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Climate change impacts of bioenergy technologies: A comparative consequential LCA of sustainable fuels production with CCUS

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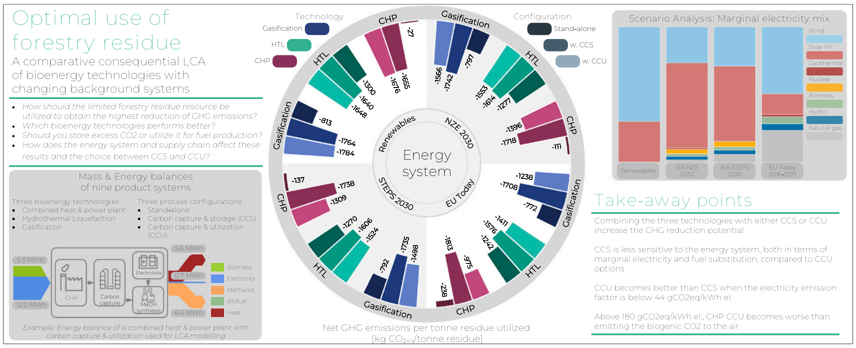
HIGHLIGHTS

- A comparative study has been performed of forestry residue utilisation pathways for liquid biofuels.
- Three technologies; CHP, gasification, and HTL with CCUS have been modelled.
- Climate change impacts were estimated using consequential LCA modelling.
- All three bioenergy technologies showed potential for net savings of GHG emissions.
- Study emphasizes impact of renewable electricity expansion when comparing CCS and CCU.

GRAPHICAL ABSTRACT



- How should the limited forestry residue resource be utilized to obtain the highest reduction of GHG emissions?
- Which bioenergy technologies performs better?
- Should you store excess CO2 or utilize it for fuel production?
- How does the energy system and supply chain affect these results and the choice between CCS and CCU?

Example: Energy balance of a combined heat & power plant with carbon capture & utilization used for LCA modelling

Combining the three technologies with either CCS or CCU increase the GHG reduction potential

CCS is less sensitive to the energy system, both in terms of marginal electricity and fuel substitution, compared to CCU options

CCU becomes better than CCS when the electricity emission factor is below 44 gCO2eq/kWh el.

Above 180 gCO2eq/kWh el., CHP CCU becomes worse than emitting the biogenic CO2 to the air

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ABSTRACT

The use of sustainable biomass can be a cost-effective way of reducing the greenhouse gas emissions in the maritime and aviation sectors. Biomass, however, is a limited resource, and therefore, it is important to use the biomass where it creates the highest value, not only economically, but also in terms of GHG reductions. This study comprehensively evaluates the GHG reduction potential of utilising forestry residue in different bioenergy technologies using a consequential LCA approach. Unlike previous studies that assess GHG impacts per unit of fuel produced, this research takes a feedstock-centric approach which enables comparisons across systems that yield diverse products and by-products. Three technologies—combined heat and power plant with carbon capture, hydrothermal liquefaction, and gasification—are assessed, while considering both carbon capture and storage (CCS) or carbon capture and utilisation (CCU). Through scenario analysis, the study addresses uncertainty, and assumptions in the LCA modelling. It explores the impact of energy systems, fuel substitution efficiency, renewable energy expansion, and the up/down stream supply chain. All technology pathways showed a potential for net emissions savings when including avoided emissions from substitution of products, with results

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Abbreviations: BOP, balance of plant; CCS, carbon capture and storage; CCU, carbon capture and utilisation; CHP, combined heat and power plant; GHG, greenhouse gas; HTL, hydrothermal liquefaction; IEA, international energy agency; IPCC, the intergovernmental panel of climate change; LCA, life cycle analysis; LCIA, life cycle impact assessment; LHV, lower heating value; NZE, net zero emissions; RED, renewable energy directive; RFNBO, renewable fuel of non-biological origin; SR, sensitivity ratio; STEPS, stated policy scenario.

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varying from −111 to −1742 $kgCO_{2eq}$ per tonne residue. When combining the bioenergy technologies with CCU the dependency on the energy system in which they are operated was a significantly higher compared to CCS. The breakpoint was found to be 44 kg CO_{2eq}/kWh electricity meaning that the marginal electricity mix has to be below this point for CCU to obtain lower GHG emissions. Furthermore, it is evident that the environmental performance of CCU technologies is highly sensitive to how it will affect the ongoing expansion of renewable electricity capacity.

1. Introduction

The European Commission has made a long-term strategy called the European Green Deal to achieve their goal of making Europe the first climate neutral continent by 2050 – an economy with net-zero greenhouse gas (GHG) emissions (European Commission, 2023a). In reaching this ambitious goal the transportation sector, especially the heavy-duty transport, is highlighted as one of the biggest challenges. The heavy-duty transport, such as maritime transportation and aviation, is less suited for electrification due to the heavy load and long travel distances. Therefore, heavy-duty transportation requires alternative liquid or gaseous fuels in the transition. The maritime sector constitutes 12 % of the total CO_2 emission from transportation globally (IEA, 2023). The European Commission has made dedicated initiatives to push the transition in this sector called ReFuelEU (European Commission, 2023b). The initiative is based on the GHG emissions of the energy used in ships, with a reduction of 6 % by 2030, 26 % by 2040 and 75 % by 2050 compared to a fossil baseline. This allows the maritime sector to explore many different types of fuels and the value of the sustainable fuels will heavily depend on its GHG emissions.

Currently, the trend in the maritime sector is towards bio- and e-methanol when it comes to liquid carbon fuels, however, many other types of fuels are also being researched and developed. A techno-economic assessment of e-fuel production by CONCAWE (Soler et al., 2022) recently concluded that the production cost and GHG abatement costs for biofuels will be lower than those of e-fuels. For 2050, they estimated a GHG abatement costs between 380 and 810 dollars per tonne avoided CO_2 for e-fuels compared to 10–320 dollars for biofuels. Utilising readily available biomass resources can thereby provide economically cheaper CO_2 reductions compared to relying solely on renewable electricity. The utilisation of biomass for fuel production and bioenergy, however, faces a significant challenge due to the limited availability of sustainable biomass, which are biomass with limited impact land-use, food prices and other environmental factors such as the types of biomass listed in RED II Annex IX (European Commission, n.d.). According to estimates by the International Energy Agency (IEA), approximately 100 exajoules per year (EJ/year) of sustainable biomass could be accessible. This includes sources like woody residues, organic wastes, forest plantations, and short rotation woody crops on marginal land (IEA, 2022). While these resources have the potential to support up to 50 EJ of liquid biofuel, accounting for conversion losses, it is essential to recognize the finite nature of sustainable biomass. In 2022, the global energy supply reached 632 EJ, with fossil fuels contributing 501 EJ, and 118 EJ of this was allocated to the transportation sector (International Energy Agency, 2023). Even in a scenario where all available biomass resources as estimated by IEA are allocated to the transportation sector, they could only meet approximately 42 % of the current fossil energy demand for transportation. This underscores the necessity of strategic biomass allocation, considering not only economic value but also the paramount importance of reducing greenhouse gas (GHG) emissions. Allocating biomass where it can deliver the highest value, both economically and in terms of GHG reductions, becomes crucial in navigating the complex landscape of sustainable energy solutions.

In a study by Mortensen et al. (Mortensen et al., 2020), the role of electrification and hydrogen in breaking the bottleneck in biomass supply in the future renewable energy system was assessed. Hydrogen can react with biogenic carbon in various forms such as CO and CO_2 in syngas from biomass gasification/pyrolysis, CO_2 from biogas production, or CO_2 captured from flue gas from combustion of biomass. Adding external hydrogen to these systems can enhance the carbon conversion efficiency from biomass to final energy carriers. Another option for further GHG reductions from bioenergy technologies is permanently storing of biogenic CO_2 which could offer the opportunity to achieve net-zero GHG emissions, as concluded by the IPCC (IPCC, 2021). This can be achieved for various bioenergy technologies where a fraction of the biogenic carbon is captured as CO_2 and permanently stored (Lozano et al., 2020). Also capturing and storing the CO_2 from the flue gas in biomass fired power plants or waste incineration plants can result in an overall carbon negative process as described by Bisinella et al. (B. et al., 2022).

The GHG reductions of different bioenergy technologies and process configurations can be estimated using life-cycle assessment (LCA) which is a standardized method to systematically assess the environmental impacts of technologies and systems (ISO14040, 2006). The literature on environmental impact assessments using the LCA methodology for sustainable fuel production is extensive and has covered a wide variety of fuel types and production pathways. Some examples includes large projects supported by the European Commission (Soler et al., 2022; Prussi et al., 2020) which evaluated the environmental performance, in terms of GHG emissions, for various sustainable fuel production pathways, with the ultimate goal to support decision makers in the transition towards sustainable fuels. In the JEC-WTT report (Prussi et al., 2020), more than 250 different pathways were modelled, and it was found that the conversion pathways and feedstock used have a substantial impact on the results. Synthetic diesel derived from wood was highlighted to have low GHG emissions while for e-fuels, the source of the electricity where the determining factor for its GHG emission reduction potential. Many other studies focus on environmental impact from sustainable fuel productions and compared a multitude of different options (Roack et al., 2022; Yadav et al., 2020; Ringsred et al., 2021; Sun et al., 2019), including methane, methanol, biodiesel, and sustainable aviation fuel. However, due to differences in goals, system boundaries, methodology applied, and assumptions made, it is very difficult to compare the results between two different studies directly. These are all issues raised in earlier studies for bioenergy and advanced biofuels such as the study by Cherubini et al. (Cherubini et al., 2009). In studies by Jong et al. (Jong et al., 2017) and Moretti et al. (Moretti et al., 2022), assessing the GHG emissions from renewable jet fuel production, the importance of by-products and how they are handled in the LCA was highlighted. The by-products are typically either modelled by allocation, used in attributional LCA, or with system expansion and substitution which is used in consequential LCA. This modelling choice can have a large impact on the results, especially when assessing systems with large quantities of valuable by-products.

Common for most of the LCA studies on sustainable fuel production found in the literature is that they aim to estimate the climate change impacts per energy unit of fuel produced. This approach makes sense from a regulatory perspective, as the requirements defined in the REFuelEU for example are based on the reduction in emissions per energy unit of fuel. The challenge is that not all fuel and energy types can serve the same purposes and one should therefore be careful when trying to compare estimated GHG reductions between different types of fuel. An alternative approach is to look at the systems from the perspective of the feedstock. This has been done by Nedenskov et al. (B. et al., 2022) to analyse the impact of installing carbon capture on an existing waste incineration unit and by Chang et al. (Chang et al., 2023) to assess a multitude of different technologies for wastewater treatment and disposal. Assessing the climate change impacts from the perspective of a fixed amount of feedstock allows for comparisons of systems which produced vastly different products.

The overall research question motivating this study has been *How should this limited resource of biomass be utilised to obtain the highest reduction in GHG emissions?* Answering this question requires the systems to be analysed from the perspective of the feedstock. The question is obviously very broad as it covers multiple types of feedstocks, and the use of bioenergy covers many different technologies in our energy system. Thus the objectives of this study is to:

- Establish mass- and energy balances for bioenergy technologies combined with carbon capture and storage or utilisation for liquid fuel production.
- Conduct consequential LCA for comparing the GHG reduction potential.
- Analyse the impact of the background energy system in which the processes are operating.

This will help answer the knowledge gaps found in the literature of bioenergy and sustainable fuel production which are; a need for more thorough sensitivity analysis of how the background energy system affect the GHG reduction potential of the bioenergy technologies, assessing the impact of LCA methodology and assumptions, and how the by-products containing carbon can be utilised. The overarching aim of this paper is therefore to provide a consistent and transparent evaluation of the climate change impacts of various bioenergy technologies operated in different background systems.

2. Material and methodology

2.1. Life cycle assessment

To quantify the climate change impact of the bioenergy pathways a consequential LCA was modelled. The LCA was conducted in accordance with the ISO14040 standard (ISO14040, 2006). For this study the functional unit is defined on the input side as *one tonne of dry forestry residue*, as this allows for comparison between technologies that leads to multiple outputs. The goal of the study is to assess the environmental impacts in terms of climate change for three bioenergy technologies, combined heat and power plant (CHP), hydrothermal liquefaction (HTL), and gasification. The modelling also considers different process configurations for either capturing and storing carbon (CCS) or utilisation of the carbon to maximise the carbon to fuel conversion efficiency (CCU). In all the pathways assessed the main output is liquid biofuel except for CHP stand-alone and CHP with CCS pathways. These are used as the reference scenarios in the assessment. In addition to the processes described, the system boundary also includes transportation and handling of the feedstock and products. Descriptions of the technologies and pathways included are presented in Section 2.3.

System expansion has been applied, following key LCA principles, for all the products leaving the system boundary including electricity, heat, methanol, and biocrude. This is done by subtracting the alternative marginal products that are avoided as a consequence of introducing these new products to the market. The main products of this study, methanol and biocrude, are assumed to substitute fossil fuels used in the maritime sector 1 to 1 on an energy basis based on LHV as they will have similar properties and use cases compared to the fossil fuels used in the maritime sector today. Their impact is measured as avoided GHG emissions when substituting fossil fuels with an emission factor of 93 gCO2eq/MJ which is the emission factor for diesel reported in the Ecoinvent database (substitution, consequential, long-term, version 3.9.1). This includes both fossil CO_2 emissions from combustion and emission from extraction and refining of the product. The geographical scope of the study is centred around Europe and three different supply chains have been assessed, presented in detail in Section 2.6. The temporal scope of the assessment is the estimated lifetime of the processes, which are assumed to be 30 years, starting in 2030. For background data on material and energy consumption and substitution, the Ecoinvent database (substitution, consequential, long-term, version 3.9.1) was used. The specific datasets can be found in the Supplementary material. The global warming potentials are quantified as GHG emissions (CO_2 equivalents) for a 100-year time horizon using the sixth assessment report by the Intergovernmental Panel on Climate Change (IPCC, 2021). Biogenic CO_2 emissions were modelled as defined by Christensen et al. (Christensen et al., 2009) with a characterization factor of 0 kg CO_{2eq}/kg CO_2 whereas permanently stored biogenic CO_2 has a characterization factor of -1 kg CO_{2eq}/kg CO_2 stored. This assumes that the biomass used is carbon neutral and potential negative effect for using it as bioenergy - such as nutrient depletion and decline in soil productivity – has not been considered.

2.2. The cradle: forestry residue feedstock

This study considers forestry residue as the feedstock for all the processes with the following characteristics 49 % moisture, 3.97 % ash, and a lower heating value (LHV) of 19.9 MJ/kg dry mass (TNO, 2023). Forestry residues is one of the feedstocks listed in the RED II Annex IX by the EU (European Commission, n.d.) for producing advanced biofuels. These residues do not have a direct material use and is currently therefore either left in the forest to decompose or used for energy purposes. As a residue product it is considered constrained in availability, meaning that the amount of residue available is directly dependent on the production of virgin wood products. For this study it is assumed that a fraction of the residue is unused and thereby available for the bioenergy processes. If the feedstock is fully utilised, demanding it for the processes assessed in this study will force the previous user to find alternatives and this could potentially reduce the overall avoided GHG emissions significantly. However, this shift will be the same for all technologies studied and it will not affect the comparison between the technologies, hence is not included in the LCA modelling. The 'cradle' of this LCA is thereby considered from the point of collecting and handling the residues.

2.3. Bioenergy processes

In this study, three technologies for producing sustainable fuels from forestry residue are assessed. They are combined heat and power plant (CHP) with carbon capture, Hydrothermal Liquefaction (HTL), and gasification. For each of the three technologies, three configurations are considered. First the stand-alone version of the technology, secondly a CCS configuration which focusses on CO_2 storage, and finally a CCU configuration which maximises the fuel output. Utilising forestry in stand-alone combined heat and power plants have been done for many years and is used as the *business-as-usual* scenario in this study. These combinations lead to in total nine product systems, as shown in Fig. 1. In the figure, the overall energy balances of the nine systems are illustrated. Each of the technologies are described in more details in the following sections and the parameters are based on state-of-the-art data from pilot plant operation or process modelling. A full list of all the process parameters used and references can be found in the Supplementary material.

2.3.1. Combined heat and power plant

The combined heat and power plant has been modelled in ThermoFlex, a software developed by Thermoflow (Thermoflow, 2023), and recovers the energy of the biomass as electricity and heat. After the combustion of the biomass, flue gas condensation is added to recover the residual energy as low temperature heat. The system is designed to

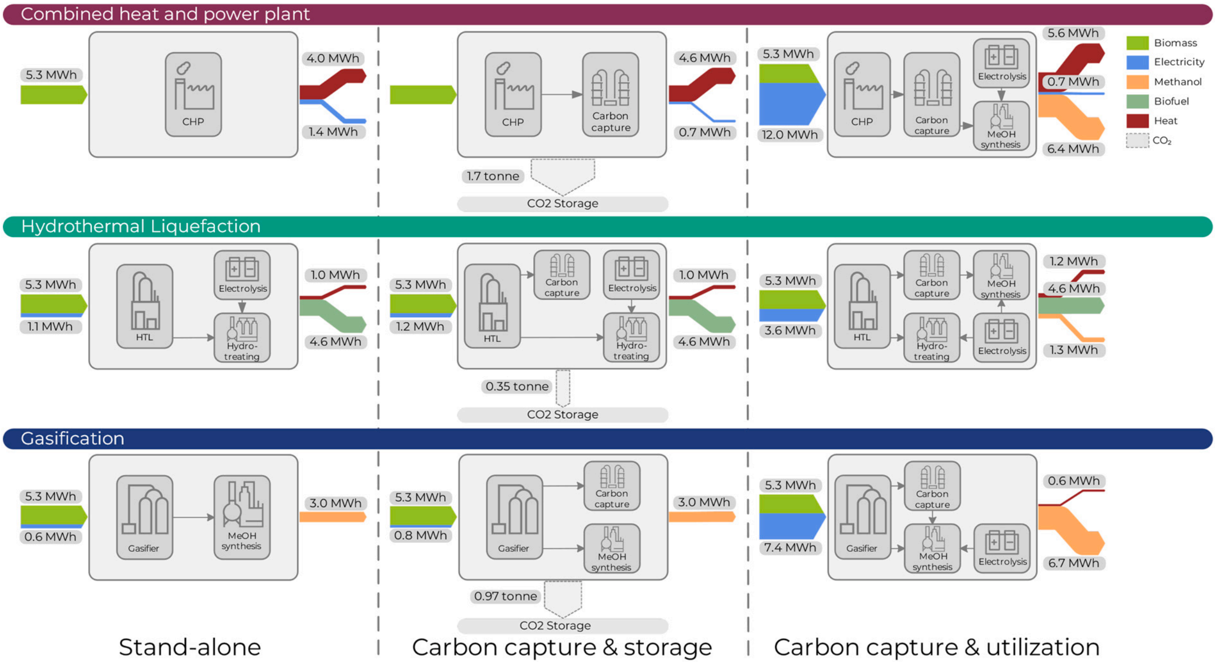

Fig. 1. Overview of the nine scenarios assessed in this study, including three main bioenergy technologies and three process configurations for each. This figure shows both an overview of the process configuration and the overall energy balances in terms of inputs and outputs for processing 1 t of dry forestry residue (5.3 MWh). All product energy streams are based on lower heating values.

maximise the overall thermal efficiency, which means that heat pumps are used to increase the temperature of low temperature heat to a supply temperature for district heating of 85 °C. This assumes that the plant is located in an area with district heating, and this is therefore considered an optimistic scenario. If the plant did not have access to district heating the electric efficiency will be slightly higher, however, the overall thermal efficiency of the plant will be much lower, thereby reducing the GHG emissions savings potential from the plant.

In the stand-alone configuration, only including the CHP plant and flue gas condensation, 25.8 % of the energy is recovered as electricity and 75.4 % as district heating based on the LHV of the dry feedstock. For both the CCS and CCU pathways the CO_2 from the combustion is captured in a downstream amine-based carbon capture unit with a 90 % capture efficiency and then either permanently stored (see Section 2.3.5) or used for methanol production (see Section 2.3.6). The additional electricity and heat required to capture the CO_2 is provided from the CHP plant. The waste heat from the carbon capture unit is recovered for district heating using heat pumps. This means that in the CCS and CCU pathways the total thermal efficiency of the plant remains almost unchanged with 13.7 % as electricity and 86.7 % as heat for district heating.

2.3.2. Hydrothermal Liquefaction

Hydrothermal Liquefaction (HTL) is a thermochemical process in which the main product is a biocrude with a yield of 45.3 % on dry mass basis. The process uses water as the reactor medium, which allows for wet biomass to be processed without the need for drying. It operates at critical pressure and temperature, 300–350 bar and 390–420 °C, and the produced aqueous phase is partly recirculated to enhance the yield of biocrude (Jensen et al., 2017). The produced biocrude contains oxygen, nitrogen, and acids which needs to be removed before it can be used as a transportation fuel. Refining of the biocrude via hydrotreating with a hydrogen consumption of 37.3 g H_2 per kg biocrude followed by distillation is assumed. The oxygen from the biocrude is thereby removed as water and a small fraction of the carbon is lost in a gaseous by-product.

Besides the biocrude the HTL process produces a gas phase, an aqueous phase, and a solid phase of the ash from the biomass. Both the ash and wastewater are considered waste and need to be handled at waste treatment facilities. The light components from the gas phase are combusted to produce heat for the process which makes the HTL process self-sufficient in terms of heat. A considerable amount of the carbon from the biomass, approximately 26 %, ends up as CO_2 in the gas phase after the HTL process. In both the CCS and CCU pathways the CO_2 is captured using a physical solvent and either stored or used to produce methanol (Lozano et al., 2020).

2.3.3. Gasification

The gasification plant has been modelled as a bubbling fluidized bed gasifier in Thermoflex, where the forestry residue is converted into a syngas in the presence of oxygen, steam, and CO_2. After the gasifier the syngas is cleaned and shifted with a water gas shift reaction to obtain the correct ratio between hydrogen and CO/CO_2 for the downstream methanol synthesis. This means that in the stand-alone scenario, methanol is produced without any requirement for external hydrogen. However, most of the CO_2 from the syngas is removed and is thereby a carbon loss in the stand-alone scenario. To increase the carbon efficiency, the CO_2 fraction can be either stored or utilised with external hydrogen to produce additional methanol. This has been considered in the CCS and CCU pathways respectively. With heat integration, the gasifier process is self-sufficient in terms of steam. The oxygen is supplied by an air-separation unit, however, in the CCU pathway this is not required as there is a surplus of oxygen from the electrolysis unit.

2.3.4. Electrolysis

Whenever the processes require hydrogen for fuel synthesis or upgrading it is in this study assumed to be produced via PEM electrolysis, which uses electrical power to split water into hydrogen and oxygen. PEM electrolysis operates at around 30 bars and has a specific power consumption of 51.3 kWh el. per kg H2 based on lower heating value (Noordende and Ripson, 2022). Furthermore, it is possible to recover heat corresponding to ~13 % of the hydrogen which can be supplied to a district heating network. The GHG emissions from the materials, manufacturing, and balance of plant (BOP) for the electrolyser are very low compared to the electricity requirement for operating the system. This study assumes 0.13 kg CO_2/kg H2 for the combined BOP of the electrolysis unit as reported by Bareiss et al. (Bareiss et al., 2019). For comparison the GHG emissions from the electricity requirement to operate the system, when only using wind and solar power, is 2.15 kg CO_2/kg H2. Furthermore, it is assumed that the hydrogen production will follow the fluctuations in the renewable electricity production. The impact this will have on the marginal electricity production is discussed in Section 2.4.

2.3.5. CO_2 storage

The captured CO_2 is liquified before it is transported by ship to a designated storage area where is can be permanently stored. This is done in a liquefaction unit where the CO_2 is pressurised to 15 to 18 bar and cooled to −25 to −30 °C. Transportation of CO_2 can take place in road tankers, sea carriers, or by pipeline, however, for pipeline transportation the CO_2 is transport as pressurised gas and not in liquid form to avoid phase change. The choice of transportation depends on the amount of CO_2, the lifetime of the transportation scheme, transport logistics, and the destination (Danish Energy Agency, 2021). The supply chain assessed in this study, described in detail in Section 2.6, includes sea carriers and pipeline transportation of CO_2.

2.3.6. Methanol synthesis

Methanol synthesis is used to convert CO_2 and CO into liquid fuels by combining it with hydrogen based on the main reactions shown in Eqs. (1)–(3). The reaction is exothermic, which means it produces heat, and the heat is used in the down-steam distillation process to separate methanol from the water. The process is thereby assumed to be self-sufficient in terms of heat. An overall carbon conversion of 96 % is assumed where the small loss is from a gas purge in the synthesis loop (Detz, 2019).

$$CO_2 + 3H_2 \leftrightharpoons CH_3OH + H_2O + \text{Heat (Methanol)} \tag{1}$$

$$CO + 2H_2 \leftrightharpoons CH_3OH + \text{Heat (Methanol)} \tag{2}$$

$$CO_2 + H_2 \leftrightharpoons CO + H_2O \text{ (RWGS)} \tag{3}$$

2.3.7. Energy balances

In Fig. 1 the overall mass and energy balances are shown for the three technologies and three different process configurations. In the stand-alone configuration of the processes, the CHP scenario is different in that all energy from biomass is recovered as electricity and heat whereas for both HTL and gasification the energy is converted into fuels. This means that in the CCS pathways, a much larger portion of CO_2 can be stored in the CHP case as none of the carbon is used for fuel production. HTL has the highest conversion to fuel in the stand-alone process, which means that is has the lowest potential for carbon storage of only 0.35 t of CO_2 per tonne of dry residue. The requirement for electricity increases significantly in all the CCU pathways, showing that obtaining a high carbon to fuel efficiency is energy intensive. The total amount of liquid fuel produced is highest in the CHP and gasification CCU pathway with 6.4 and 6.7 MWh respectively per tonne of dry residue compared to 5.9 MWh for HTL. However, the amount of electricity required to obtain the high fuel production is significantly higher when considering CHP and gasification with CCU.

2.4. Electricity for electrolysis

In all CCU pathways focussing on optimizing the fuel output, hydrogen is a key energy source, demanding substantial electricity to produce hydrogen via electrolysis. The choice of technologies supplying the electricity significantly influences the LCA and overall performance of these scenarios. From a regulatory perspective, hydrogen and renewable fuels of non-biological origin (also known as RFNBOs) must be produced from renewable sources in the EU (The Europen Commission, 2023). This was defined as a delegated act under the Renewable Energy Directive in 2023. The act clarifies the principle of "additionality" for hydrogen production, which means that the electricity used must be supplied from newly built renewable electricity production capacity. It is only allowed to connect directly to the electricity mix in bidding zones with above 90 % renewables, however, only very few regions are above this globally. The question from a consequential modelling perspective is how the expansion of renewables is impacted by a marginal increase in demand for renewable electricity for electrolysis. Here two extreme scenarios are considered, either the expansion rate of renewables is fully unconstrained or fully constrained:

Assuming that the expansion rate is **unconstrained** implies that an increase in demand for renewable electricity will increase the expansion rate accordingly to match the increased demand. This means that all the electricity used for electrolysis can be assumed to be from renewable sources when assessing the climate change impact of the system. An increased demand will thereby not affect the remaining electricity production and consumption. Furthermore, it is assumed that the electrolysis can be fully aligned with the fluctuations and intermittency in renewable wind and solar electricity production.

On the other hand, the expansion rate of renewables could also be assumed fully **constrained**. This could be the case if the bottlenecks in the renewable electricity expansion, such as limited production capacity and grid connection issues, causes the rate at which new renewables can be built to be capped. In this scenario a marginal increase in demand for renewable electricity for electrolysis will take the electricity from other consumers and force them to find alternatives. From a modelling perspective it is assumed that the increased demand will be supplied by the marginal electricity mix and not only the capacity of renewables. The estimations of the marginal mixes used in the modelling are described in the following section.

The baseline assumption for the LCA modelling conducted in this study is that the expansion of renewables is fully constrained as it allows for assessment of different energy systems. However, since the actual impact will most likely be somewhere in between the extreme scenarios outlined here, the impact of the assumption is assessed and discussed in Section 3.2.1.

2.5. Energy system scenarios: future marginal electricity

As the aim of this study is to estimate the consequences of utilising additional forestry residue with consequential LCA modelling, the impacts are assumed to only affect marginal suppliers. For electricity generated in the product systems, it is assumed that future marginal electricity will be displaced. For heat, it is assumed the heat generated from electric heat pumps will be displaced, it is thereby directly linked to the future marginal electricity. According to the approach by Weidema et al. (Weidema et al., 1999), long-term marginal energy technologies are technologies whose future capacity is expected to change within the temporal scope of the study. The marginal mix for electricity should thereby represent the share of technologies that would increase or decrease in capacity when the demand for electricity is marginally increased or decreased. This means that technologies that is being phased out will not be part of the marginal electricity mix when the demand is increased, as opposed to the average mix which is often considered in attributional modelling.

Determining these marginal mixes relies on future projections of how the energy system will react to changes and is therefore associated with high uncertainty. Due to the high uncertainties, this study considers four different marginal mixes for electricity. The energy scenario analysis will assess how the marginal electricity mix changes the overall results and conclusions of the technology comparison. To estimate the marginal electricity mix, the methodology by Muñoz and Weidema has been used (Muñoz and Weidema, 2023). The method estimates the marginal mix based on either recent historical data or forecasted data of the electricity production. Below are short descriptions of the four energy systems for electricity generation considered in this study and Fig. 2 shows the resulting marginal electricity mixes ranked from lowest to highest environmental impact in terms of climate change. More details on the energy systems are provided in the Supplementary material.

IEA NZE – This is the baseline assumption for the marginal electricity mix used in this study. It is based on the Net Zero Emissions (NZE) scenario from IEAs World Energy Outlook report (International Energy Agency, 2023). The marginal mix is estimated by comparing the current electricity production worldwide (2022 data) to the projected production capacities for 2030 in the NZE scenario.

IEA STEPS – The second scenario is the Stated Policy Scenario (STEPS) which is also from IEA (International Energy Agency, 2023). In this scenario the marginal electricity mix is estimated from current production to projected production in 2030 when considering the stated policy worldwide.

EU Today – The third scenario is referred to as *Europe today*. It considers the recent advancements in electricity production in Europe from 2016 to 2021 (International Energy Agency, 2023). The marginal mix estimated represent a scenario where the recent trend in Europe continues in the future.

Renewables – Finally, the fourth scenario is a theoretical optimistic scenario. Here it is assumed that the marginal mix is made up from renewable sources only, in this case 30 % solar power and 70 % wind power. Electricity produced from wind have the lowest environmental impact on climate change and is therefore prioritised.

The GHG emissions factors for the different electricity mixes shown in Fig. 2 uses Ecoinvent as the background database which means that it includes the emissions associated with construction and materials use. In this approach, the production of electricity from renewable sources is still associated with some GHG emissions, something which is not always included when assessing electricity mix emission factors. Fig. 2 also includes a comparison of emission factors for both marginal and average electricity mixes. Here it is shown that the four marginal electricity mixes used in this study have low emission factors compared to using the average mix. This is because the marginal mixes only consider technologies that are expected to increase in capacity, and since we are transitioning towards a more sustainable energy system, these new technologies will have a lower environmental impact than the average electricity mix. An example is the use of coal for electricity production, which is still used today, however, since it is being phased out globally it is not included in any of the estimated marginal electricity mixes.

2.6. Biomass and CO_2 supply-chain scenarios

The GHG emissions from transportation depends on the location of the facility relative to the feedstock and off take of products as well as the method of transportation. To assess the impact of these up- and downstream transportation on climate change, three different supply-chains have been considered. The scenarios are based on where forestry residue is available and on ongoing projects regarding offshore CO_2 storage.

Fig. 3 shows an illustration of the three scenarios and the transport distances and transport method assumed in the modelling. In all the scenarios the facility is assumed to be located at an industrial marine port and thereby no transportation for the produced fuels is required. In the baseline scenario (A) the facility is located at the port of Gothenburg in Sweden, close to forestry residue from the Baltic Sea area. Storing of the CO_2 is based on the Northern Lights project (Equinor et al., 2023) where CO_2 is transported by ship to a terminal in western Norway for intermediate storage before it is transported 110 km by pipeline to be stored deep under the seabed. In the second supply-chain (B) the facility is located at Port of Rotterdam with the residues being imported by ship from the Baltic Sea area. The storage of CO_2 is based on the Porthos project (EBN et al., 2023) where the CO_2 is transported by pipeline to depleted gas fields in the North Sea, approximately 20 km from the coast, where it will be stored. The transportation of CO_2 is thereby much shorter in this scenario at the cost of longer transport of the residues. Finally, in scenario C the residues are assumed imported from Canada to the facility at the Port of Rotterdam while the CO_2 is transported to and stored as part of the Northern Lights project.

3. Results and discussion

3.1. Baseline: LCIA breakdown

A breakdown of the LCA results of the climate change impact category for all nine combinations of process technology and configuration is illustrated in Fig. 4. The results shown here are based on the NZE 2030 scenario, however, similar breakdowns of LCA results for all four energy

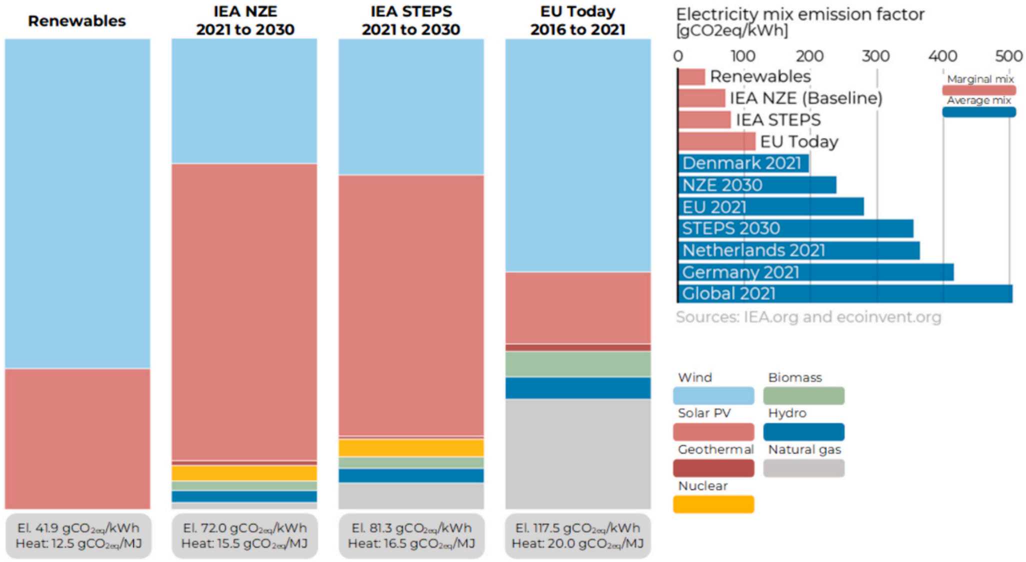

Fig. 2. Estimated marginal electricity mix and their corresponding life cycle GHG emission factors. The scenarios are ranked from lowest to highest environmental impact in terms of climate change. The figure also shows a comparison of life cycle GHG emission factors of the estimated marginal mixes and average electricity mixes.

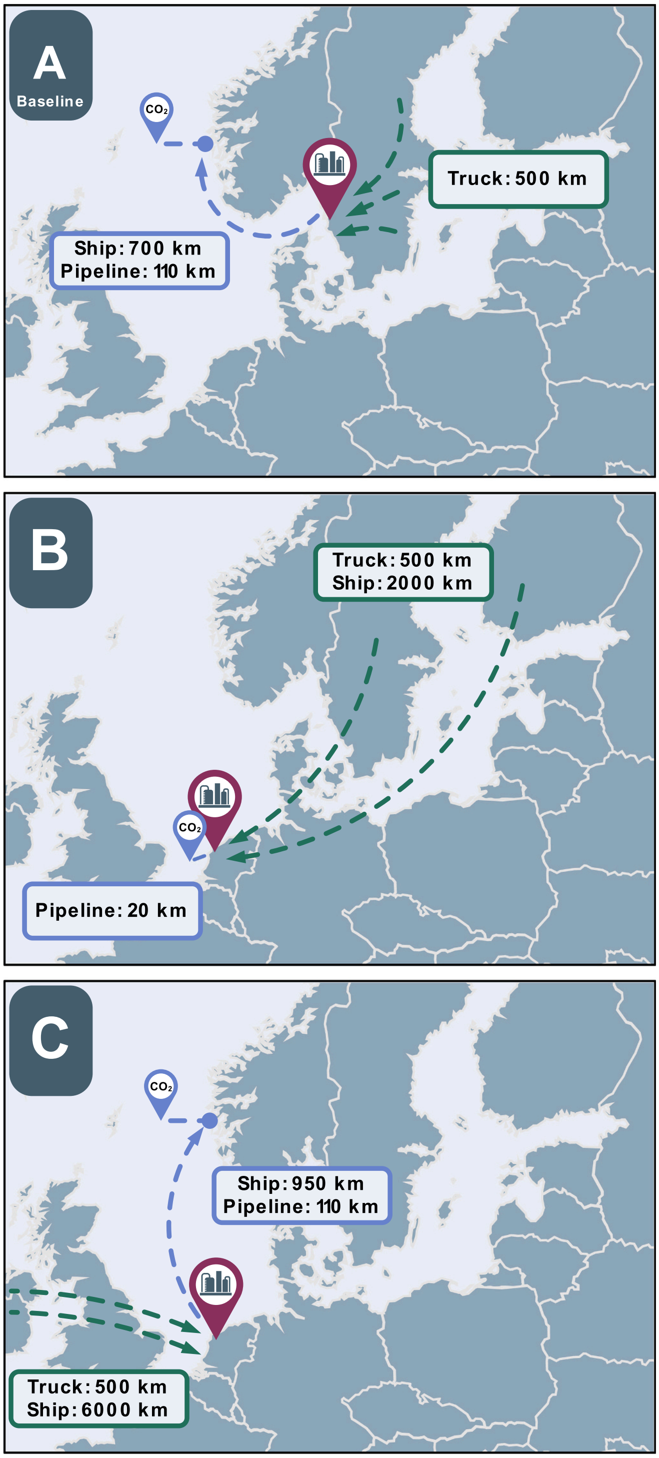

Fig. 3. Illustration of the three supply-chain considered to assess the impact of up- and down-stream transportation emissions on climate change. The red marker indicates the assumed location of the bioenergy facility, the green arrows show the sourcing of the forestry residue, and finally the blue arrows show the assumed transportation of the CO_2 to the storage site.

systems can be found in the Supplementary material. All the pathways assessed achieve net GHG savings when considering avoided emissions, but with a wide range from -111 to -1742 kgCO_{2eq} per tonne of residue. The stand-alone CHP pathway achieves the highest net savings of GHG emissions, due to the relatively low impact of the produced electricity and heat, however, when adding carbon capture and storing the scenario obtains the second highest net GHG savings by storing 1659 kg of CO_2 per tonne of residue. Hydrothermal Liquefaction on the other hand is much more stable across the three process configurations as most of the fuel is produced in the stand-alone process. The largest contribution to positive emissions is from the electricity consumption in the CCU pathways which ranges from 258 kg CO_{2eq} for HTL to 866 kg CO_{2eq} for CHP. This is followed by feedstock handling, transport emissions, and chemical use whereas the impacts of waste handling are insignificant across all scenarios.

Comparing the CCS and CCU pathways, shows that the CO_2 results in more avoided emissions when it is converted to fuel and replaces fossils compared to when it is stored. This is most noticeable in the CHP CCU case where the methanol produced from the 1659 kg capture CO_2 result in 2191 kg CO_{2eq} avoided when substitution fossil fuels. This is because when it is converted to fuels, it does not only replace the fossil emissions from the combustion but also the GHG emissions associated with extraction and refining the fuels. However, for all three technologies the CCS pathways still obtain the lowest net GHG emissions. This shows that when using the NZE 2030 marginal electricity mix for the processes, the additional avoided GHG emissions from producing fuels is not enough to outweigh the emissions from the additional energy use in the CCU pathways.

Fig. 4 also shows the net GHG emissions when excluding the potentially avoided emissions from product substitution. This shows the physical GHG emissions added or removed from the atmosphere as a consequence of utilising the residues in the respective pathway. For a bioenergy technology to be considered as *carbon dioxide removal* as defined by IPCC (IPCC, 2021) the net GHG emissions without avoided emissions will have to be negative. This means that physical CO_2 emissions are removed from the atmosphere and thereby require storage of biogenic CO_2. From Fig. 4, all the CCS scenarios obtain net negative emissions varying from only -10 kg CO_2/t residue for HTL to -1408 kg CO_2/t residue for CHP.

The GHG intensities and whether the CCS pathways can be considered net negative emission technologies depends on a wide range of external factors. The following sections will focus on how the energy system, fuel market, and supply-chain will affect the LCA results, but these are far from the only relevant factors. In a study by Gelfand et al. (Gelfand et al., 2020) the emission intensities were found to differ substantially between different biomass types and soil organic carbon and energy production potential of the specific arable land. Another study by Fuss et al. (Fuss et al., 2018) also investigate the side effects of bioenergy with carbon capture and storage which they summarised as climate effects induced by biomass provision, resource needs, and broader environmental and sustainability effects from the coupled land-energy system. These also includes direct and indirect land use changes caused by the deployment of large-scale bioenergy. For this study these effects have not been modelled in detail since they are assumed to be the same across all nine products systems and they thereby do not impact the relative comparison between the systems. It is, however, important to emphasise that these factors can have a significant impact on the absolute GHG savings potentials and whether the pathways can be net negative in terms of GHG emissions.

3.2. *Sensitivity analysis*

Several different methods are used to assess the sensitivity and uncertainty of the LCA results. This section describes the scenario analysis of the energy system in which the processes are operating in terms of electricity emission factor, a sensitivity analysis of the fuel substitution efficiency, and finally, a scenario analysis of both the upstream and downstream supply-chain. For the process input parameters, a local sensitivity analysis (also called perturbation analysis) is conducted to identify the impact of each parameter on climate change which can be found in the Supplementary material. The results from the local sensitivity analysis show that the parameters concerning carbon yield or losses have the highest impact, followed by electrolysis efficiency in the

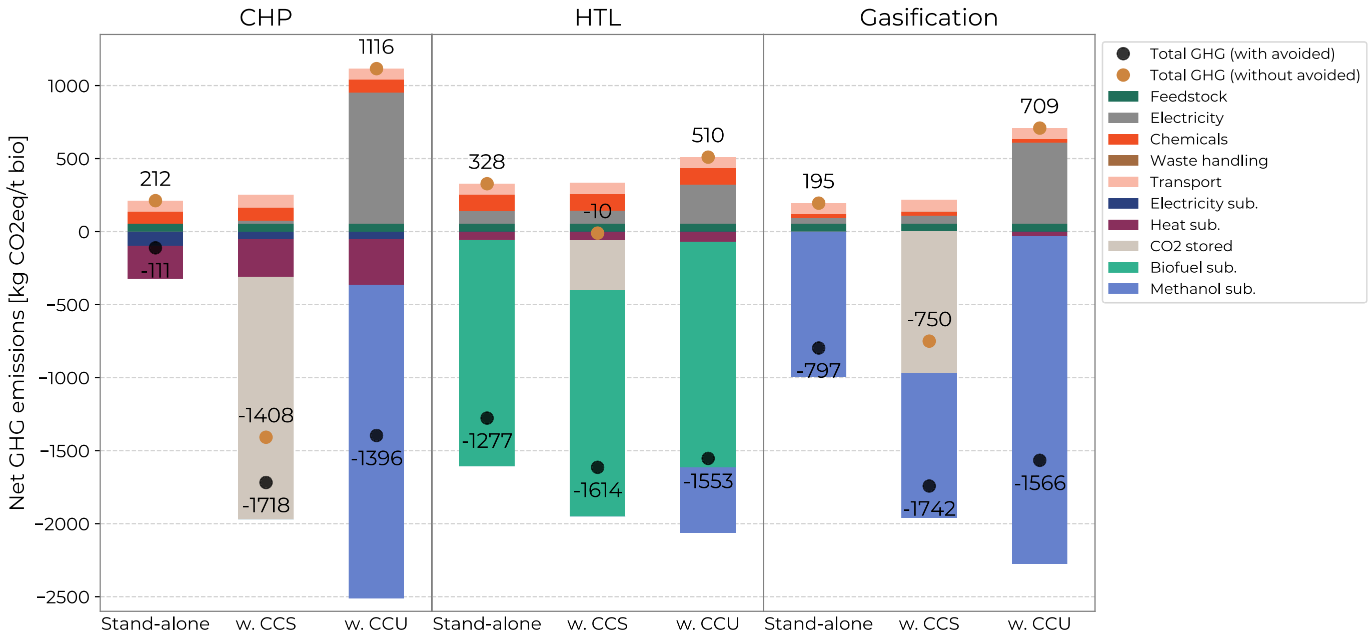

Fig. 4. Breakdown of the climate change impacts in the baseline scenario, using the NZE 2030 marginal electricity mix, for the three processes (CHP, HTL, and gasification) and three configurations (Stand-alone, CCS, and CCU) as presented in Section 2.3. The results are presented as net CO_2 equivalents per tonne of biomass residue.

CCU pathways.

3.2.1. Scenario analysis: marginal electricity mix

Fig. 5 shows the resulting net GHG emissions including avoided emissions of the nine scenarios when implemented in four different energy systems. From the figure, it is observed that the CCS and CCU pathways perform better than the stand-alone across all energy systems and technologies, which means that from a climate change perspective it is always beneficial to capture and store or utilise the excess CO_2 with these technologies. Looking at the CHP case, the CCS pathway obtain high net GHG savings across all energy system as most of the carbon is stored with a relatively low energy requirement and is thereby not

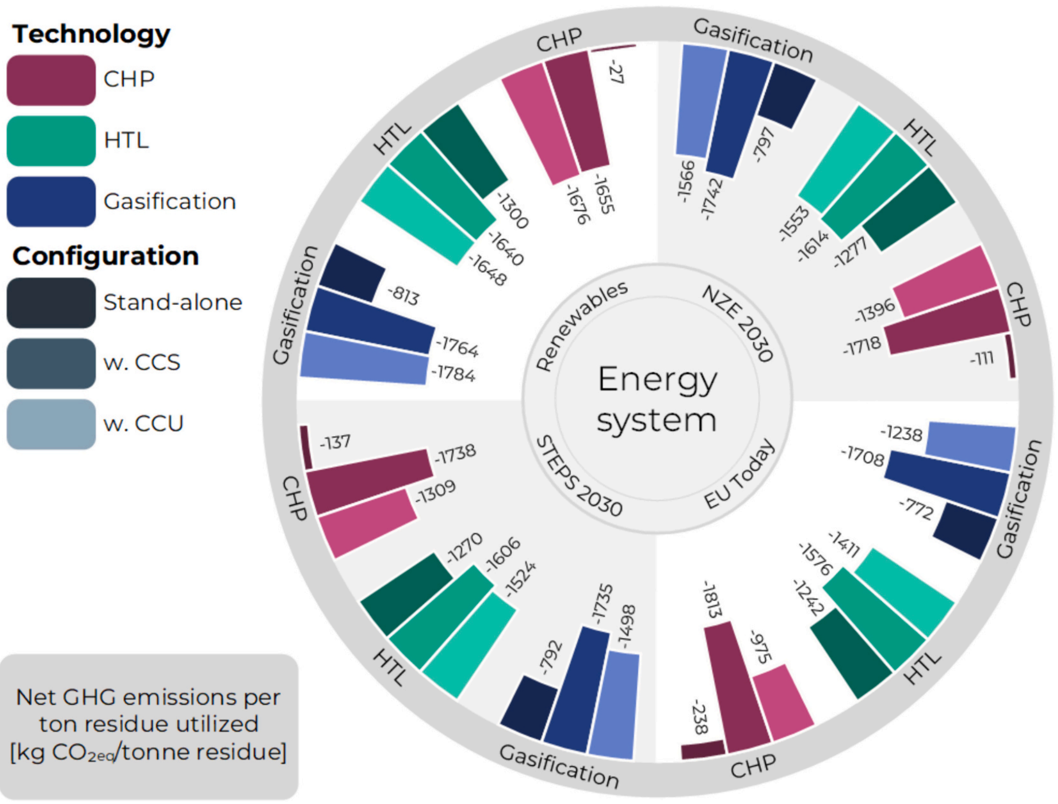

Fig. 5. Comparison of the climate change impacts of the four energy system scenarios presented as the overall avoided GHG emissions measured as kg CO_2eq per tonne of biomass residue used (shown here as negative emissions).

affected much by the energy system in which it is operated. On the other hand, the performance of the CHP CCU pathway is very dependent on the energy system, with results varying from −840 to −1710 kg net CO_{2eq}, due to the production of hydrogen from electrolysis. While HTL obtains the highest net GHG savings when it is operated in the Renewables scenario, the difference between the four energy systems is only 6 % to 18 % between the best- and worst-case scenario. For gasification, there is a large jump from the stand-alone pathway to both CCS and CCU, but it is only in the CCU pathway where there is a significant difference between the energy systems. Finally, from Fig. 5 it is observed that across all three technologies the CCS pathways obtain higher net savings of GHG emissions compared to CCU in three of the energy systems. Only in the most ambitious *Renewables* energy system, is the electricity emission factor low enough to favour converting the captured CO_2 into fuels instead of storing it. This conclusion not only depends on the marginal electricity emission factor in the energy system, but also on the substitution efficiency of the fuels and the transport emissions associated with handling the CO_2 storage. The impact of these three factors will be discussed in the following sections.

To identify the breakpoints where the choice of technology and configuration changes, a sensitivity analysis of the emission factor of the marginal electricity mix is shown in Fig. 6. The intuitive observation is that the GHG savings are largest with a low electricity emission factor, as the emissions from the energy required to the system are reduced. The exceptions are the CHP stand-alone and CCS pathways which have the opposite trend. This is because these systems are delivering electricity and heat to the energy system instead of using it and the substitution value thereby increase in a more fossil based energy system.

Fig. 6 is also used to assess the assumption of how the expansion of renewables reacts to an increased demand for renewable electricity. The conservative assumption used in this study is that the expansion of renewables is fully constrained, which means that the demand for renewable electricity to electrolysis will impact the marginal electricity mix and not only the capacity of renewables. Under this assumption, it can be observed in Fig. 6 that the GHG savings decreases when the emission factor for electricity increases, especially in the CHP CCU and gasification CCU pathways that require a lot of hydrogen. For the CHP CCU case it means that converting the CO_2 to methanol becomes a less effective solution than emitting it to the air in an energy system with an emission factor higher than 178 gCO_{2eq}/kWh. An alternative assumption, where the expansion of renewables is assumed to be fully unconstrained, the increase in demand for renewable electricity is always met with a corresponding increase in renewable electricity production. The GHG emissions for the electricity used in the electrolysis are thereby low and independent of the energy system in which it is operated. As can be seen in Fig. 6 this results in almost flat curves, and in the case of CHP with CCU the increasing emission factor of the marginal electricity would lead to a decrease in the net GHG emissions. Moreover, in the unconstrained scenarios, the CCU pathways are favoured over CCS in all three technologies, since the fuels produced from only renewable electricity will avoid more emissions when substituting fossil fuels than can be stored as CO_2. On the other hand, when it is assumed to be constrained, the CCU pathways are only favoured over the CCS pathways for all three technologies when the emission factor is below 44 gCO_{2eq}/kWh. As mentioned in the methodology, the actual impact on the expansion of renewables when demanding renewable electricity for electrolysis will most likely be somewhere in between the two extreme cases shown here (illustrated in the Fig. 6 as the greyed area).

The highest potential GHG savings are obtained in the CCU pathways if it can be assured that the electricity used for hydrogen production is from renewable sources which would not otherwise have been built (fully unconstrained). This is however, surrounded by large uncertainties as the results changes drastically if the expansion of renewables is not fully unconstrained. The CCS pathways are much less impacted by variations in the marginal electricity mix, and all obtain savings between −1500 to −2000 kg CO_{2eq}. When comparing the technologies, the performance of all the HTL pathways is much less sensitive compared to gasification and CHP, with savings varying between −1200 to −1750 kg CO_{2eq}. This is primarily due to HTL having a high biomass to fuel conversion in the stand-alone process and it has a lower requirement for external energy for the fuel production.

From Fig. 5 we can conclude that the best technology and configurations heavily depends on both the marginal electricity mix and assumption on whether the expansion of renewables is constrained or unconstrained. Thus, the main findings are summarised and sorted into three different cases of energy systems and assumptions.

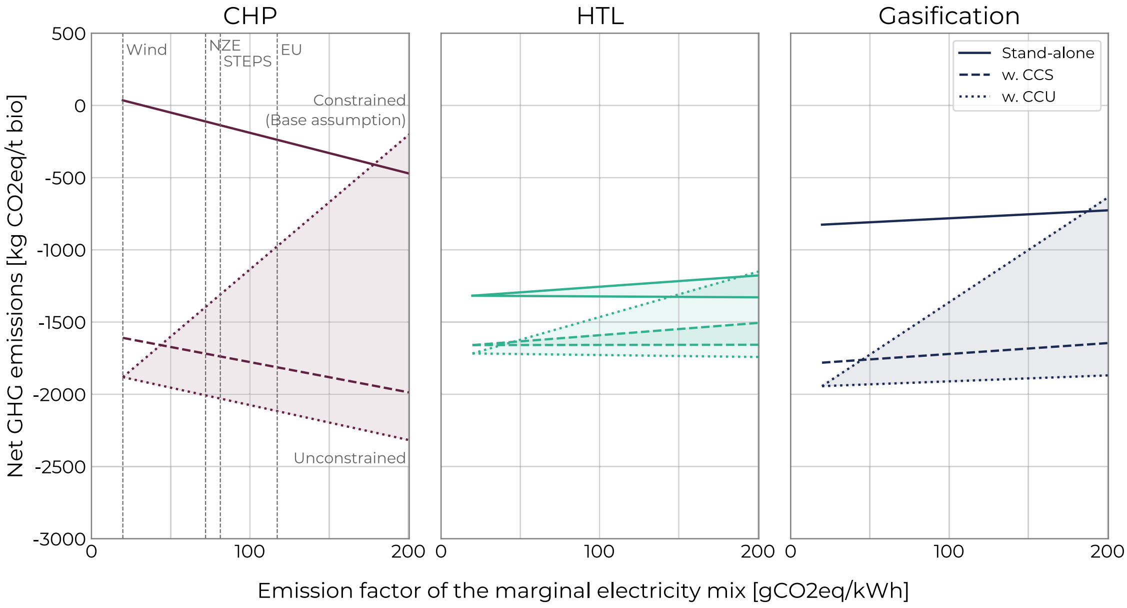

Fig. 6. Sensitivity analysis of the life-cycle emission factor of the marginal electricity mix measured as gCO2eq per kWh of electricity. For all the scenarios using hydrogen for electrolysis two results are shown, one where the renewable electricity expansion is assumed constrained (the base case assumption used in this study) and one where it is unconstrained. The greyed areas represent all the possible solutions in between the two extremes.

- First, in a **renewable electricity scenario**, with a low life-cycle emission factor for marginal electricity, CCU outperforms CCS. This occurs when the emission factor is below 44 gCO_{2eq}/kWh assuming the fuels can substitute fossil 1-to-1 on an energy basis. Gasification CCU is the best performing pathway as it has the highest carbon to fuel conversion.
- Secondly, in a **constrained mixed electricity scenario**, above 44 gCO_{2eq}/kWh, CCS will outperform CCU in terms of GHG reduction potential due to the high emissions for hydrogen production when doing CCU. The highest GHG reductions are obtained by CHP CCS followed by gasification CCS. In this scenario HTL becomes the best performing technology for producing sustainable fuels as it has a much lower requirement for hydrogen compared to CHP and gasification.
- Finally, in an **unconstrained mixed electricity scenario**, above 44 gCO_{2eq}/kWh, CCU will again outperform CCS in terms of GHG reduction potential as it will have access to low emission hydrogen for fuel production. The highest GHG emission reductions are obtained by CHP CCU since the electricity and heat produced will have a high value in terms of avoided GHG emissions.

The LCA approach used in this study is limited as it can only give insights into how different background systems and assumptions affect the results. Ultimately, holistic energy system optimisation modelling, considering both biomass and renewable electricity as constrained in demand, is required to find the optimal solution. Furthermore, the approach is limited in estimating how the electricity production will react to a change in demand for renewable electricity. Thus, the results can only estimate the solution space between the two extreme assumptions, fully constrained and fully unconstrained expansion of renewables.

3.2.2. *Fuel substitution emission sensitivity analysis*

It is not only the emissions from the production of sustainable fuels that are dependent on the energy system, the potential for avoided emissions when substituting the fuels will also change as the transportation sector transitions towards a more sustainable future. In this study it is assumed that the produced fuels, both the methanol and biocrude, will substitute fossil fuel in the maritime sector 1-to-1 on an energy basis. This will both avoid the fossil CO_2 emissions from burning the fuel and the emissions from extracting, handling, and refining the fuels. Under these assumptions, this means that converting 1 t of biogenic CO_2 into hydrocarbon fuel can have a higher GHG reduction potential compared to storing the CO_2. However, as we transition towards a more sustainable energy system the potential for avoided emissions will be lower, both due to sustainable fuels taking up a larger share of the fuel mix and the emissions in the extraction, handling and refining process of the fossil fuels decreasing. Fig. 7 shows the sensitivity of the net GHG emissions when lowering the fuel substitution GHG emission factor. All the fuel producing pathways will have a lower positive impact on climate change when lowering the emission factor of the fuel and the gap between the CCS and CCU pathways becomes larger. This means that as we transition towards a more sustainable transportation sector, storing the biogenic CO_2 as negative GHG emissions becomes more favourable compared to producing fuels. It is, however, important to also consider that producing the fuels in a future energy system will mean that the GHG emissions for the energy usage will also be lower as shown and discussed in Section 3.2.1.

3.2.3. *Supply-chain scenario analysis*

To assess the impact of transportation emissions on the overall net GHG emissions, a scenario analysis of different supply-chains has been performed. The results are shown in Fig. 8 for the three supply-chains outlined in Section 2.6. The transportation emissions included are the upstream sourcing of the forestry residue and the downstream CO_2 transport to the storage site. Emissions from transportation of the produced fuels are neglected as the bioenergy facility is assumed to be located at an industrial port in all scenarios. The emissions from transport of the feedstock take up most of the total transport emissions. Sourcing the residues locally, as assumed in scenario A, results in 73.7 $kgCO_{2eq}/t$ residue utilised which increases to 326.3 $kgCO_{2eq}/t$ when the residues are assumed imported from Canada to Europe (Scenario C). The emissions from transportation of CO_2 differs between the technologies as the amount of CO_2 to be stored changes. In scenario C which has the longest transportation route for the CO_2, the GHG emissions varies from 4.7 to 22.8 $kgCO_{2eq}/t$ residue in the HTL CCS and CHP CCS pathway respectively. Generally, the transportation is dominated by the sourcing of the residues, however, the associated fossil fuel emissions are low compared to the bioenergy products in the systems (the produced fuels and biogenic CO_2 stored) even when traded internationally.

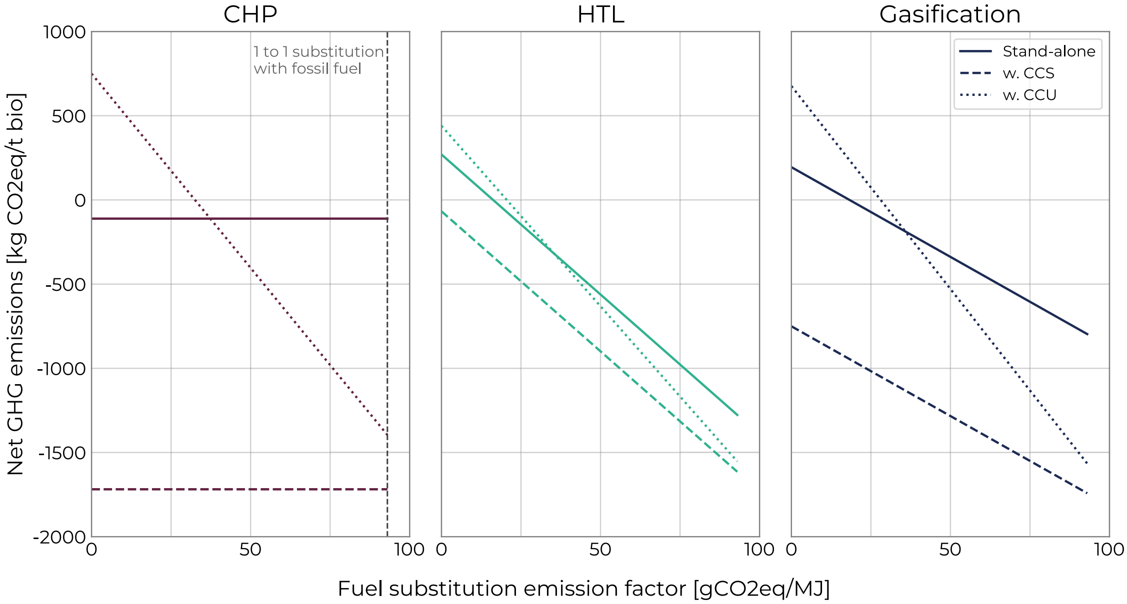

Fig. 7. Sensitivity analysis of the fuel substitution emission factor. The base assumption used in this study is 93 gCO_{2eq}/MJ fuel which include both the avoided fossil CO_2 emissions and the extraction, handling, and refining of the fuels.

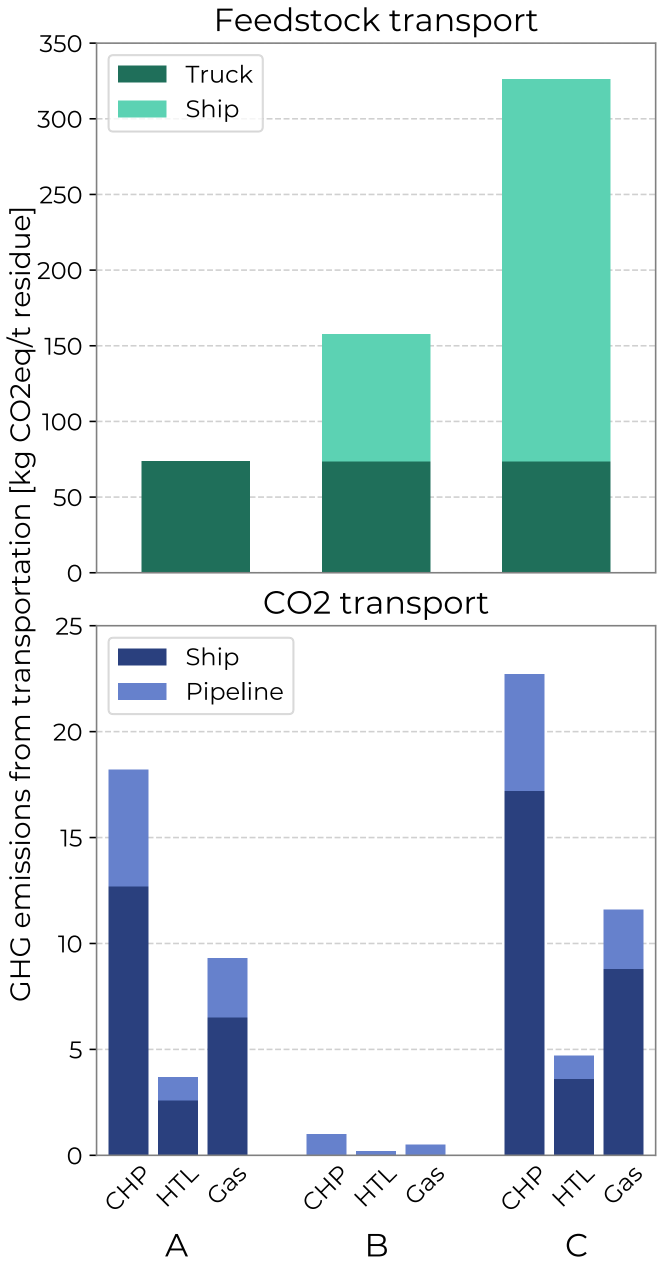

Fig. 8. Climate change impact, measured as GHG emissions, for the transportation of biomass feedstock and CO_2 in the three supply-chain scenarios outlined in Section 2.6.

4. Conclusions

The climate change impacts of three technologies (CHP, HTL, and gasification) and three process configurations for utilising forestry residue have been analysed using a consequential LCA approach. All technology pathways showed a potential for net GHG savings when including avoided emissions from substitution of the products, with results varying from −111 to −1742 $kgCO_{2eq}$ per tonne residue in the baseline scenario. Combining the bioenergy technologies with either CCS or CCU increased the GHG reduction potential for all three technologies and across all four energy systems analysed in this study. HTL showed the most consistent results in terms of climate change impacts due to its high biomass to fuel conversion in the stand-alone process and its limited requirement for external energy.

When combining the bioenergy technologies with CCU the dependency on the energy system was a lot higher compared to CCS. This was due to the high demand for electricity for hydrogen production required to upgrade the CO_2 to hydrocarbon fuel. It is only in the theoretical *renewables* energy system scenario that the emission factor was low enough for CCU to be favoured over CCS. The breakeven was at 44 kg CO_{2eq}/kWh meaning that the marginal electricity mix will have to be below this point for CCU to obtain lower GHG emissions. This was under the assumption that the expansion of renewable electricity capacity is constrained. On the other hand, if the expansion of renewables is assumed to be unconstrained, all the electricity for electrolysis could come from new wind power. In this case, CCU will have a higher GHG reduction potential across all the energy scenarios.

The comparison between CCS and CCU also depends on the transportation of the CO_2 and the fuel substitution efficiency. If the emission factor of the fuel substituted decreases as the sector transitions towards more renewables, converting the CO_2 to hydrocarbon fuels becomes less favourable. For transportation on the other hand, a longer supply chain for storing the CO_2 will make utilising it for fuel production more feasible in comparison. However, the emissions from transportation of the CO_2 only had a small contribution to the overall emissions of the systems, ranging from 4.7 to 22.8 $kgCO_{2eq}$/t residue for the three technologies. The GHG emissions from transportation were dominated by sourcing of the residue, however, these emissions were still low compared to the carbon products even when traded internationally.

The overall conclusions are that the best use of 1 t of forestry residue strongly depends on the electricity production and fuel substitution of the system. Carbon storge is the “safe” option as it will always provide negative emissions and is not sensitive to the change of the future energy system. CCU may become favoured over CCS in the long term, when the marginal electricity mix transitions towards renewables, but only as long as it can substitute fossil fuels. Furthermore, if the CCU pathways can be supplied by renewable electricity capacity that would not have been built otherwise and thereby forcing an increase in the expansion rate of renewable capacity, then the CCU pathways will have a higher overall GHG reduction potential. From this study, it is evident that the environmental performance of CCU technologies is highly sensitive to how it will affect the ongoing expansion of renewable electricity capacity. This is a critical finding when discussing CCS vs. CCU. However, accurately predicting these impacts on the future electricity system are very challenging which is why this study considers both a fully constrained and unconstrained electricity market.

CRediT authorship contribution statement

Andreas Krogh: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Martin Junginger:** Methodology, Writing – review & editing. **Li Shen:** Methodology, Writing – review & editing. **Jeppe Grue:** Supervision, Conceptualization, Writing – review & editing. **Thomas H. Pedersen:** Conceptualization, 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 A. Supplementary data

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