected sectors, e.g., electrolysis, hydrogen storage, and renewable electricity production, compared to the processes themselves.

The investment cost is heavily dominated by investments in renewable electricity, which in this Danish scenario is provided by offshore wind. The high amount of heat production in the P2X pathways allows for reduction in backup heating units like heat pumps, which leads to a reduction in the investment cost as shown in Fig. 13. In the G2L methanol pathway the backup heating units can only be partly removed which leads the around half the economic gain compared to the P2X pathways. This is, however, not enough to offset the high renewable electricity costs for either of the processes.

The Total annual socioeconomic cost for building the full energy systems is shown and compared in Fig. 14. It generally follows the same tendency as the total hydrogen requirement shown in Fig. 9 which proves to be the dominant factor when determining socioeconomic cost.

Additionally, Fig. 14 shows the sensitivity of the cost parameters for hydrogen production and renewable electricity respectively. Here it is observed that HTL pathway is the least affected by changes in the cost parameters compared to pyrolysis and G2L. The P2X pathways have the highest reliance of renewable electricity and hydrogen and is thereby the most sensitive pathways to variations in cost parameters. It is important to note that the changes in renewable electricity presented here affect the entire energy system and not only the specific processes.

4. Conclusion

Using the modelling framework developed in this study, state-of-the-art data available in literature were used to objectively compare the performance of six promising technology pathways for converting lignocellulosic biomass into carbon-based fuels. The evaluated performance includes both energy efficiencies and system integration potential. Based on the modelling results the following conclusion can be drawn.

HTL is observed to be the most energy efficient pathways with a total energy to fuel efficiency of 68.4%. This is followed by fast pyrolysis and the G2L pathways (42.8%–44.3%) and finally the P2X pathways at

Table 3
Investment cost, lifetime and operation and maintenance cost for the pathways and sectors most affected in the models.

Process	Investment [MEUR/ unit]	Lifetime [Years]	O. & M. [% of inv.]	Process	Investment [MEUR/ unit]	Lifetime [Years]	O. & M. [% of inv.]
Wind [MW]	1.03	30	1.67%	P2MeOH	2.26	20	2.35%
Offshore Wind [MW]	1.9	30	2.51%	P2FT	1.9	25	5.58%
Photic Voltaic [MW]	0.6	40	1.5%	HTL[1]	1.47	20	5%
Electrolyser [MW]	0.6	20	3%	Fast Pyrolysis[1]	0.83	25	6.8%
Hydrogen Storage [GWh]	29.7	48	0.01%	G2L FT	3.62	25	2.85%
				G2L MeOH	2.12	20	1.84%

[1]*Due to the hydrotreating step not being included in the cost estimate in (Danish Energy Agency, 2022), fast pyrolysis and HTL are increased by 50% compared to the reference values.*

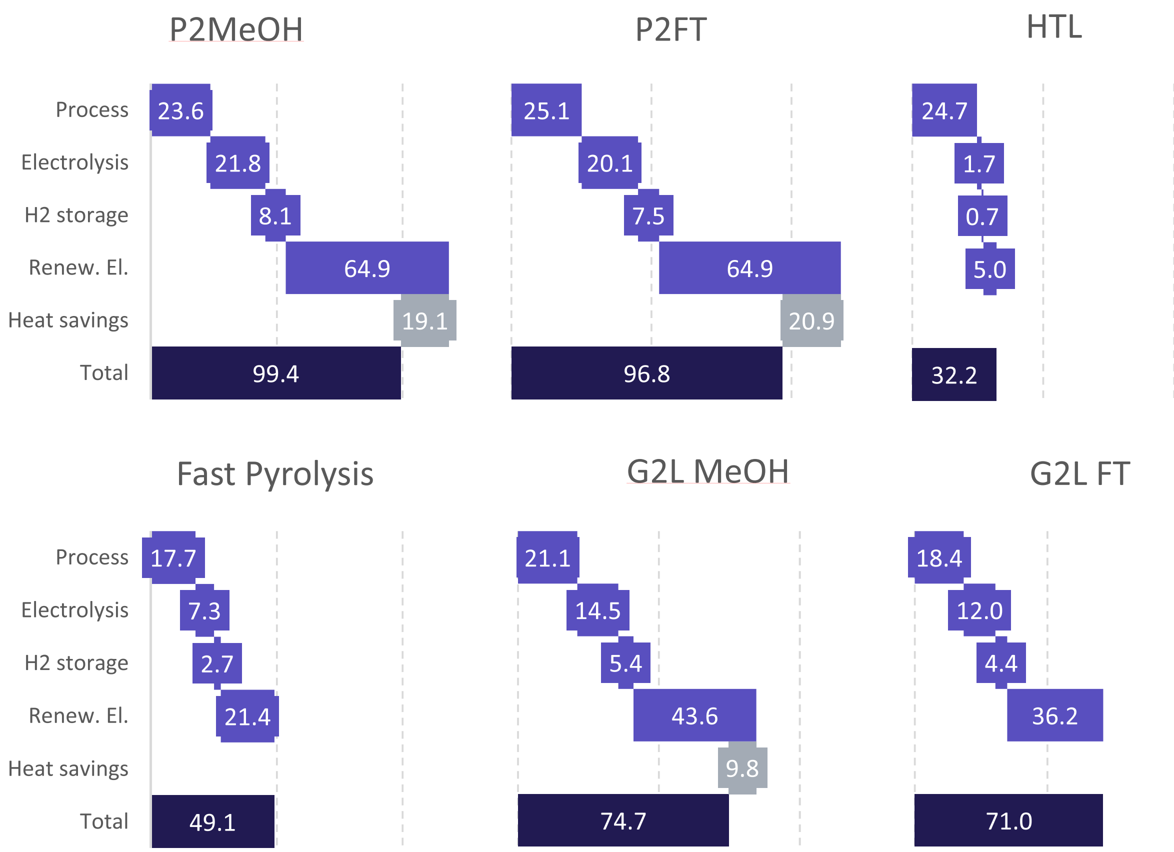

Fig. 13. Socioeconomic investment cost per fuel produced [EUR/MWh]. Potential for heat savings can be observed when process heat makes other technologies like heat pumps obsolete within the system.

32.7%–33.8%. In terms of biomass conversion all G2L and P2X pathways obtain a high conversion (100%–122%) whereas HTL and pyrolysis only have a conversion of 79.4% and 66.8% respectively. Utilization of hydrogen is necessary for producing and upgrading fuels in all six pathways. The highest dependency on hydrogen, and thereby also renewable power, was observed in the P2X pathways as all energy from the biomass is used for heat production. This is the main contribution to why the P2X pathways lacking behind the other options in terms of total energy to fuel efficiency.

Implementing the six technology pathways into a future Danish fossil free scenario provided insight into potential challenges from an energy system perspective. It was observed that the fuel distillation cuts reported throughout all pathways did not fit the projected demands for jet fuel. This is especially a challenge for the direct liquefaction pathways, HTL and fast pyrolysis, as these are expected to be less flexible in terms of targeting specific fuel cuts. It was also found that the significant amount of heat production in the P2X pathways is a challenge to handle from an energy system perspective. Only a small amount of the heat could be integrated in the energy system.

As part of the system integration modelling, the socioeconomic investment cost associated with each pathway was estimated. The largest differences between the pathways came from the connected technologies, electrolysis, hydrogen storage and renewable electricity. For all G2L and P2X pathways, investments into the surrounding technologies heavily outweighs the processes themselves due to the high demand for hydrogen. This resulted in HTL and fast pyrolysis being the cheapest options. Looking at the total system cost, investment in renewable power production proved to be the dominant factor. This results in the P2X pathways being the most expensive options. If the large amount of excess heat in these pathways could be better integrated into the system or converted to electricity instead, it could potentially remove the gap in total system cost to the other pathways.

Various challenges were highlighted for all the different pathways analysed in this study. It can thereby be concluded that no single

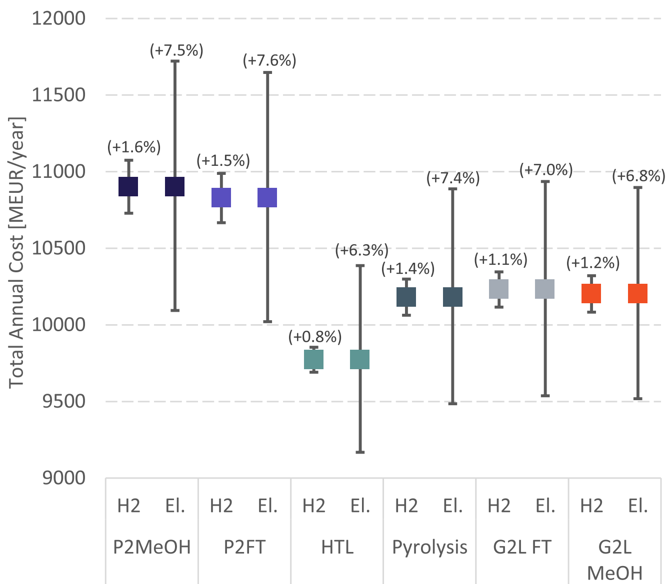

Fig. 14. Total annual system investment cost from a socioeconomic perspective. The error bars show sensitivity of ±25% investment cost on electrolysers/hydrogen storage and renewable electricity production.

technology can solve the challenge of supplying sustainable fuels in the future. Further research is required to determine to the optimal combination of the various technologies and how it is affected by different energy systems around the globe.

CRediT authorship contribution statement

Andreas Krogh: Conceptualization, Investigation, Methodology, Writing – original draft. **Eliana M. Lozano:** Writing – review & editing. **Jakob Z. Thellufsen:** Methodology, Writing – review & editing. **Jeppe Grue:** Supervision, Conceptualization. **Thomas H. Pedersen:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.134336.

References

Bahri, S., Basak, U., Upadhyayula, S., 2021. Rational design of process parameters for carbon-neutral and sulfur-free motor fuel production from second-generation biomass generated syngas. J. Clean. Prod. 279 https://doi.org/10.1016/j.jclepro.2020.123559.

Cervi, W., Lamparelli, R., S, J., Junginger, M., de Jong, S., van der Hilst, F., 2020. Spatial modeling of techno-economic potential of biojet fuel production in Brazil. Bioenergy 12, 136–157. https://doi.org/10.1111/gcbb.12659.

Christensen, T., Aasberg-Pedersen, K., Mortensen, P., 2021. eFuels Technology for Converting CO2 and Renewable Electricity to Renewable Synthetic Fuels. Haldor Topsoe, Copenhagen.

Comission, European, 2021. Regulation of the European Parliament and of the Council on the Use of Renewable and Low-Carbon Fuels in Maritime Transport and Amending Directive. Brussels.

da Silva, C., van der Wielen, L., Pousada, J., Mussatto, S., 2016. Techno-economic and Environmental Analysis of Oil Crop and Forestry Residues Based Biorefineries for Biojet Fuel Production in Brazil. TUDelft.

Danish Energy Agency, 2022. Technology Data - Renewable Fuels. ENERGINET.

de Jong, S., Hoefnagels, R., Faaij, A., Slade, R., Mawhood, R., Junginger, M., 2015. The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-ecnomic comparison. Biofuels, Bioproducts & Biorefining 9, 778–800. https://doi.org/10.1002/bbb.1613.

de Jong, S., Antonissen, K., Hoefnagels, R., Lonza, L., Wang, M., Faaij, A., Junginger, M., 2017. Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. Biotechnol. Biofuels. https://doi.org/10.1186/s13068-017-0739-7.

de Jong, S., Stralen, J., Londo, M., Heofnagels, R., Faaij, A., Junginger, M., 2018. Renewable jet fuel supply scenarios in the European Union in 2021-2030 in the context of proposed biofuel policy and competing biomass demand. Bioenergy. https://doi.org/10.1111/gcbb.12525.

European Commission. Reducing emissions from aviation [Online]. Available: https://ec.europa.eu/clima/eu-action/transport-emissions/reducing-emissions-aviation_en. Accessed 25 11 2021.

European Commission, 2021b. Proposal for a Regulation of the European Parliament and the Council on Ensuring a Level Playing Fiels for Sustainable Air Transport. Brussels.

European Commission. Renewable Energy – Recast to 2030 (RED II)," [Online]. Available: https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en. Accessed 30 03 2022.

Green Hydrogen Systems, 2022. HyProvide A-Series, Green Hydrogen Systems.

Hannula, I., 2015. Synthetic Fuels and Light Olefins from Biomass Residues, Carbon Dioxide and Electricity. VTT Technical Research Centre of Finland, Otaniemi, Finland.

International Energy Agency, 2021. World Energy Outlook. IEA.

Jensen, J.U., 2018. PIUS - Hydrofaction(TM) Platform with Integrated Upgrading Step. Aalborg Universitetsforlag.

Jensen, C., Guerrero, J., Karatzos, S., Olofsson, G., Iversen, S., 2017. Fundamentals of Hydrofaction: Renewable Crude Oil from Woody Biomass. Biomass Conversion and Biorefinery, pp. 495–509. https://doi.org/10.1007/s13399-017-0248-8.

Jones, A., Meyer, P., Snowden-Swan, L., Padmaperuma, A., 2013. Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels. Pacific Northwest National Laboratory.

Kaltschmitt, M., Neuling, U., 2018. Biokerosene -Status and Prospects. Springer-Verlag, Hamburg.

Korberg, A., Skov, I., Mathiesen, B., 2020. The role of biogas and biogas-derived fuels in a 100% renewable energy system. Energy 199. https://doi.org/10.1016/j.energy.2020.117426.

Korberg, A., Brynolf, S., Grahn, M., Skov, I., 2021a. Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Renew. Sustain. Energy Rev. 142 https://doi.org/10.1016/j.rser.2021.110861.

Korberg, A., Mathiesen, B., Clausen, L., Skov, I., 2021b. The role of biomass gasification in low-carbon energy and transport. Smart Energy 1. https://doi.org/10.1016/j.segy.2021.100006.

Liu, W., Best, F., Crijns-Graus, W., 2021. Exploring the pathways towards a sustainable heating system - a case study of Utrecht in The Netherlands. J. Clean. Prod. 280 https://doi.org/10.1016/j.jclepro.2020.125036.

Lozabo, E., Pedersen, T., Rosendahl, L., 2020. Integration of hydrothermal liquefaction and carbon capture and storage for the production of advanced liquid biofuels with negative CO2 emissions. Appl. Energy 279. https://doi.org/10.1016/j.apenergy.2020.115753.

Lund, H., Thellufsen, J.Z., Østergaard, P.A., Sorknæs, P., Skov, I.R., Mathiesen, B.V., 2021. EnergyPLAN - advanced analysis of smart energy systems. Smart Energy 1. https://doi.org/10.1016/j.segy.2021.100007.

Lund, H., Thellufsen, J., Sorknæs, P., Mathiesen, B., Chang, M., Madsen, P., Kany, M., Skov, I., 2022. Smart energy Denmark. A consistent and detailed strategy for a fully decarbonized society. Renew. Sustain. Energy Rev. 168 https://doi.org/10.1016/j.rser.2022.112777.

Paardekooper, S., Lund, H., Chang, M., Nielsen, S., Moreno, D., Thellufsen, J., 2020. Heat Roadmap Chile: a national district heating plan for air pollution decontamination and decarbonisation. J. Clean. Prod. 272 https://doi.org/10.1016/j.jclepro.2020.122744.

Ringsred, A., van Dyk, S., Saddler, J., 2021. Life-cycle analysis of drop-in biojet fuel produced from British Columbia forest residues and wood pellets via fast-pyrolysis. Appl. Energy 287. https://doi.org/10.1016/j.apenergy.2021.116587.

Silva, d., 2016. Techno-economic and Environmental Analysis of Oil Crop and Forestry Residues Based Biorefineries for Biojet Fuel Production in Brazil. TU Delft.

Skov, I., Schneider, N., Bundgaard, C., Korberg, A., Mathiesen, B., 2021. Energy System Effects of Fast Pyrolysis and HTL. Department of Planning Aalborg University, Aalborg.

Snowden-Swan, L., Billing, J., Thorson, M., Schmidt, A., Santosa, M., Jones, S., Hallen, R., 2020. Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2019 State of Technology. Pacific Northwest National Laboratory, Oak Ridge.

Tabak, S.A., Yurchak, S., 1990. Conversion of Methanol over ZSM-5 to Fuels and Chemicals. Mobil research and development corporation. https://doi.org/10.1016/0920-5861(90)85007-B.

Tanzer, S., Posada, J., Geraedts, S., Ramirez, A., 2019. Lignocellulosic marine biofuel: technoeconomic and environmental assessment for production in Brazil and Sweden. J. Clean. Prod. 239 https://doi.org/10.1016/j.jclepro.2019.117845.

Thellufsen, J., Nielsen, S., Lund, H., 2019. Implementing cleaner heating solutions towards a future low-carbon scenario in Ireland. J. Clean. Prod. 214 https://doi.org/10.1016/j.jclepro.2018.12.303.

Valmet, 2017. HOFOR Moves toward CO2 Neutrality by Utilizing the Capabilities of CFB. Valmet.

Xue, B., Yu, Y., Chen, J., Luo, X., Wang, M., 2017. A comparative study of MEA and DEA for post-combustion CO2 capture with different process configurations. Int. J. Coal Sci. Technol. 4, 15–24. https://doi.org/10.1007/s40789-016-0149-7.

Yuan, M., Thellufsen, J., Lund, H., Liang, Y., 2020. The first feasible step towards clean heating transition in urban agglomeration: a case study of Beijing-Tianjin-Hebei region. Energy Convers. Manag. 223 https://doi.org/10.1016/j.enconman.2020.113282.