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Assessment of feasible site locations for biofuel production based on technoeconomic modelling and GHG impact analysis

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HIGHLIGHTS

- A modelling framework was used to assess optimal sites for biofuel production.
- The study includes both technoeconomic and GHG impact assessments.
- Inputs include spatial biomass availability and critical infrastructure parameters.
- Presented as a case study of implementing hydrothermal liquefaction in Denmark.
- Geographical Information System is used, and results are shown on a 1 by 1 km grid.

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ABSTRACT

Large scale bioenergy is expected to play an increasing role in the industry, heat and power production and transportation in the future. Both biomass availability and cost-effective mobilization are necessary to facilitate large bioenergy production sites. This study uses a Geographical Information System approach to map the economic and environmental feasibility of future biofuel production sites via Hydrothermal Liquefaction. The methodology includes process modelling, biomass and infrastructure mapping, technoeconomic analysis and greenhouse gas impact assessment and is implemented having Denmark as case study. Three supply-chains were evaluated for the upgrading of the biofuel which are chemical stabilizing, on-site hydrotreating, and centralised hydrotreating. The two feedstocks assessed were imported forestry and domestic agricultural residue resulting in a total of six different implementation scenarios. The results for the case study indicate that for forestry residue the proximity to an industrial port is the most dominating factor when determining feasible site locations. The performance in the agricultural residue scenarios is more impacted by infrastructure parameters. In the on-site hydrotreating scenario the best performing locations are found close to the hydrogen line to reduce connection expenses. For centralised hydrotreating the results favour being close to existing refineries to reduce intermediate transportation of the biocrude.

1. Introduction

The use of bioenergy is expected to play a major role in the transition away from fossil-based energy. In the roadmap Net Zero Emissions by 2050′ by the International Energy Agency IEA [1], bioenergy represents 18% of the total energy supply in 2050. The increasing role of biomass and biofuels are seen in the industry, transport sector as well as heat and power production. Based on the road map the share of bioenergy in transport and industry is expected to increase to 16% and 15% respectively. For the transportation sector the use of biofuels mainly targets the heavy transport, with 21% of shipping and 45% of aviation being supplied by bioenergy by 2050 [1]. The use of bioenergy is constrained by sustainability and land requirements, however, it can be a cheaper option compared to the alternatives such as hydrogen and efuels. In a

Abbreviations: ILUC, indirect land use change; RED, renewable energy directive; GIS, geographical information system; GHG, greenhouse gas; HTL, hydrothermal liquefaction; TAN, total acid number; daf, dry ash free; LHV, lower heating value; RPR, residue to product ratio; SSR, sustainable removal rate; Y, yield; DM, dry matter; LCoE, Levelized Cost of Energy; CCS, carbon capture and storage; CCU, carbon capture and utilisation.

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report by Concawe and Aramco [2] the production cost of various biofuels is estimated at 0.3 to 1.1 € per liter of diesel equivalent. This is significantly lower that the estimated cost for comparable e-fuels at 1.5 to 2.9 € per liter of diesel equivalent, which highlights the importance of utilizing the available biomass resources.

Traditionally the use of bioenergy occurs mainly locally in cooking and house heating. However, the shift towards more use of bioenergy in industry, transportation, and power production favours larger production facilities. This transition requires more complex supply-chains of the available biomass resources. In addition to the spatial availability of biomass, cost-effective mobilization and energy conversion are impacting the deployment of large-scale bioenergy use in the future [3].

To avoid competition with food production and negative environmental impacts associated with direct and indirect land use change (ILUC), the future use of biomass for energy purposes are to be based on 2nd generation biomass. In the Renewable Energy Directive (RED II), the European Commission defined a full list of 2nd generation feedstocks that meets certain sustainability criteria and are certified for the production of advanced biofuels [4]. These include various waste products such as crop residues, forestry residues, livestock manure, municipal solid waste, sewage sludge, etc.

Literature on biomass availability assessments is extensive and has covered a wide variety of locations and methods. Several studies have been conducted to estimate the 2nd generation biomass potential in the European countries [5,6]. They consider the management practices and environmental risks for agricultural residue, forestry residue, and biogenic waste, to include both the residue needed to preserve soil quality and the amount already used in other industries. The assessments are based on residue to product ratios and sustainable removal rates to align with technical and environmental constraints. Studies like these provide an overview of the bioeconomy potential within a given country and which biomass feedstocks that have the highest energy potential. More recently, various Geographical Information System (GIS) methods have been reported aiming at providing higher-resolution data for supply-chain analysis. In the geo-localized methodology approach presented in [7], the biomass potential for agricultural residue, forestry residue, urban greenery management, and food waste were evaluated for different regional divisions in the EU. It was found that 8500 PJy^{-1} were the total theoretical availability with agricultural residues and forestry residues being the largest contributors. The GIS approach has also been applied for higher resolution studies on European level presented as explicit spatial assessments of the crop residue potential on a 1 by 1 km grid [8,9]. In the study by Scarlet et al., the theoretical crop residue potential is estimated between 4434 and 8453 PJ in Europe [8]. The assessment then includes both technical and environmental constraints by considering organic carbon content in the topsoil, soil erodibility, and protected areas. This is defined as the sustainable potential and was estimated at 2601 PJ.

Furthermore, a GIS approach can also be used to assess infrastructure parameters which plays a key role when determining feasible site locations in centralised vs. distributed configurations due to trade-offs between transportation costs and economics of scale that are important from an economic and environmental perspective. Several studies have used a GIS based approach to optimize the supply-chain for various technologies and locations. GIS data for both feedstock availability and infrastructure are used as an input to an economic model and thereby economically optimal locations can be identified. The parameters investigated include the impact of scale, integration, transport and supply-chain [3] and optimization models are used to determine the economic feasibility of various locations for the given scenarios [10–12]. These studies, however, are based on a single feedstock and predetermined site locations or co-location with existing facilities.

The aim of this study is to make a broader assessment of location feasibility from both an economic and environmental perspective. In this sense, the methodology presented does not comprise an optimization procedure to find the best locations from a defined list of options but evaluates economic and environmental performance in broader areas, resembling a sensitivity analysis that can facilitate future optimizations. This is done by combining technoeconomic assessment and GHG impact modelling with spatial availability of feedstock and location of critical infrastructure parameters. The assessment of feedstock availability in this study also considers the current use of the feedstock and how this affects the availability for short term implementation. This consideration was not included in other similar studies which instead made the assessment for a much larger area. The GIS based methodology was applied to a case study in Denmark but can be replicated for other locations where the data sources for biomass and infrastructure are available. For the advanced biofuel production, the technology Hydrothermal Liquefaction (HTL) is considered in this study. It is chosen due to its high oil yield and potential flexibility in terms of feedstock [13], however, other technologies can be evaluated in a similar way. GIS based studies of HTL was also found to be underrepresented in the literature and the aim is therefore also to contribute to the state-of-the-art in this area. In HTL the feedstock is converted to a crude oil in a single step under high pressure and temperature and subsequently hydroprocessed to drop-in biofuel (i.e., hydrocarbon fuels which are chemically identical to the existing fossil-based fuels) which can be used in both the maritime and aviation sector. The supply-chain around the HTL process can be designed in various configurations and multiple parameters are identified to have an impact on the economic and environmental feasibility of the facility. In addition to the feedstock availability, the infrastructure parameters assessed in this study includes the future hydrogen line, power grid, existing refineries, industrial ports, and airports. The impact of these parameters on the implementation of Hydrothermal Liquefaction is determined via technoeconomic assessment and life cycle analysis. The inclusion of the future hydrogen line in the assessment broadens the potential feasible sites for hydrotreating beyond co-location with existing fossil refineries. The assessment can consider any location by including the distance to the projected hydrogen line in Denmark. This is different to all the studies which relies on predefined locations and allows for a much broader assessment of feasible site locations in various scenarios and feedstocks.

The feedstocks assessed in this study are forestry residue and agricultural residue. They were chosen based on the RED II Annex IX listing of certified feedstocks for advanced biofuel production while considering the HTL process and the potentials in Denmark. First agricultural residue was chosen as the potential in Denmark is very high, with 59.3% arable land which is among the highest in the world [14]. Secondly, forestry residue was chosen as it was found to be the most common and closest to commercialization of the feedstocks for HTL even though the potential in Denmark is considerably lower than many other European countries.

The three main knowledge gaps found in the literature are spatial assessment of residue availability not considering current use, possible locations of the bioenergy facility being limited to existing refineries or industry, and HTL technology was found underrepresented in GIS based studies. To improve on these areas the objective of this work is to develop a GIS methodology that combines technoeconomic and GHG impact analysis with mapping of feedstock availability and critical infrastructure parameters to be able to identify feasible site locations. Furthermore, the purpose is to evaluate the relative impact of the spatial parameters on the economic and environmental performance for different feedstocks and implementation scenarios. The contribution from this study to the research field, is thereby, to provide insight into how the location of large-scale bioenergy site affect the feasibility of the plant and which parameters are the most important for different scenarios. This paper presents a case study of implementing HTL in Denmark, but the methodology can be applied to arbitrary technologies and locations.

2. Methodology

A stepwise approach was adopted to combine various data sources and modelling inputs which includes mass/energy balances, biomass and infrastructure mapping, different implementation scenarios, technoeconomic assessment and carbon footprint analysis. The general methodology is outlined in Fig. 1 and will be presented stepwise in the following sections. The spatial estimations of biomass resources are partly based on the methodology presented by [8] for estimating agricultural residue potential. This combination of both technoeconomic assessment and GHG impact analysis with mapping of available biomass resources and critical infrastructure, can be used to identify the most feasible site locations from both an economic and environmental perspective. A case study will show how the model works in identifying optimal locations for future HTL facilities in Denmark presented on a 1 × 1 km nationwide grid.

2.1. Estimating spatial availability of biomass

Both the theoretical and available potentials of agricultural residues and forestry residues are assessed based on a GIS approach. This is conducted based on publicly available data such as land cover maps and locations of existing facilities combined with constant conversion factors as illustrated in Fig. 1. The feedstocks are evaluated based on the properties shown in Table 1.

2.1.1. Agricultural residues

The theoretical sustainable potential of agricultural residue is estimated using field data and soil maps as illustrated in Fig. 2. For each field the area is multiplied by the corresponding soil specific crop yield for wheat, rye, barley, oats, and rape seed. All the data is provided by the Danish ministry of Food, Agriculture and Fisheries from 2021 [16].

Table 1
Properties for the two feedstocks analysed. The energy potentials are calculated based on lower heating values on dry ash free basis [15].

		Agricultural residue	Forestry residues
Moisture content	%	11.1	48.9
Ash content	%	7.1	4.0
LHV (daf)	GJ/t	18.5	19.6

Maize stalks is not included in the assessment as it is almost exclusively used for animal feed in Denmark and thereby it is not an available residue. This assessment assumes average yields, however, these are highly dependent on weather conditions and the total production will vary from year to year. From the perspective of an HTL facility relying on these feedstocks, the implications of a lower yield will be on the transportation distance required to supply a constant input of the feedstock to the plant. A full uncertainty analysis of the yields is beyond the scope of this study, but it will directly affect both the economic expenses and emissions for the transport in the agricultural residue scenarios.

The total annual crop production estimated for each field is multiplied by residue to product ratios and sustainable removal rates, as shown in Table 2, to estimate the amount of residue produced and how much can be removed while maintaining soil fertility, see Eq. (1). The sustainable removal rate will vary based on the soil, but average values are assumed in this study [5]. To visualise the sustainable residue potential, it is converted into a 1 × 1 km nationwide grid by doing a summation of the residue available in all fields located within a 10 km radius from each cell. This will produce a full nationwide heatmap, showing the agricultural residue potential throughout the country, a small fraction of the full map is shown in Fig. 2. Residue transportation distances are not calculated directly by this map, but as the radius required for the capacity of the plant. For the purpose HTL modelling all the crop residues are assumed to have the same composition as all

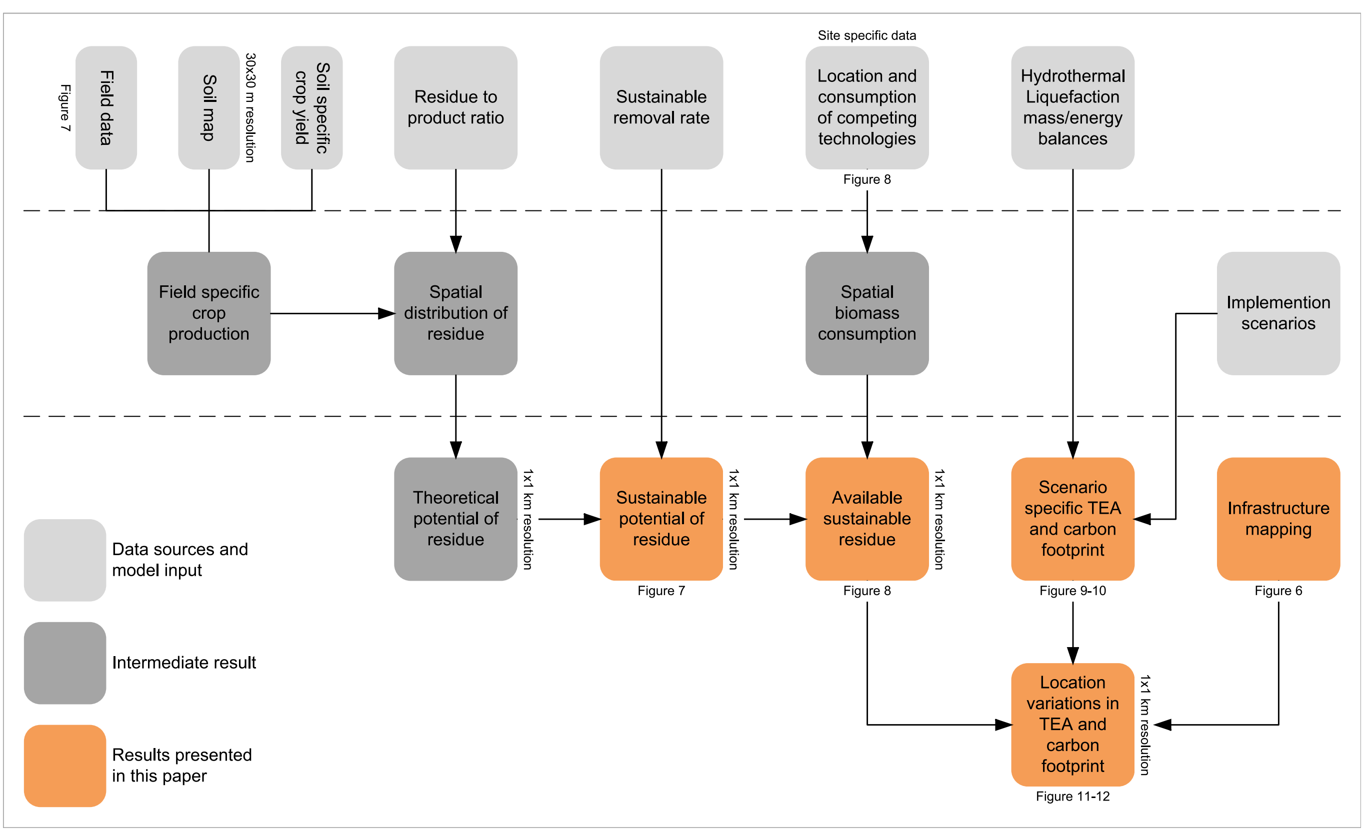

Fig. 1. Flowchart illustrating the data sources, processes, and outputs of the proposed methodology. The maps which are presented as figures in this present study are marked with orange.

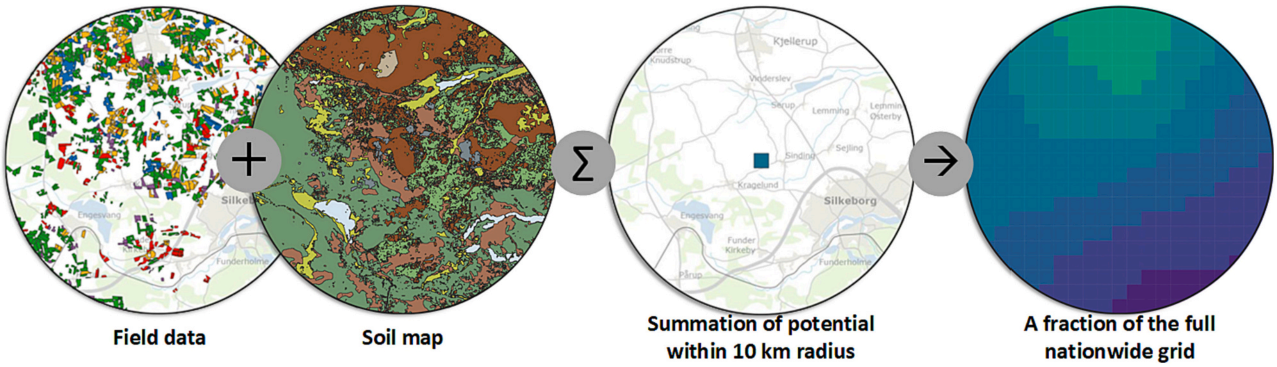

Fig. 2. Illustration of the methodology used for spatial assessment of the agricultural residues. The outcome is a nationwide 1 × 1 km grid which serves as a heat map to visualise the residue potential throughout the country.

Table 2
Crop specific residue to product ration and sustainable removal rate.

Crop	Residue to product ratio [17]	Sustainable removal rate [5]
Wheat	0.9	0.4
Rye	1	0.4
Barley	0.9	0.4
Oats	1	0.4
Rape seed	1	0.5

lignocellulosic feedstocks perform reasonably similar.

$$\text{Theoretical agricultural residue potential} = \sum A_{\text{field},ij} \cdot Y_{ij} \cdot \text{RPR}_i \cdot \text{SRR}_i \left[\frac{\text{tonnes}}{\text{year}}\right] \quad (1)$$

Where $A_{\text{field},i,j}$ is the area of a field for each crop (i) and soil type(j), Y is the crop yield, RPR is the Residue to product ratio and SRR is the sustainable removal rate.

A part of the agricultural residue is already used today in Denmark for other energy purposes, especially for heat and power production. To estimate the spatial biomass consumption of this feedstock, site specific data for all straw fired boilers above 10,000 tons/year is considered [18]. The total consumption of each boiler is then subtracted from the total potential in zones around the facility. This is a simplification of how the current agricultural residue market looks, since each farmer will sell to whomever is willing to pay the most at the given time and will then make a purchase agreement over some years. Assuming that the biomass is sourced close to the existing sites in the model will, however, make it so that the model will favour locations further away from competing technologies. This will be beneficial in the long-term to secure favourable agreements with the biomass producers as the competition will be less.

2.1.2. Forestry residues

The forestry residue potential within Denmark is limited compared to other Scandinavian countries. According to the Danish Energy Agency the production of forestry residues, including wood chips and wood pellets, was 41.5 PJ in 2020 whereas the consumption was 106.5 PJ [19]. This means that more than half of the forest residues consumed in Denmark is imported. The current use is primarily for combined heat and power plants and district heating boilers. Another report from the Danish Energy Agency estimated the sustainable potential for forestry residues to be 39 PJ in 2020 [20]. This shows that there is no unutilised potential and demanding forestry residue for biofuel production will thereby cause additional import. Therefore, spatial assessment of forestry residue is not conducted. Instead, the forestry residues will come from import via industrial ports. This makes it so, that the scenarios that uses forestry residues will heavily benefit from being located close to an industrial port to lower the transportation expenses and the associated emissions.

2.2. Process description

Hydrothermal Liquefaction (HTL) is a thermochemical process in which the main product is a biocrude. 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, which is 45.3% on mass basis and approximately 74% of the carbon [13]. Fig. 3 and Fig. 4 show the mass and energy balances for HTL and the downstream upgrading of the biocrude with a capacity of 100 MW biomass input. This capacity is much larger than any existing facility of this kind today but is comparable to existing biomass fired heat and power plants in Denmark. The figures are based on forestry residue operation, and it is assumed that agricultural residue will perform similarly on an energy basis.

This study considers two options for upgrading of the produced biocrude. First is the full upgrading which utilizes hydrotreating. This will produce a stable fuel, remove the oxygen and nitrogen content from the biocrude and increase the energy density of the fuel. A hydrogen consumption of approximately 3.8% by weight to biocrude input is required for this process [21]. The biofuel output can be distilled into different fuel cuts with approximately 25% is the kerosene (jet fuel) range and the remainder useable for maritime. Hereby, the fuel will have specifications very similar to the fossil fuels used today. Another option for fuel upgrading is to do a chemical stabilizing step. The main goal here is to produce a chemically stable fuel by removing the acid content. Due to the oxygen which will remain in the biofuel this option is not suitable for aviation and thereby only targets the maritime sector. In a report by [22] it is described how esterification is an effective method to remove the acidity of high free fatty acids in HTL oil. In the process methanol is reacting with the organic acids to form esters and water. The amount of acid to be removed from the fuel is represented by the total acid number (TAN). TAN is measured based on the milligrams of potassium hydroxide required to neutralize one gram of crude. The TAN number of the HTL biocrude is reported to be 50 mg/g biocrude in [23]. Since both the reactions of potassium hydroxide and methanol to acids is one to one on molar basis, the theoretical minimum requirement of methanol to convert all the acids to esters is the TAN number multiplied by the molar weight fraction between methanol and potassium hydroxide. This results in 29 g methanol per kg of biocrude. However, the actual process will require an over stoichiometry of methanol and the consumption is thereby set to 5% by weight to biocrude in this study, which will also account for any process losses.

The main by-products from the process are an aqueous phase and a gas phase. The aqueous phase consists of soluble organics from the biomass in addition to some produced water and inorganics. This will

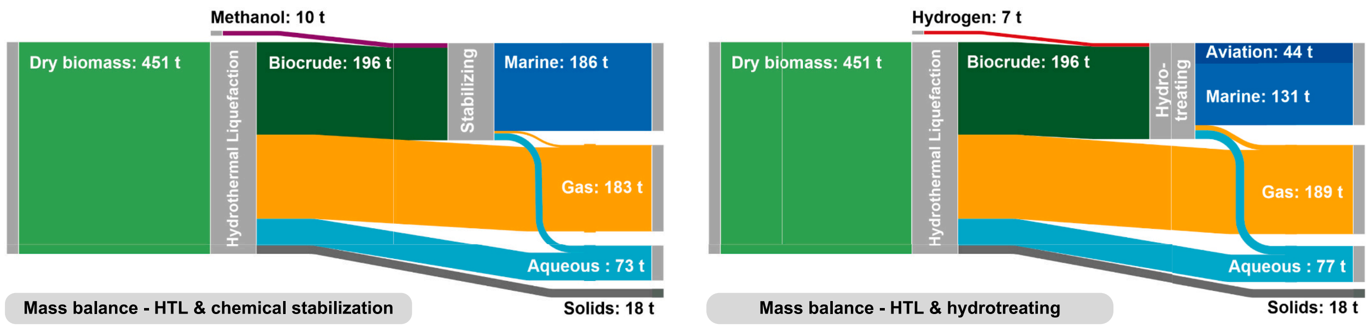

Fig. 3. Mass balances for HTL of woody biomass and biocrude upgrading. The left figure shows chemical stabilizing of the biocrude using methanol as input and the right figure utilizes hydrotreating with external hydrogen as input.

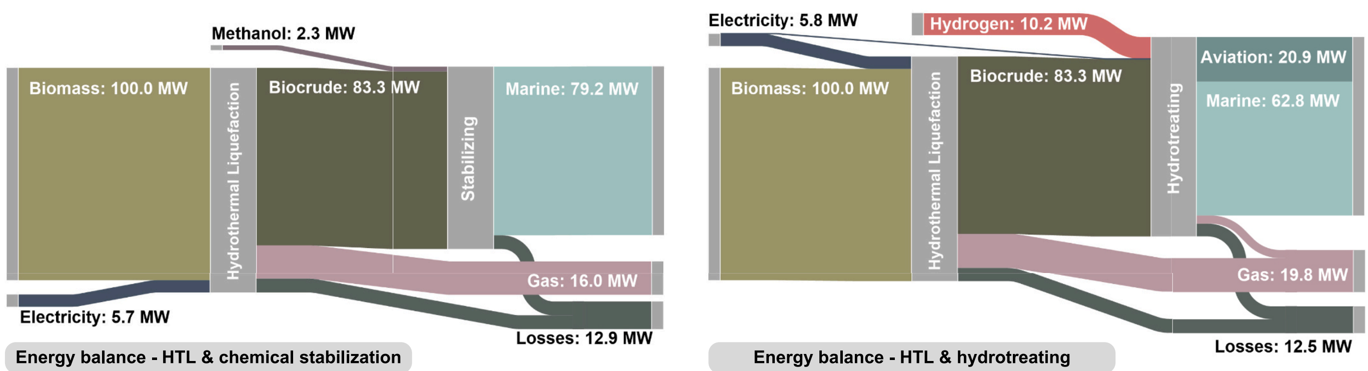

Fig. 4. Energy balances for HTL of woody biomass and biocrude upgrading. The left figure shows chemical stabilizing of the biocrude using methanol and the right figure utilizes hydrotreating with external hydrogen.

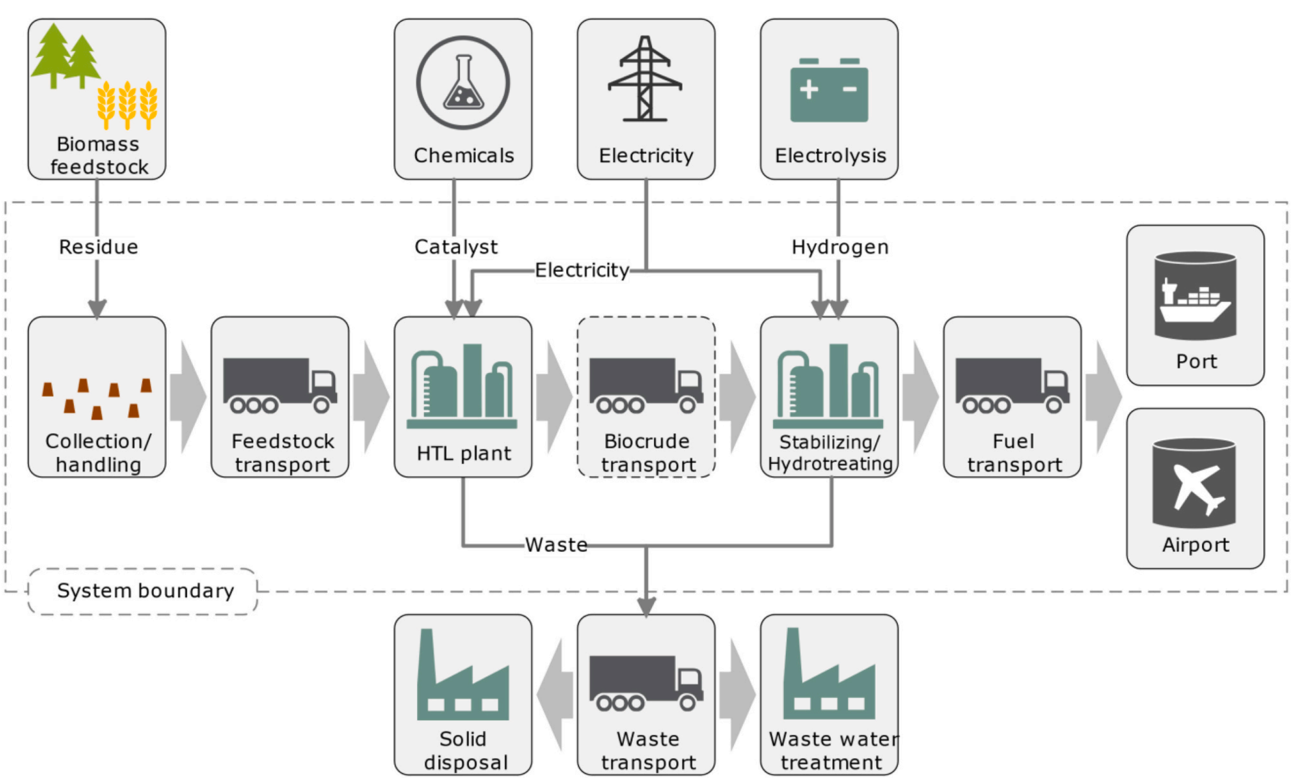

Fig. 5. Overview of the implementation strategies for the two feedstocks.

have to be treated at a wastewater facility and is from an energy perspective considered a loss. The gas phase is very CO_2 rich with approximately 87% by weight [13]. The light components of the gas, primarily hydrogen and methane will be combusted to produce process heat for the HTL process. Therefore, it is assumed that the process is self-sufficient when it comes to heating and no natural gas are required when the process is in operation. The remaining CO_2, which is approximately 20% of the carbon from the biomass, can potentially be captured and either stored or utilized for other purposes. The scope for this study, however, exclude both the capital expenses and energy requirement to capture and liquefy of the CO_2 and does not include the storage or utilisation of the CO_2 in the base cases. However, the potential different utilisation pathways for the CO_2 by-product are considered in the discussion from an environmental perspective in the GHG impact assessment. The first is a carbon capture and storage (CCS) scenario where the excess CO_2 is captured and stored underground. Secondly, a carbon capture and utilisation (CCU) scenario assumes that all the CO_2 is used for renewable methanol production which can substitute fossil fuels. The solid phase exiting the HTL process only consists of the ash from the feedstock as the carbon are not converted to char in the severe conditions used in the process [13].

2.3. Defining different implementation scenarios

HTL can be implemented in various supply-chain configurations and the implementation strategy affects the optimal site selection of the facilities. In this study two feedstocks and three supply-chain configurations are considered as described below. This results in six scenarios to be considered in the technoeconomic and GHG impact assessment. Fig. 5 shows the overall supply-chain and all the inputs and outputs from the main processes.

- *On-site chemical stabilizing (a):* In this supply-chain the produced biocrude is stabilised using esterification with methanol at the HTL site. This will produce a stable fuel suitable for the maritime sector.
- *On-site hydrotreating (b):* Here the biocrude is hydrotreated at the HTL facility in a stand-alone hydrotreater to remove acids, oxygen, and nitrogen to produce a fuel that can be distilled into approximately 25% kerosene (jet fuel) and the remaining for maritime.
- *Centralised hydrotreating (c):* This supply-chain is similar to the on-site hydrotreating, the difference is that the hydrotreating are done at an existing refinery. It is still assumed to be a stand-alone biofuel hydrotreater, however, cost reduction can be obtained due to economics of scale, synergy, and current infrastructure at the refinery.

2.4. Spatial assessment of critical infrastructure

From the implementation scenarios defined there are several factors, other than the biomass availability, that are of importance in the assessment of both economic and environmental performance of future biofuel facilities. These includes critical infrastructure like refineries, industrial ports, airports, future hydrogen line, and the power grid, which are all visualized in Fig. 6. The hydrogen line is not currently in place and is instead based on the vision towards 2040 outlined in the European Hydrogen Backbone report [24]. The importance of each of these parameters depends on the specific feedstock and supply-chain configuration and will be used as inputs in the technoeconomic and GHG impact assessment.

2.5. Technoeconomic assessment

The parameters used for the cost estimations are shown in Table 3 and include both capital and operational cost assumptions. The capital costs for both the HTL and hydrotreating plant is based on fixed capital investment estimations reported in [25]. The cost is scaled to a capacity on 100 MW input using a scaling exponent of 0.7 and converted to 2023 EUR using the Chemical Engineering Plant Cost Index. This means that if it is not technically feasible to build the facility at this capacity, a smaller capacity will result in a higher estimated cost of the produced fuel. To account for possible synergies and economics of scale at existing refineries, the fixed capital investment is assumed to only be 66% in the centralised hydrotreating scenarios. The chemical stabilisation process is in his study assumed to be 33% of the full hydrotreating capital cost as it is less complex. The fixed operational costs for maintenance and operation are based on the Standardized Cost Estimation for New

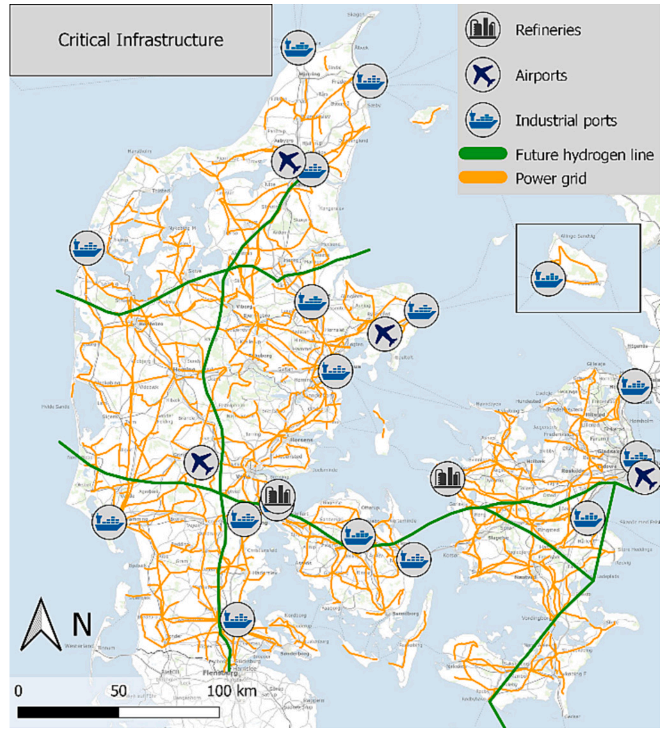

Fig. 6. Overview of existing infrastructure (refineries, industrial ports, airports, future hydrogen line, and power grid). This is the data sources used in combination with the technoeconomic and GHG impact assessment to assess location specific feasibility of future HTL facilities.

Table 3
Parameters for the technoeconomic model.

		Unit	Base
Fixed capital investment	HTL	million EUR	115.6 (Forestry residue) [25] 124.7(Agricultural residue) [25]
	Hydrotreating	million EUR	105.6 (Forestry residue) [25] 105.6 (Agricultural residue) [25]
	Hydrogen line	Million EUR/km	0.29 [2]
Variable cost	Biomass cost	EUR/dry t	137.3 (Imported Forestry residue) [27] 89.5 (Agricultural residue) [27]
	Electricity	EUR/MWh	81.3 [27]
	Hydrogen	EUR/kg	4.3 [28]
	Transport	EUR/t/km	0.162 [30]
	Solid disposal	EUR/t	107 [31]
	Aqueous phase treatment	EUR/m^3	4.26 [32]
	Methanol	EUR/t	395 [33]
	CO_2 revenue	EUR/t	100 (minus 26.7 for liquefaction) [29]

Technologies (SCENT) methodology [26]. The cost of both forestry and agricultural residues as well as electricity are based of projection from the Danish Energy Agency for 2030 [27]. Feedstock cost and transportation within Denmark are separated to allow for specific locations to be evaluated separately. This study assumes the use of renewable hydrogen from electrolysis which price is dominated by the electricity cost, but it also includes capital investments, fixed operational cost, and gradually change of the stacks over the lifetime of the plant [28]. The revenue from CO_2 is in this study fixed at 100 EUR/t but has a very high uncertainty. A cost of 26.7 EUR/t is assumed for liquefaction of the CO_2 which is estimated from capital and operational expenses [29]. Based on the total capital and operational expenses the levelized cost of energy (LCoE) is calculated and mapped in the 1 by 1 km nationwide grid for each feedstock and scenario. It is defined as the total operational cost for producing 1 GJ of finished fuel. All implementation scenarios are based on a 10% interest rate and a plant lifetime of 25 years.

2.6. GHG impact assessment

The purpose of the GHG impact assessment is to estimate the environmental feasibility in terms of greenhouse gas emissions for the production and use of the fuel. The only impact category assessed in this study is *climate change*, which is measured as gCO_{2eq}/MJ_{fuel} defined in the IPCC 2021 GWP100. The methodology is based on the RED II rules for calculating the greenhouse gas impact of biofuels, bioliquids and their fossil fuel comparators. Since the fuels produced in the two scenarios, stabilizing and hydrotreating, vary in energy density the reference flow is defined on energy basis as 1 MJ of finished fuel. This also allow for comparison with different fuel types and the fossil baseline of 94 gCO2eq/MJ provided in the RED II. The current GHG savings threshold for transport biofuels are 65% compared to this fossil baseline. This study includes the emissions starting from the collection and handling of the biomass and ends when the finished fuel is delivered at the harbours and airports. This type of study is referred to as well-to-tank. All the carbon from the biomass feedstock is considered biogenic and therefore counts as zero in the GHG impact assessment.

The feedstocks considered in this study are waste products. This means that all the emissions during the primary production of wood or crops are allocated those products, hence, for this study the feedstock emissions only cover the commercial diesel use for collection and handling of the waste products. The hydrogen used for the hydrotreating of the biocrude is assumed produced from electrolysis using renewable electricity, however, energy is still required for pressurization and dispensing the hydrogen. A report from the European Commission [34] reports an emission factor of 9.5 gCO_{2eq}/MJ_{H2} when using wind power for the electrolysis which is used for this study. For comparison the emission factor for traditional fossil production of hydrogen is 109.4 gCO_{2eq}/MJ_{H2}. Emission factors for the remaining inputs, electricity, chemicals, waste handling, and transport are all taken from the Ecoinvent v3.9 LCA database.

3. Results and discussion

3.1. 2nd generation biomass availability in Denmark

Agricultural residue has the largest theoretical potential in Denmark with 57.6 PJ of which 38.3 PJ is estimated to be available for biofuel production as shown in Table 4 for the year 2021. For forestry residue the theoretical potential is 41.5 PJ, but more than double that amount is used today for energy purposes. This means that future biofuel production from forestry residue will have to be based on import in the short term. This can change in the long term if the existing heat and power plants are phased out or converted to a different feedstock. Assuming a HTL facility capacity of 100 MW biomass input with 8000 h of operation a total of 12 and 17 facilities can be built using forestry residues and agricultural residue if we were to use all the theoretical potential for HTL biocrude production. Only including the resources available today, the number of facilities decreases to 0 and 11.3. The biocrude potential using available agricultural residue is 32.6 PJ, which is 10.8% of the total fossil biocrude consumption for Denmark in 2020. Assuming that up to 25% can used for aviation fuel, the available aviation fuel potential is 8.2 PJ. For comparison the combined domestic and international aviation sector in Denmark consumed 45.1 PJ in 2019 [19]. The available and theoretical potential of the agricultural residue corresponds to approximately 1.8 to 2.7 million barrels of diesel equivalent aviation fuel and 5.5 to 8.2 million barrels of diesel equivalent marine fuel per year.

Table 4
Overview of biomass and biocrude potentials from forestry and agricultural residue. The grey italic values are calculated based on lower heating values on dry ash free basis. Reference year 2021.

	Unit	Forestry residues	Agricultural residues
Biomass potential and availability			
Theoretical potential	Tonne (daf)	*2,079,158*	3,111,350
	PJ	41.5 [19]	*57.6*
Available potential	Tonne (daf)	0	2,070,852
	PJ	0	*38.3*
Biocrude production			
Biomass conversion efficiency	energy	85% [13]	85% [35]
Biocrude lower heating value	MJ/kg	36.7	36.7
Theoretical biocrude potential	tonne	*961,172*	*1,333,133*
	PJ	35.3	48.9
Available biocrude potential	tonne	–	*760,003*
	PJ	–	32.6
Total number of HTL facilities possible at 100 MW biomass capacity			
Theoretical potential	#	12.2	17.0
Available potential	#	–	11.3

3.1.1. Spatial agricultural residue availability

The spatial theoretical sustainable potential of agricultural residue is shown in Fig. 7. The size and location of 209,632 fields, shown on the left in Fig. 7, and a 30 × 30 m grid resolution soil map was used in the assessment. The total potential is shown on the right side of Fig. 7 and is relatively evenly spread across the country resulting in multiple areas with more than 40,000 t $year^{-1}$ residue potential within the 10 km radius. The different crop residues are not considered individually as the HTL yields are assumed to be comparable between the different crop residues. The total theoretical potential from the spatial assessment conducted in this study is 3.11 million dry ash free tonnes $year^{-1}$ (57.6 PJ). This is 7% below the estimated potential of 62 PJ reported in [20] which is deemed acceptable for this assessment.

Approximately one third of the available feedstock is used in existing straw fired heat and power plants, which is subtracted from the theoretical potential in zones around the plant(s) as illustrated in Fig. 8. The size of the zones is made in such a way that the plant(s) absorbs approximately 50% of the total theoretical potential whenever possible. Some large plants and cluster of plants had to take up more than 50% from the neighbouring area. Subtracting the existing use of agricultural residue from the total theoretical potential results in a map of the available potential shown on the right-hand side in Fig. 8. This is the map that is used for estimating the spatial economic and environmental feasibility of the agricultural residue scenarios.

3.2. Identifying feasible site locations

To identify feasible site locations for future HTL facilities, the mapping of biomass availability and critical infrastructure are combined with the technoeconomic analysis and GHG impact assessment. The

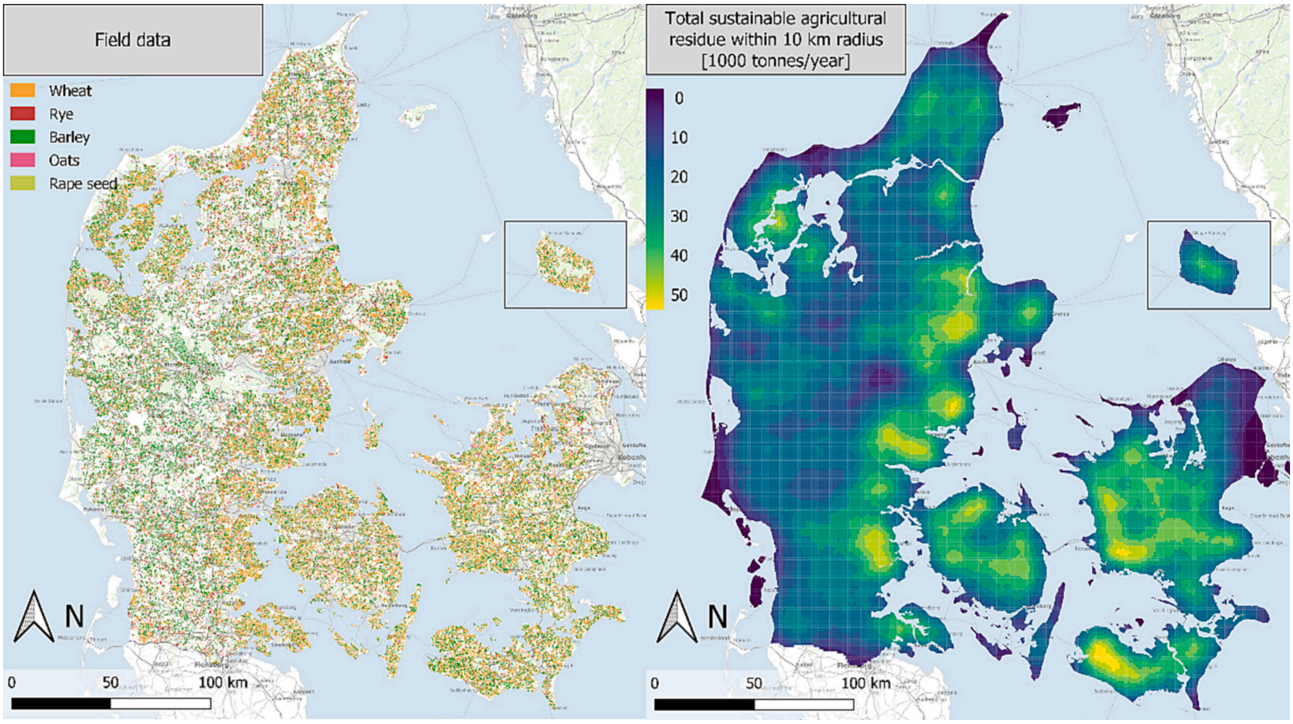

Fig. 7. Field map of the five different crops (wheat, rye, barley, oats, and rape seed) used in the assessment (left) and the theoretical potential of sustainable agricultural residues (right). Each cell shows the potential in 1000 t year^{-1} within a 10 km radius.

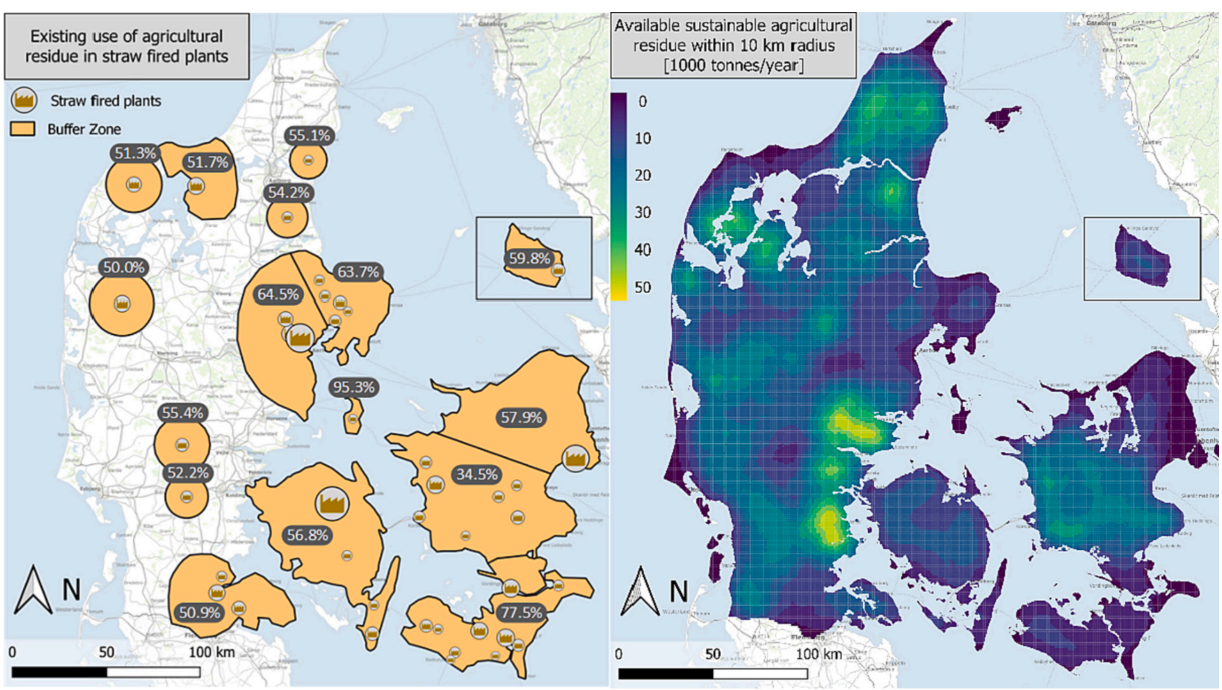

Fig. 8. Existing straw fired power plants with above 10,000 t straw year^{-1} consumption and their corresponding zone from which the biomass is assumed collected. The percent indicates the amount of the sustainable biomass within the given zone which is required for the straw fired power plants. The capacities of the straw fired plants are indicated by the relative size of the icons. A total of 42 power plants and 16 zones (left). The resulting spatial availability of sustainable agricultural residue when subtracting the current use. Each cell shows the potential in 1000 t year^{-1} within a 10 km radius (right).

results are plotted on a 1 × 1 km nationwide grid and shown in Fig. 9 and Fig. 10 for forestry residue and agricultural residue respectively. The difference between the best and worst performing locations in this assessment are 4.8% to 11.1% for the LCoE and 4.7% to 9.5% for the GHG impact. Generally, the most feasible locations are the same from both an economic and environmental perspective across all scenarios. The only observed variation is in the on-site hydrotreating scenarios, where the cost for connecting to the hydrogen line are not penalised in the GHG impact assessment due to the electricity for hydrogen transport being considered renewable.

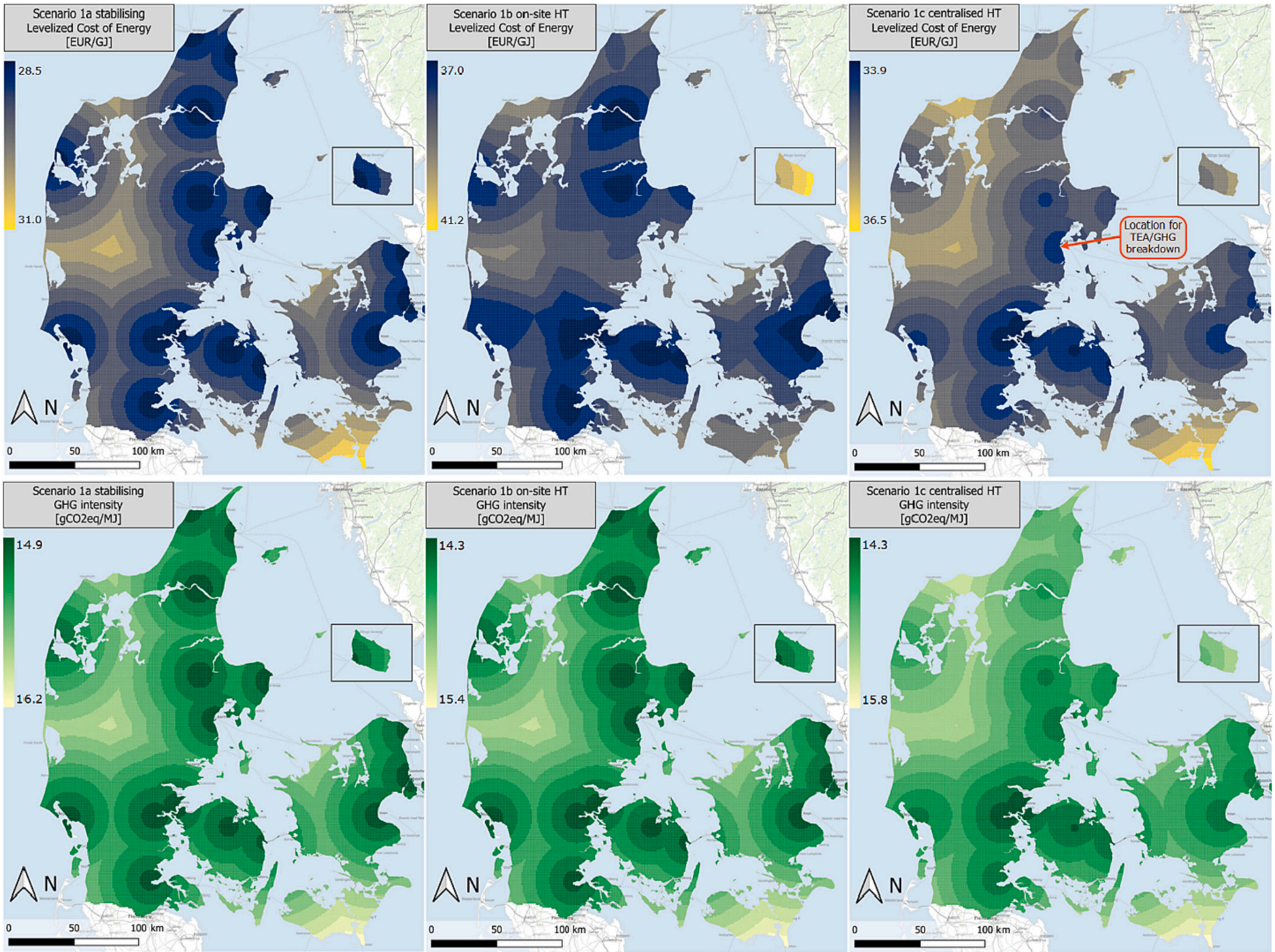

Fig. 9. Mapping of estimated LCoE (top) and GHG impact (bottom) results for all three scenarios using forestry residue.

The forestry residue scenarios, shown in Fig. 10, are all dominated by the proximity to the nearest industrial port as this both lowers the required transport distance of the imported residue and maritime fuel offtake of the finished fuels. For the agricultural residue scenario on the other hand, the feedstock availability is much more evenly spread across the country. This means that other parameters have a larger impact when estimating the best performing locations. Looking at the different supply-chains for agricultural residue, the stabilizing scenario follows the availability of the residue. In the on-site hydrotreating scenario the hydrogen line has a larger impact on the economic performance and the best locations are identified close to that. Finally, in the centralised hydrotreating scenario both the economic and environmental modelling favours being close to one of the existing refineries to lower the intermediate transport of the biocrude. These trends can also be observed in the forestry residue scenarios, but to a lesser extend since the industrial ports are so dominating in the results.

3.3. Breakdown of the technoeconomic assessment

The breakdown of the estimated levelized cost of energy of each scenario are shown in Fig. 11 and are within a cost range of 26.4 to 38.0 EUR/GJ fuel. The cheapest fuel cost is obtained in the scenarios which only include chemical stabilizing of the biocrude and targeting maritime only. These are 24.9 to 25.2% cheaper compared to on-site hydrotreating mainly caused by the lower capital investment and utility cost. This means that for the scenarios including full hydrotreating to be economical competitive the aviation (kerosene) fraction of the fuel will have to be sold at a premium compared to the maritime fraction. Comparing the two hydrotreating supply-chains, on-site and centralised, shows that conducting the upgrading at an existing refinery is overall 9.0 to 10.1% cheaper than on-site upgrading. This shows that the capital is the dominating factor in the LCoE assessment over the addition transport expenses. Finally, the estimated LCoE are lower for agricultural residue in all supply-chains compared to forestry residue. The capital expenses are lower for forestry since it is a more energy dense feedstock, however, both the biomass and transport cost are lower in the agricultural residue scenarios.

3.4. Breakdown of the GHG impact assessment

The breakdown of the estimated GHG impact for each of the supply-chains and feedstocks are shown in Fig. 12. All the scenarios are above the current greenhouse gas savings threshold for transport biofuels of 65% reduction defined in the RED II. The largest contributors to the GHG emissions are the electricity consumption for running the processes and the catalyst used in the HTL process. The emissions from electricity assume the use of current Danish electricity mix and will be lower over time as the electricity grid transitions to be more and more renewable. The catalyst used in the process are potassium carbonate and sodium hydroxide and their carbon footprint are based on the Ecoinvent 3.9 database [34]. Due to their high impact on the total GHG emissions there are large potential for improvements, e.g. lowering the consumption,

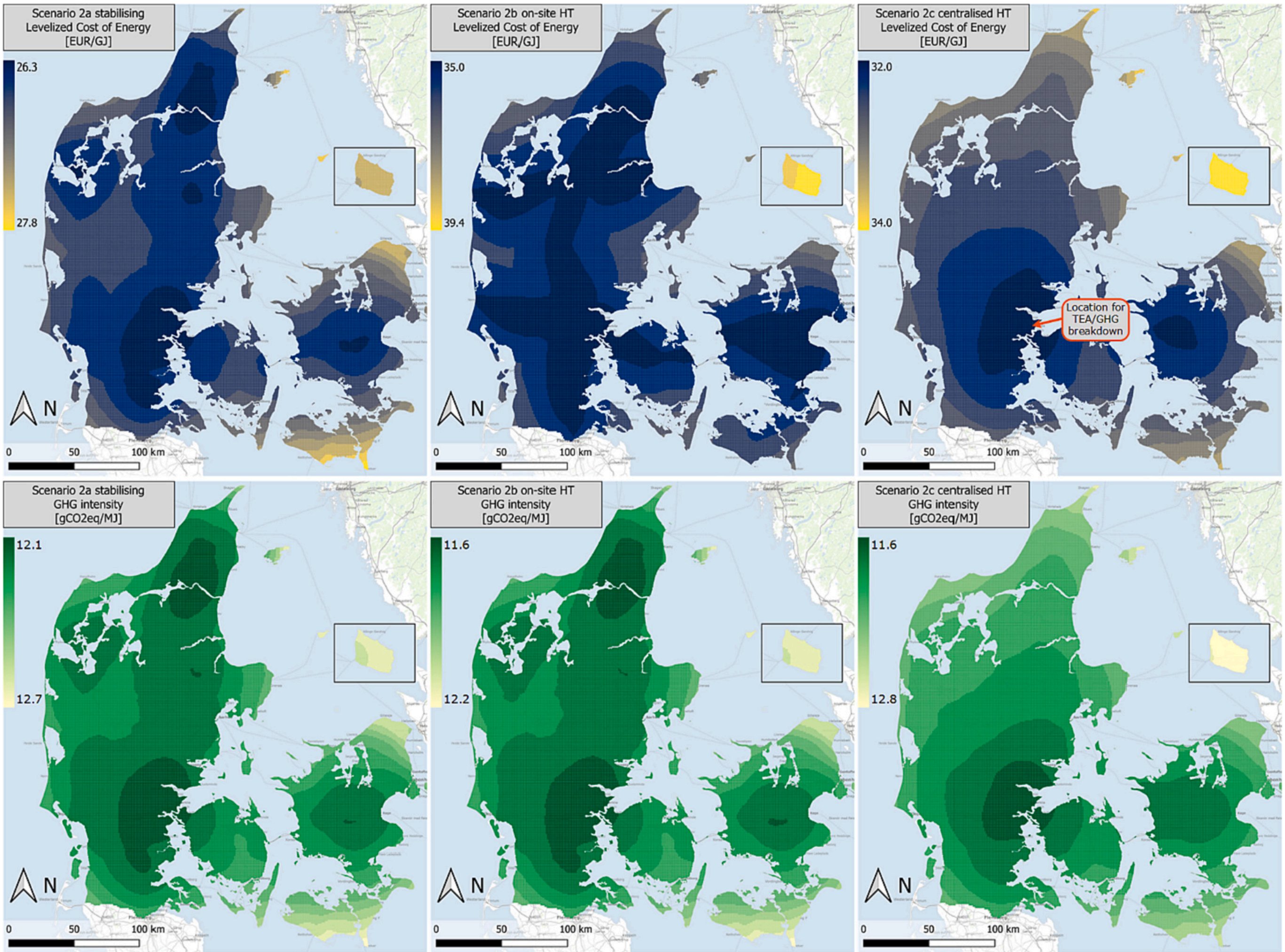

Fig. 10. Mapping of estimated LCoE (top) and GHG impact (bottom) results for all three scenarios using agricultural residue.

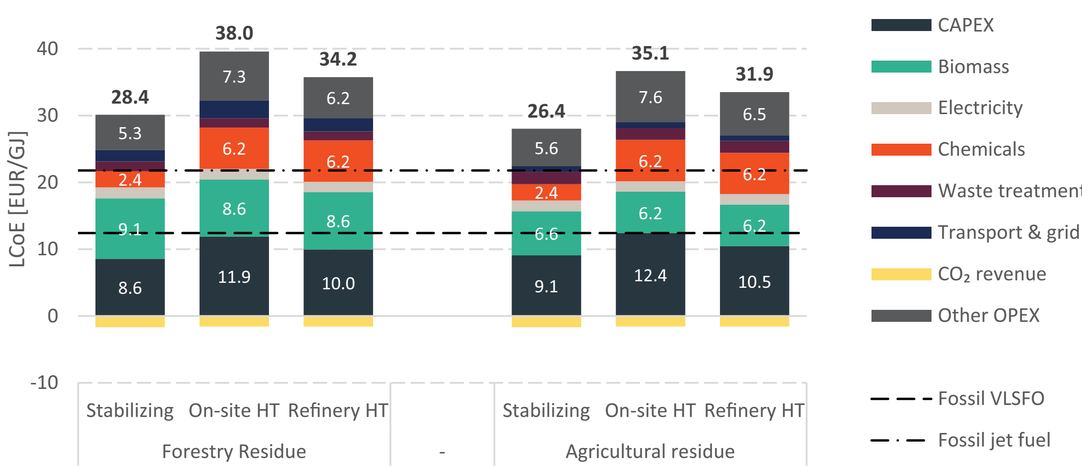

Fig. 11. Estimated Levelized Cost of Energy for the three supply-chains and two feedstocks. The LCoE is defined as EUR/GJ of upgraded fuel produced. For comparison the cost of fossil VLSFO and jet fuel from January to April 2023 are shown.

producing them more sustainable or change to other types of catalyst with a lower carbon footprint. This could lead to another ~5% reduction in GHG emissions relative to the fossil baseline. The emissions for feedstock handling cover the diesel use are similar between the two feedstocks. The different between forestry and agricultural residue is in the transport since the forestry residue is assumed to be imported. This means that from an environmental perspective, the agricultural residue scenarios perform better than the forestry residue in all scenarios.

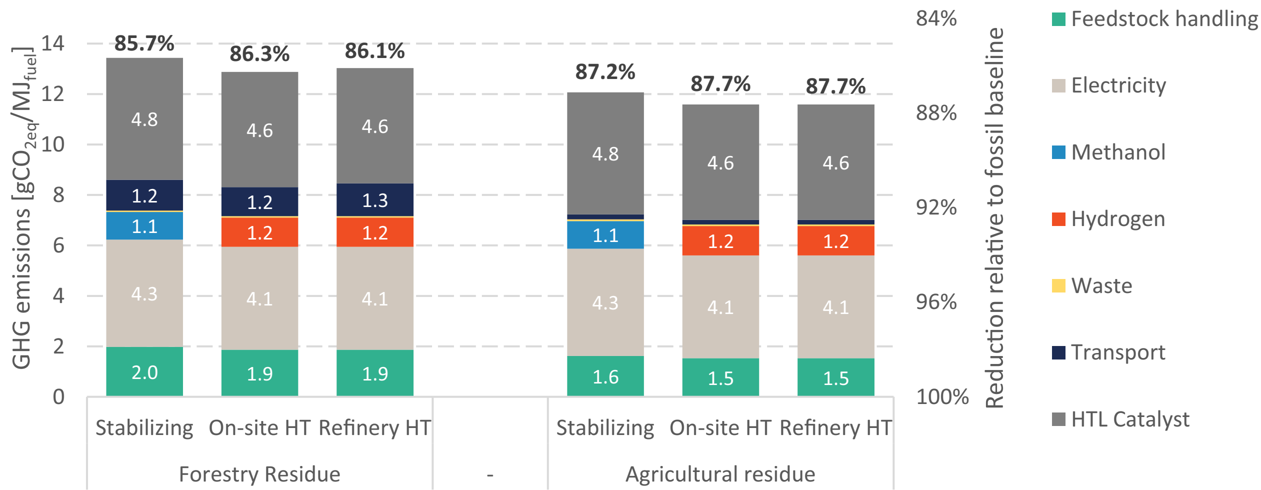

Fig. 12. Total estimated GHG emission for the three supply-chains and two feedstocks. The results are presented as gCO_{2eq}/MJ fuel and reduction relative to the fossil baseline of 94 gCO_{2eq}/MJ.

3.4.1. CO_2 by-product CCUS

Capturing and storing (CCS) or utilizing (CCU) the CO_2 fraction of the gas by-product from the HTL process can have a significant impact on the environmental feasibility of the produced fuels. This has been modelled and discussed in previously studies and are here assessed by only considering the additional electricity and hydrogen consumption [36,37]. For a full system the eFuel production and all emissions related to the CO_2 handling and transportation will have to be considered but this was outside the scope for this study. Thereby the results presented in Fig. 13 for the GHG emissions of the two alternative scenarios are optimistic estimates. The forestry residue with centralised hydrotreating is used as the example, however, all supply-chain will have a similar trend. In the CCS scenario 90% of the CO_2 content in the gas phase is captured and stored. The quantity of captured CO_2 is more than the total emissions for the scenario and results in −6.3 gCO_{2eq}/MJ biofuel produced. In the other scenario, carbon capture and utilisation, the CO_2 from the gas is combined with additional external hydrogen to produce methanol. Assuming a fossil fuel emission factor of 94 gCO_{2eq}/MJ and that the methanol can replace fossil-based fuels 1 to 1 on energy basis, the GHG savings from fossil fuels replacement outweighs the savings in the carbon capture and storage scenario. This is because it is not only the emissions from the combustion of the fossil fuels that are substituted but also the emissions from extracting and refining the fuel. The methanol synthesis requires a lot of additional hydrogen, but since this is assumed from renewable wind energy it has a relatively low impact on the total GHG emissions. The emission from hydrogen production increases from 1.2 gCO_{2eq}/MJ_{fuel} in the base case and CCS scenario to 4.1 gCO_{2eq}/MJ_{fuel} in the CCS scenario. Also, the GHG emission savings from the fuel replacement heavily depends on what type of fuels that are replaced and whether they can be replaced 1 to 1.

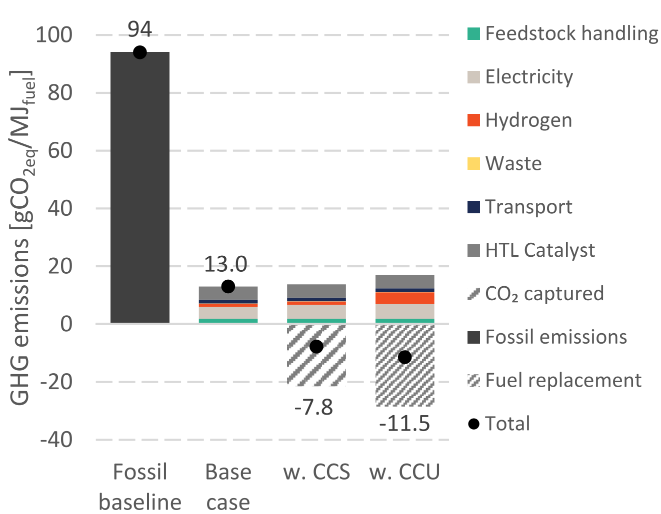

Fig. 13. GHG impact estimates for storage or utilisation of the CO_2 by-product in the forestry residue with centralised hydrotreating scenario.

4. Conclusion

This study assessed the future implementation of large-scale biofuel production by combining process modelling, biomass and infrastructure mapping, technoeconomic assessment and GHG impact analysis. The available potential for agricultural residue in Denmark were found to be 38.3 PJ and being relatively evenly spread across the country. The current use of forestry residue for energy purposes were found to heavily outweigh its theoretical potential. This means that an additional demand for biofuel production will thereby be supplied from import. The mapping of the technoeconomic and GHG impact results showed that the forestry residue scenarios are heavily dominated by the proximity to the nearest port. Agricultural residue on the other hand, while still being impacted by the availability of the residue, were more impacted by the infrastructure parameters. In the on-site hydrotreating the best locations were found close to the hydrogen line whereas for centralised hydrotreating they were at the existing refineries.

The breakdown of the technoeconomic results provided key estimates for the LCoE in the three different supply-chains which were in the range 26.4 to 38.0 EUR/GJ fuel for the chosen locations. The largest contributors were the capital expenses followed by biomass and utility costs. The lowest LCoE were found to be the chemical stabilizing scenarios which were 24.9 to 25.2% lower compared to on-site hydrotreating. Comparing on-site to centralised hydrotreating showed that the assumed reduction in hydrotreating capital investment heavily outweigh the additional intermediate transport of the biocrude in terms of LCoE estimates. The breakdown of the GHG impact estimates showed that all scenarios were within the sustainability criteria provided in the RED II with 85.7% to 87.7% reduction relative to the fossil baseline. The largest contributors were the electricity consumptions and catalyst for the HTL process. Across all three supply-chains the agricultural residue scenarios has lower GHG impact since the emissions from transportation were a lot lower compared to the imported forestry scenarios.

CRediT authorship contribution statement

Andreas Krogh: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Eliana M. Lozano:** Writing – review & editing, Supervision, Methodology. **Jeppe Grue:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Thomas H. Pedersen:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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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