Supporting information to

”Life cycle assessment of amending biomass-fired energy plants with carbon capture and storage”

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Contents

A. Methods and modelling

This section includes data and details relevant to the LCA modelling.

A.1. Biomass

The LCA modelling is performed for both wood pellets and wood chips. However, initial results showed very similar results from the two types of biomass, and thus, the results for the wood chips were moved to the supporting information (SI). Wood chips are relatively unprocessed, while wood pellets are dried and pelletised. Selected key characteristics of the wood biomass are presented in Table 1.

Table 1 The main characteristics of the two wood biomasses used. WW: Wet weight.

Biomass type	LHVwet [MJ/ kg_{ww}]	Moisture content [%ww]	TS [%ww]	LHVdry [MJ/ kg (total solids)]	Source
Wood pellets	17.5	7	93	19	[1]
Wood chips	9.9	42.3	57.7	19	[2]

The LCI for forest operations and biomass production is based on Röder et al. (2015) [3] and is summarised in Table 2.

Table 2 LCI for forest activities according to Röder et al. [3] pr. ton biomass produced for wood pellets and wood chips.

Forest activities, wood pellet production			
Description	**Value**	**Unit**	**Comment**
Diesel use, site establishment	51.12	MJ/t oven dry wood	Ecoinvent process: diesel, burned in agricultural machinery, market for diesel, burned in agricultural machinery, GLO
Aviation, fertiliser application	19.64	metric ton*km	0.17 L/t oven-dry wood. Transporting 1 t 1 km uses 0.0069 kg kerosene = 0.0087 L kerosene. To use 0.17 L of kerosene, we would transport 1 t 19.64 km. Ecoinvent process: transport, freight, aircraft, dedicated freight, short haul
Diesel use, herbicide application	9.72	MJ/t oven dry wood	Ecoinvent process: diesel, burned in agricultural machinery, market for diesel, burned in agricultural machinery, GLO
Diesel use, forest residue harvester	207.36	MJ/t oven dry wood	Ecoinvent process: diesel, burned in agricultural machinery, market for diesel, burned in agricultural machinery, GLO
Diesel use, forest residue forwarder	146.52	MJ/t oven dry wood	Large truck which transports wood from the forest to a collection point. Ecoinvent process: diesel, burned in agricultural machinery, market for diesel, burned in agricultural machinery, GLO Ecoinvent process: diesel, burned in agricultural machinery, market for diesel, burned in agricultural machinery, GLO
Diesel use, forest residue drum chipper	66.6	MJ/t oven dry wood	Ecoinvent process: diesel, burned in agricultural machinery, market for diesel, burned in agricultural machinery, GLO
Nitrogen fertiliser DAP, as N	0.72	kg/t oven dry wood	Ecoinvent process: inorganic nitrogen fertiliser, as N, nutrient supply from diammonium phosphate, RER
Nitrogen fertiliser urea as N	1.88	kg/t oven dry wood	Ecoinvent process: inorganic nitrogen fertiliser, as N, nutrient supply from urea, RER
Glyphosate	0.028	kg/t oven dry wood	Ecoinvent process: glyphosate, glyphosate production, RER
Biomass-based energy for pelleting	2880	MJ/t pellets produced	Assumed to be powered by residual biomass and modelled as the energy use from a diesel-powered process, but instead powered by heat from wood biomass. Ecoinvent process: heat, district or industrial, other than natural gas, heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014, DK
Electricity use, pelleting	152.41	kWh/t pellets produced	Marginal electricity
Forest activities, wood chip production			

Description	Value	Unit	Comment
Diesel use, site establishment	51.12	MJ/t oven dry wood	Ecoinvent process: diesel, burned in agricultural machinery, market for diesel, burned in agricultural machinery, GLO
Aviation, fertiliser application	19.64	metric ton*km	0.17 L/t oven-dry wood. Transporting 1 t 1 km uses 0.00692393586100246 kg kerosene = 0.008655 L kerosene. To use 0.17 L of kerosene, we would transport 1 t 19.64 km. Ecoinvent process: transport, freight, aircraft, dedicated freight, short haul
Diesel use, herbicide application	9.72	MJ/t oven dry wood	Ecoinvent process: diesel, burned in agricultural machinery, market for diesel, burned in agricultural machinery, GLO
Diesel use, forest residue harvester	207.36	MJ/t oven dry wood	Ecoinvent process: diesel, burned in agricultural machinery, market for diesel, burned in agricultural machinery, GLO
Diesel use, forest residue forwarder	146.52	MJ/t oven dry wood	Large truck which transports wood from the forest to a collection point. Ecoinvent process: diesel, burned in agricultural machinery, market for diesel, burned in agricultural machinery, GLO Ecoinvent process: diesel, burned in agricultural machinery, market for diesel, burned in agricultural machinery, GLO
Diesel use, forest residue drum chipper	66.6	MJ/t oven dry wood	Ecoinvent process: diesel, burned in agricultural machinery, market for diesel, burned in agricultural machinery, GLO
Nitrogen fertiliser DAP, as N	0.72	kg/t oven dry wood	Ecoinvent process: inorganic nitrogen fertiliser, as N, nutrient supply from diammonium phosphate, RER
Nitrogen fertiliser urea as N	1.88	kg/t oven dry wood	Ecoinvent process: inorganic nitrogen fertiliser, as N, nutrient supply from urea, RER
Glyphosate	0.028	kg/t oven dry wood	Ecoinvent process: glyphosate, glyphosate production, RER

A.2. Counterfactual

It is assumed that the counterfactual for the biomass used for energy is that it is left to decay naturally on the forest floor. As such, the carbon will be released regardless of whether it is being used for energy or not, only with a temporal delay. It is assumed that the natural decay follows a first-order exponential decay function, in line with Nielsen et al. [4]. Table 3 shows roughly how much C is emitted over time (respectively after 20 years and 100 years) from the wood biomass, depending on the half-life of the wood. It is assumed that the biomass is sourced from a temperate climate. According to Nielsen et al. [4], in a temperate climate, the half-life is respectively 5, 15 and 10 years for sawdust, stems, and tops and branches.

The biomass used in this study is primarily waste biomass, so it is assumed to have a half-life similar to that of tops and branches of 10 years. As such, leaving the biomass in the forest would result in temporary C storage, which is accounted for by assuming that the C not emitted is stored. After 100 years, all the C is emitted, resulting in no net C storage.

Table 3 The percentage of C in wood biomass emitted to the atmosphere depending on the half-life of the wood. Values are based on Nielsen et al. *[4]*.

Harvest time / Half-life [yrs]	**5**	**10**	**15**	**25**	**35**
C emitted [%], 20 years after harvest	90	75	60	45	30
C emitted [%], 100 years harvest	100	100	100	90	85

A.3. Carbon capture and storage

A.3.1. CO_2 capture

An amine-based carbon capture (CC) process is modelled. The LCI and relevant sources are summarised in Table 4.

Table 4 Life cycle inventory to capture 1000 kg CO_2 using an amine-based carbon capture process.

Input	**Values**	**Unit**	**Source**
Electricity use	519	kWh	Process modelling from Rambøll, incl. CO_2 purification, drying and compression to 15 bars. Assumed to be covered by internal electricity production.
CO_2	1111	Kg	Process modelling from Rambøll.
Water	840	Kg	[5]. Ecoinvent: tap water, market group for tap water, RER
Activated carbon	0.07	Kg	[5]. Ecoinvent: activated carbon, granular, activated carbon production, granular from hard coal, RER and spent activated carbon, granular, treatment of spent activated carbon, granular from hard coal, reactivation, RER
Amine solution (Monoethanolamine)	1.50	Kg	[5]. Ecoinvent: monoethanolamine, market for monoethanolamine, GLO
NaOH	0.12	Kg	[5]. Ecoinvent: sodium hydroxide, without water, in 50% solution state, market for sodium hydroxide, without water, in 50% solution state, GLO
Output	**Values**	**Unit**	**Source**
CO_2, captured	1000	Kg	Calculation, assuming a 90% capture rate
CO_2, escaped	111	Kg	Calculation, assuming a 90% capture rate
Ammonia emission	0.05	kg	Assumption from Tore Hulgaard, Rambøll
Heat, recovered	1576.3	MJ	Process modelling from Rambøll

A.3.1. CO_2 transportation

Transportation of CO_2 is complex and requires specialised equipment. Most options for CO_2 also require some interim storage: CO_2 transportation by ship requires an interim storage facility at least as big as the ship's capacity [6]. Meanwhile, CO_2 transportation by lorry may require a smaller storage facility. These interim storages are not included in the modelling.

Ship transportation

Ship transport of CO_2 can take place at different temperatures and pressures. However, -30 °C and 15 bars obtain optimal conditions, providing a reasonable CO_2 density without demanding very heavy steel constructions to withstand higher pressures. According to NIRAS [6], it is expected that ships transporting liquefied natural gas can be rebuilt to carry CO_2. However, Svendsen [7] mentioned that Project Greensand intends to build new tanker ships for the specific purpose of transporting CO_2. Rambøll [8] suggests ships for the transportation of CO_2 with a net carrying capacity of 5500-8000 t CO_2, while Svendsen [7] suggests a larger net carrying capacity of 11000-12000 t CO_2.

No data was found specifically for the ship transportation of CO_2. However, various Ecoinvent processes may be used as proxies. See Table 5, which suggests that the CC impact of ship transportation may vary between 0.008-0.02 kg CO_2-eq/(ton*km). This emission covers heavy fuel oil and other inputs to sail the ships.

The process used in the modelling of this study is “transport, freight, sea, tanker for liquefied natural gas, market for transport, freight, sea, tanker for liquefied natural gas, GLO” as it was deemed a suitable proxy because CO_2 at Medium pressure is a liquid, like the liquefied natural gas transported in the process.

Table 5 Ecoinvent processes, which may be used as a proxy for CO_2 ship transportation and their climate change impacts. The blue process is used in the modelling.

Ecoinvent 3.9.1 process	**Environmental Footprint 3.1 - a. Climate change- with LT [kg CO_2-eq/(metric ton*km)]**	**Comment**
transport, freight, sea, container ship with reefer, freezing,market for transport, freight, sea, container ship with reefer, freezing,GLO	0.020	Reefer between -35°C and -18°C.
transport, freight, sea, tanker for liquefied natural gas, market for transport, freight, sea, tanker for liquefied natural gas, GLO	0.011	
transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas, market for transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas, GLO	0.008	Other liquid goods not specified.

Pipeline transportation

According to the Danish Energy Agency and Energinet [9], transmission pipelines for CO_2 mainly operate at high pressure, typically between 80 and 160 bars. This study considers 120 bars and ambient temperature as reasonable conditions. Danish Energy Agency and Energinet [9] argue that the existing natural gas network is unsuitable for the transportation of CO_2 due to lower pressures in the NG network, which would not fit the high-pressure transportation of CO_2. Thus, making the reuse of this pipe infrastructure difficult.

Pipeline transportation is beneficial because it uses minimal energy compared to, e.g. lorry transportation. However, there is a pressure loss over distance, meaning the CO_2 has to be re-pressurised (or 'boosted') back to an appropriate pressure. The energy requirement of this boost is deeply dependent on the pipe's diameter and the transportation velocity. Typically, the cost of the chosen pipeline dimensions is compared to the cost of booster stations and energy use for pumping, where low velocity leads to a large pipeline diameter and therefore a high price for establishing the pipeline, but a lower need for booster stations. This study assumes that the pipe diameter is chosen to obtain an acceptable pressure loss.

For the pressure loss at Urban pressure, the gas velocity is assumed to be approximately. 4.5 m/s, and the pipe diameter is approximately 0.5 m. As a result, the pipe will lose max. 10 bar over the 50 km, it is transported under these conditions, and according to process modelling from Rambøll, boosting the pressure from 20 to 30 bars uses 10 kWh / 1000 kg CO_2.

For the pressure loss at High pressure, the velocity is assumed to be approximately 1 m/s and a pressure loss of 0.3 bar/km is used. At High pressure, the pressure cannot decrease too much, so as not to risk two-phase flow in the pipeline, and as a result, booster stations are introduced whenever the pressure reaches 90 bars. Boosting the pressure from 90 to 120 bars uses 0.7 kWh/1000 kg CO_2.

Again, data was not found specifically for CO_2 pipeline transportation. However, various Ecoinvent processes may be used as proxies. See Table 6, which suggests that the CCI of pipeline transportation may vary between 0.012-0.088 kg CO_2-eq/(ton*km). The reason for the significant difference in impact between the onshore and offshore petroleum pipes is that the onshore pipelines are powered by electricity. In contrast, the offshore pipelines are powered by diesel.

The processes used in the modelling of this study are “transport, pipeline, onshore, petroleum, market for transport, pipeline, onshore, petroleum, RER” and “transport, pipeline, offshore, petroleum, market for transport, pipeline, offshore, petroleum, GLO” for respectively offshore and onshore pipeline transportation of CO_2.

Table 6 Possible Ecoinvent processes, which may be used as a proxy for CO_2 pipeline transportation and their climate change impact. The blue process is used in the modelling.

Ecoinvent 3.9.1 process	**Environmental Footprint 3.1 - a. Climate change- with LT [kg CO_2-eq/(metric ton*km)]**	**Comment**
transport, pipeline, onshore, petroleum, market for transport, pipeline, onshore, petroleum, RER	0.012	
transport, pipeline, offshore, petroleum, market for transport, pipeline, offshore, petroleum, GLO	0.060	
transport, pipeline, onshore, long distance, natural gas, market for transport, pipeline, onshore, long distance, natural gas, GLO	0.088	
transport, pipeline, offshore, long distance, natural gas, market for transport, pipeline, offshore, long distance, natural gas, GLO	0.084	

Lorry transportation

According to Rambøll [8], lorries for CO_2 transportation will typically be able to transport 25 tons of CO_2 at a time. Further, the lorries will have a minimal loss of CO_2, limited to emissions from the filling of CO_2, quantified to be less than 0.1% of the CO_2 carried. Today, relatively small amounts of CO_2 are transported by lorry in a liquefied state, typically at 15-20 bars and at -30 °C.

No LCI was found specifically for the lorry transportation of CO_2 by lorry. The Ecoinvent process for a lorry with a freezing reefer (-35 to -18°C) is assumed to be a suitable proxy for the lorry transportation of CO_2. Various Ecoinvent processes may be used as proxies, see Table 7, suggesting that the CC impact of lorry transportation may vary between 0.139-0.281 kg CO_2-eq/(ton*km). Most of the impacts come from the fuel use.

The process used in the modelling of this study is “transport, freight, lorry with reefer, freezing,market for transport, freight, lorry with reefer, freezing,GLO” because it is the market group for this type of transportation.

Table 7 Possible Ecoinvent processes, which may be used as a proxy for CO_2 lorry transportation and their climate change impact. The blue process is used in the modelling.

Ecoinvent 3.9.1 process	Environmental Footprint 3.1 - a. Climate change-with LT [kg CO_2-eq/(metric ton*km)]	Comment
transport, freight, lorry with reefer, freezing,market for transport, freight, lorry with reefer, freezing,GLO	0.139	Lower impact due to a mix of lorry sizes, incl. very large lorries (>32 tons)
transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing, market for transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing, GLO	0.281	

A.3.2. CO_2 injection

CO_2 injection may occur both onshore and offshore; however, offshore injection attracts more attention, potentially due to its distance from high-population areas.

According to NIRAS [6], dealing with CC at Amager Bakke, Copenhagen, there are two current options for injecting CO_2 in a Danish context: inspired by the Norwegian Northern Lights project and the Danish Greensand project:

- Northern Lights aims to accept CO_2 from Northern Europe, which is shipped to a harbour and loaded to an on-shore receiving terminal, where the CO_2 is pressurised and transported 110 km by pipeline and finally injected three km into the underground [6,10]. There is approximately 910 km by ship from Copenhagen to the receiving terminal.
- The Danish Greensand project aims to accept CO_2 from the areas around the North Sea, where the CO_2 will be shipped to an offshore platform and injected into depleted Danish hydrocarbon fields in the North Sea. In March 2023, the Greensand project successfully injected CO_2 captured at Antwerp into the depleted Nini West oil field as a pilot project [6,11]. There is approximately 650 km from Copenhagen to Nini West.

The geological reservoirs considered for CCS are often found at depths of 800-1000 m, as the CO_2 injected at these depths behaves like a liquid or supercritical fluid. The injected CO_2 is expected to become increasingly securely sequestered over time, employing several mechanisms: high pressure, causing the CO_2 to sink deeper into the deposit and the process of carbonation, where the CO_2 is sequestered as carbonates [12].

Great care should be exercised in choosing a fitting sink, and long-term monitoring should be applied to ensure safe disposal [13]. However, according to IPCC [12], it is very likely that the CO_2 injected in appropriate and properly managed reservoirs is retained at an efficiency >99% at both the 100 and 1000-year time scales. This study uses a long-term CO_2 loss of 1% from the reservoirs. According to IPCC [12] leaks may occur due to, e.g. failure in the storage seal caused by natural disasters or mismanaged injection wells.

Underground injection of CO_2 is considered an established technology in the context of enhanced oil recovery with CO_2, which is analogous to CCS [13]. According to Núñez-López, Gil-Egui and Hosseini [14], the energy used to inject CO_2 is highly site-specific, as it depends strongly on the local conditions, including local geology, depth and reservoir conditions. However, the minimum pressure required for CCS is, in several cases, reported as 150 bars [15,16], but it may be much higher. This study uses a pressure of 290 bars, which aligns with the Northern Lights CCS project.

A.4. Uncertainty assessment

A global uncertainty approach, quantifying the analytical parameter uncertainty, is used as presented in Bisinella et al. [17]. They argue that often, only a few parameters drive the uncertainty of an LCA. The analytical parameter uncertainty is quantified based on only the sensitive parameters, as only these parameters will significantly impact the results. Literature values for the sensitive parameters are found, and as the standard, a uniform distribution was applied to avoid favouring values within the range. In cases where no literature values are found, +/- 20% of the default value is used as a conservative approximation.

Literature data was found to investigate common ranges of the four consistently sensitive parameters: The CO_2 capture efficiency (CCapEff), the amount of CO_2 stored (CO2Storage), the electricity production in percentage of LHV (ElRec) and the distance of lorry transportation for the biomass (kmTruck-Biomass).

The first three parameters (CCapEff, ElRec, kmTruck-Biomass) depend on the modelled technologies, while the last parameter (kmTruck-Biomass) depends on the specific scenario and therefore stands out. Further, the kmTruck-Biomass parameter has already been investigated in the scenarios in the main paper.

For the CO_2 capture efficiency (CCapEff), literature data suggests a span between 85-95% [18] and this is used for the analytical uncertainty assessment. This is also supported by a range of other papers [e.g. 16,19,20]. Thus, a uniform distribution between 85% and 95 % is used.

For the electricity production in percentage of LHV (ElRec), this study considers a Rankine engine and the electrical efficiency was commonly reported between 21-28% for a typical organic Rankine cycle [21,22]. However, advanced hybrid systems report higher efficiencies up to 44.6% [23]. Assuming that the more common organic Rankine engine is used, the variability used for the analytical uncertainty assessment is a uniform distribution between 21% and 28%.

For the amount of CO_2 stored (CO2Storage), mainly the value of 99% was found in the literature [15,16,24]. It seems it stems originally from IPCC [12], although Emborg et al. [25] assume that 100% of the CO_2 injected is stored. Due to the strong favouring of the value of 99%, a triangular distribution is used for this parameter, with the standard +/-20% range, only capped at 100%. Thus, the lower bound of 79.2% is used for this parameter, along with the maximum 100% and the mode is set to 99%.

The distance of biomass lorry transportation (kmTruck-Biomass) depends on the specific modelled case. The default range of +/- 20% is applied, resulting in a uniform distribution between 400 km and 600 km.

The diesel used for drying the biomass prior to pelletisation proved sensitive in the maximum scenario. However, seeing as the analytical parameter uncertainty is only quantified for the default scenario, where the parameter is not used, it is excluded from the assessment. However, relevant literature is still available in Table 8.

The literature data used is summarised in Table 8, and the distributions and ranges are summarised in Table 9. The results of the analytical parameter uncertainty for the default scenario are summarised for CCI in Table 10.

Table 8 Literature ranges used for the analytical parameter uncertainty.

Parameter	Description	Literature values	Source	Comment
CCapEff	CO_2 capture efficiency [%]	90	[19]	Amine-based carbon capture
		85-95	[18]	Amine-based carbon capture
		>90	[20]	Amine-based carbon capture
		85-90	[16]	Amine-based carbon capture
CO2Storage	CO_2 stored [%]	99	[12,15,16,24]	
		100	[25]	
ElRec	Lower heating value recovered as electricity [%]	20.70	[22]	Organic Rankine Cycle
		23.6-28.3	[21]	Organic Rankine Cycle
		44.6	[23]	Advanced hybrid system, incl. Rankine cycle (2nd law efficiency)
kmTruck Biomass	Distance of biomass lorry transport [km]	Default +/- 20%		
DieselPellet drying	The amount of diesel used to dry the wood pellets [MJ/ton pellets]	3.838 MJ/kg of evaporated water	[26]	Converted to the functional unit of the study: 172.3 MJ/FU. Converted: 2347.9 MJ/1000 kg pellets.
		3.29 MJ/kg of evaporated water	[27]	Convective drying. Converted to the functional unit of the study: 147.7 MJ/FU. Converted: 2012.7 MJ/1000 kg pellets.
		2.76 MJ/kg of evaporated water		Contact drying. Converted to the functional unit of the study: 123.9 MJ/FU. Converted: 1688.4 MJ/1000 kg pellets.
		1.33 MJ/kg of evaporated water		Combination of convective and contact drying. Converted to the functional unit of the study: 59.7 MJ/FU. Converted: 813.6 MJ/1000 kg pellets.
		1.48 MJ/kg of evaporated water		Combination of convective and contact drying. Converted to the functional unit of the study: 66.4 MJ/FU. Converted: 905.4 MJ/1000 kg pellets.

Table 9 Sensitive parameters, their default values used in the default modelling and the ranges and distributions used for the analytical parameter uncertainty.

Parameter name	Description	Default Value	Distribution and range
CCapEff	CO_2 capture efficiency [%]	90	Uniform distribution, with min=85 and max=95.
CO2Storage	CO_2 stored [%]	99	Triangular distribution, with min=79.2, max=100 and mode=99
ElRec	Lower heating value recovered as electricity [%]	25	Uniform distribution, with min=21 and max=28
kmTruckBiomass	Distance of biomass lorry transport [km]	500	Uniform distribution, with min=400 and max=600
DieselPelletdrying	The amount of diesel used to dry the wood pellets [MJ/ton pellets]	2880	Uniform distribution, with min=813 and max=2880

Table 10 Standard deviation of analytical parameter uncertainty from the sensitive parameters in kg CO_2-eq/1000 MJ.

		Wood pellets		Wood chips	
Parameter name	Description	Bioenergy	Bioenergy with carbon capture and storage	Bioenergy	Bioenergy with carbon capture and storage
CCapEff	CO_2 capture efficiency [%]	N.a.	2.9	N.a.	2.9
CO2Storage	CO_2 stored [%]	N.a.	2.4	N.a.	2.4
ElRec	Lower heating value recovered as electricity [%]	1.3	0.3	1.3	0.3
kmTruckBiomass	Distance of biomass lorry transport [km]	0.8	0.7	1.3	1.1
Sum		2.1	6.3	2.6	6.7

A.5. Biomass transportation

Biomass transportation is an important part of the bioenergy value chain. All transportation options are taken from Ecoinvent and cover common freight options, and they are summarised in Table 11.

Table 11 Ecoinvent processes used to model biomass transportation and their climate change impacts.

Transportation type	Ecoinvent Process used	Unit	Environmental Footprint 3.1 - a. Climate change- with LT [kg CO_2-eq/(metric ton*km)]
Bulk carrier shipping	transport, freight, sea, bulk carrier for dry goods, market for transport, freight, sea, bulk carrier for dry goods, GLO	metric ton*km	0.007
Freight train	transport, freight train, market for transport, Europe without Switzerland	metric ton*km	0.047
Freight lorry	transport, freight, lorry 16-32 metric ton, EURO6, market for transport, freight, lorry 16-32 metric ton, EURO6, RER	metric ton*km	0.189

A.6. Energy systems

Part of the sensitivity analysis is the systematic changing of energy systems (ES). Here, all uses of electricity and heat (except energy use aboard a ship, as it is assumed the ship's engine is used to provide electricity there) are changed to depend on the ES provided in Table 14. This study uses eight different ESs, ranging from 100% fossil energy to 100% renewable, covering several marginal mixes. The ES are ordered so that ES1 is based on 100% fossil natural gas, while the following ES decrease in CCI until ES8, which has the lowest CCI and is based on 100% renewable wind energy. The approach aims to capture the possible spread of results. The Ecoinvent processes (Ecoinvent version 3.9.1) used for the modelling are listed in Table 15 for both electricity and heat. A focus is placed on Nordic locations, but a European focus is used if no Nordic process is found.

Table 12 Energy systems (ES) used in the ES analysis ranging from 100% fossil energy to 100% renewable energy.

	ES1	**ES2**	**ES3**	**ES4**	**ES5**	**ES6**	**ES7**	**ES8**
Description	100% Fossil	2030 Marginal mix	2050 Marginal mix	Baseline	100% photovoltaics	2030 Marginal mix	2050 Marginal mix	100% offshore wind
Electricity source(s)	Natural gas	IMAGE marginal mix SSP2-Base	IMAGE marginal mix SSP2-Base	31% offshore wind; 29% onshore wind; 6% photovoltaic; 34% NG	Photovoltaic	IMAGE marginal mix SSP2-RCP2.6	IMAGE marginal mix SSP2-RCP2.6	Offshore wind
Climate change impacts of electricity [kg CO_2-eq/kWh]	0.478	0.367	0.228	0.168	0.091	0.031	0.030	0.020
Heat source(s)	Natural gas	IMAGE marginal mix SSP2-Base	IMAGE marginal mix SSP2-Base	27% heat from cogeneration of wood chips, 73% heat pump based on baseline electricity	Heat pump, based on photovoltaic electricity	IMAGE marginal mix SSP2-RCP2.6	IMAGE marginal mix SSP2-RCP2.6	Heat pump, based on offshore wind electricity
Climate change impacts of heat [kg CO_2-eq/MJ]	0.170	0.009	0.008	0.009	0.006	0.007	0.006	0.001

Table 13 Ecoinvent processes used for the energy modelling for electricity and heat.

Energy type	**Energy source**	**Ecoinvent process used**	**Comment**
Electricity	Natural gas	electricity, high voltage, electricity production, natural gas, conventional power plant, NO	
	IMAGE marginal mix	electricity, high voltage, market group for electricity, high voltage, DK	
	Photovoltaic	electricity, low voltage, electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted, DK	
	Onshore wind	electricity, high voltage, electricity production, wind, 1-3MW turbine, onshore, DK	
	Offshore wind	electricity, high voltage, electricity production, wind, 1-3MW turbine, offshore, DK	
Heat	Natural gas	heat, district or industrial, natural gas, heat and power co-generation, natural gas, conventional power plant, 100MW electrical, NO	
	IMAGE marginal mix	heat, central or small-scale, other than natural gas | market group for heat, central or small-scale, other than natural gas | RER	No Nordic alternative, so Europe (RER) is chosen
	Biomass	heat, district or industrial, other than natural gas, heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014, DK	
	Heat pump	heat, central or small-scale, other than natural gas, heat production, at a heat pump 30kW, allocation exergy, Europe without Switzerland	The electricity source is changed from "market for electricity, Europe without Switzerland" to the relevant electricity source(s) in the ES

A.7. Sensitivity scenarios

A.7.1. Renewable fuels

The goal of this scenario was to replace all fuels used in the modelling with renewable alternatives. The prospective database projected by *premise* [28] based on IMAGE SSP2-RCP2.6 (a scenario meeting the Paris agreement) for 2030, is used to identify renewable alternatives, and the process with the lowest CCI is chosen to reflect an optimistic scenario. This scenario is only modelled for CCI. Three fuels were identified throughout the scenario: various diesel processes, used for transportation and forest activities, kerosene, used in aviation for applying pesticides, and heavy fuel oil, used for maritime transportation.

The following exchanges are suggestions, but it is not within the authors' expertise to decide which fuels might be exchanged for others in the future. Biodiesel is assumed to be a reasonable substitute for diesel, bio-based kerosene is assumed to substitute for kerosene and bio-methanol is assumed to substitute for heavy fuel oil.

It is assumed that the substitution of diesel and kerosene with their non-fossil equivalents is 1=1, while the substitution of heavy fuel oil is based on the LHVs of the fuels. According to Ecoinvent 3.9.1, kerosene has an LHV of 43 MJ/kg and heavy fuel oil has an LHV of 41.2 MJ/kg. A total of 66 processes were considered for substituting the mentioned fossil fuels; the options with the lowest and the highest CCI are shown in Table 11. It is evident that there is significant variability in the CCI of the alternative processes.

The options with the lowest CCI are used in the scenario. Thus, diesel is exchanged with "biodiesel, from forest residues, via Fischer-Tropsch, from forest residues, RER", kerosene is exchanged with bio-kerosene "kerosene, synthetic, kerosene production, synthetic, Fischer Tropsch process, hydrogen from wood gasification, economic allocation, RER" and heavy fuel oil is changed to "methanol, unpurified, methanol synthesis, from wood, with CCS, RER", all based on an IMAGE SSP2-RCP2.6 2030 projection. As such, these processes have a different temporal scope than the rest of the scenario. The ES is changed to ES6, which is based entirely on wind energy.

Table 14 Overview of the climate change impacts (CCI) of the standard diesel and kerosene processes (grey), as well as possible future alternatives, specifically the option with the lowest CCI (green) and highest CCI (red).

Process	**CCI [kg CO_2-eq/kg]**	**Database**	**Interpretation**
biodiesel, from forest residues, biodiesel production, via Fischer-Tropsch, from forest residues, energy allocation, RER	0.142	IMAGE - SSP2-RCP2.6 - 2030	Future - Minimum
biodiesel, vehicle grade, biodiesel, from rapeseed oil, at fuelling station, RER	7.616	IMAGE - SSP2-RCP2.6 – 2030	Future-maximum
diesel, market group for diesel, RER	0.851	Standard Ecoinvent	Fossil
kerosene, synthetic, kerosene production, synthetic, Fischer Tropsch process, hydrogen from wood gasification, economic allocation, RER	0.096	IMAGE - SSP2-RCP2.6 – 2030	Future - Minimum
kerosene, synthetic, kerosene production, synthetic, Fischer Tropsch process, from natural gas, energy allocation, RER	9.523	IMAGE - SSP2-RCP2.6 – 2030	Future-maximum
kerosene, market for kerosene, Europe without Switzerland	0.855	Standard Ecoinvent	Fossil
methanol, unpurified, methanol synthesis, from wood, with CCS, RER	0.204	IMAGE - SSP2-RCP2.6 – 2030	Future - Minimum
methanol, from truck, methanol supply, produced with coal, RER	1.792	IMAGE - SSP2-RCP2.6 – 2030	Future-maximum
heavy fuel oil, market group for heavy fuel oil, RER	0.694	Standard Ecoinvent	Fossil

In addition, all the processes which rely on the combustion of fuels are altered, as it is assumed that the fossil CO_2 emissions in their LCI come from the combustion of fossil fuels. We know that other emissions contribute to the CCI, and that not all the CO_2 may come from the fuel, but this is a simplification. As all the introduced renewable fuels are biogenic, the fossil CO_2 emissions are changed to biogenic CO_2. The CO_2 changes are summarised in Table 13.

Table 15 Overview of the Ecoinvent processes altered to account for the combustion of fossil fuels. The fossil CO_2 emission listed has been changed to biogenic CO_2 emission as a simplification.

Original Ecoinvent name	Fossil CO_2 emission [kg/(unit)]	Unit
transport, freight, lorry 16-32 metric ton, EURO6, market for transport, freight, lorry 16-32 metric ton, EURO6, RER	0.11	metric ton*km
diesel, burned in agricultural machinery, market for diesel, burned in agricultural machinery, GLO	0.07	MJ
transport, freight, aircraft, short haul, transport, freight, aircraft, dedicated freight, short haul, GLO	0.70	metric ton*km
transport, freight, sea, tanker for liquefied natural gas, market for transport, freight, sea, tanker for liquefied natural gas, GLO	0.008	metric ton*km

A.7.2. Diesel-driven pelletisation

Röder et al. [3] provided two options for drying the wood biomass before pelletisation: diesel and waste wood biomass. The default modelling uses heat from waste wood biomass, but this sensitivity scenario investigates the impacts of using heat from diesel combustion instead.

Two Ecoinvent processes are used to model the different ways of drying the biomass prior to pelletisation: waste biomass (heat, district or industrial, other than natural gas, heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014, DK) and diesel (heat, district or industrial, other than natural gas, heat and power co-generation, diesel, 200kW electrical, SCR-NOx reduction, CH).

B. Results

This section includes all the results of the LCA study. All results are based on Environmental Footprint 3.1 [29].

The following results, as well as other documentation, are provided as an Excel sheet with the sheets described in Table 16.

Table 16 Overview of the Excel sheet of supporting information.

Sheet	Name	Description
1	CCI_default	Climate change impacts (CCI) of the default scenario
2	CCI_MIN	Climate change impacts (CCI) of the minimum scenario
3	CCI_MAX	Climate change impacts (CCI) of the maximum scenario
4	CCI_EnergySystems	Climate change impacts (CCI) of the energy system analysis
5	CCI_100% Renew	Climate change impacts (CCI) of the 100% renewable fuel sensitivity scenario
6	Norm_default	Normalised impacts of the default scenario
7	Pertur_default	Perturbation analysis of the default scenario
8	Uncert_default	Uncertainty analysis of the impacts of the default scenario
9	Counterfactual	Documentation of the counterfactual scenario where biomass is left in the forest
10	BiomassTransport	Result of the biomass transportation scenarios
11	CO2Transport	Result of the CO2 transportation scenarios
12	RenewableFuels	The LCIA results of relevant renewable fuels used in the 100% renewable fuel sensitivity scenario, based on EF3.1 from Activity Browser, projected by premise according to IMAGE SSP2-RCP2.6.

B.1. Wood chips, default scenario

The results shown in the main study are all based on wood pellets because early results indicated that wood chips and pellets had very similar results. The results of the default scenario, but based on wood chips instead of pellets, are shown in this section.

B.1.1. Contribution analysis, default wood chips scenario

The contribution analysis for the default scenario, but based on wood chips instead of the wood pellets used in the main study, can be seen in Figure 1. It is evident that the results are very close to those for wood pellets, with a net difference of about 1 kg CO_2-eq/1000 MJ heat.

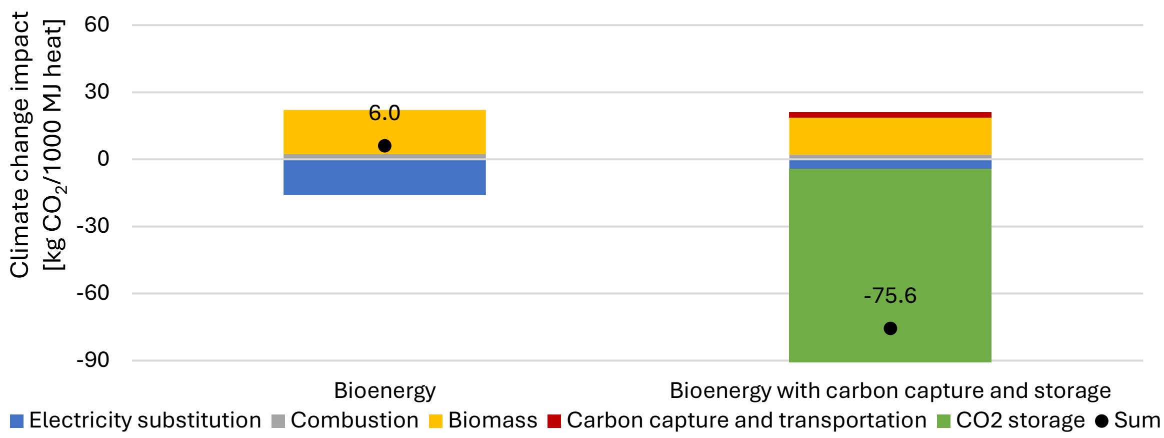

Figure 1 Contribution analysis of the default scenario, based on wood chips.

B.1.2. Characterised results default wood chips scenario

The characterised results of the default scenario, but based on wood chips (instead of the wood pellets used in the main paper), are summarised in Table 17 and Table 18, respectively, for the Bioenergy and BECCS default scenarios.

Table 17 The characterised results of the default Bioenergy scenario, but based on wood chips.

Name	Unit	Sum
EF3.1 - a. Climate change- with LT	kg CO2-Eq	6.0E+00
EF3.1 - b. Ozone depletion- with LT	kg CFC-11-Eq	-5.8E-07
EF3.1 - c. Human toxicity, cancer- with LT	CTUh	7.7E-09
EF3.1 - d. Human toxicity, non-carcinogenic- with LT	CTUh	2.2E-07
EF3.1 - e. Particulate matter- with LT	disease incidence	1.3E-06
EF3.1 - f. Ionising radiation- with LT	kBq U235-Eq	1.1E-01
EF3.1 - g. Photochemical ozone formation - with LT	kg NMVOC-Eq	1.9E-01
EF3.1 - h. Acidification- with LT	mol H+-Eq	1.5E-01
EF3.1 - i. Eutrophication, terrestrial - with LT	mol N-Eq	6.4E-01
EF3.1 - j. Eutrophication, freshwater - with LT	kg P-Eq	1.4E-03
EF3.1 - k. Eutrophication, marine - with LT	kg N-Eq	5.9E-02
EF3.1 - l. Ecotoxicity freshwater- with LT	CTUe	9.7E+01
EF3.1 - m. Land use- with LT	dimensionless	1.8E+02
EF3.1 - n. Water use- with LT	m3 world Eq deprived	1.3E+00
EF3.1 - o. Resource use, minerals and metals- with LT	kg Sb-Eq	4.2E-06
EF3.1 - p. Resource use, energy carrier- with LT	MJ, net calorific value	6.4E+00

Table 18 The characterised results of the default Bioenergy with carbon capture and storage (BECCS) scenario, but based on wood chips.

Name	Unit	Sum
EF3.1 - a. Climate change- with LT	kg CO2-Eq	-7.6E+01
EF3.1 - b. Ozone depletion- with LT	kg CFC-11-Eq	1.6E-07
EF3.1 - c. Human toxicity, cancer- with LT	CTUh	1.2E-08
EF3.1 - d. Human toxicity, non-carcinogenic- with LT	CTUh	2.5E-07
EF3.1 - e. Particulate matter- with LT	disease incidence	1.5E-06
EF3.1 - f. Ionising radiation- with LT	kBq U235-Eq	1.2E-01
EF3.1 - g. Photochemical ozone formation - with LT	kg NMVOC-Eq	2.1E-01
EF3.1 - h. Acidification- with LT	mol H+-Eq	2.3E-01
EF3.1 - i. Eutrophication, terrestrial - with LT	mol N-Eq	7.8E-01
EF3.1 - j. Eutrophication, freshwater - with LT	kg P-Eq	2.0E-03
EF3.1 - k. Eutrophication, marine - with LT	kg N-Eq	6.7E-02
EF3.1 - l. Ecotoxicity freshwater- with LT	CTUe	1.1E+02
EF3.1 - m. Land use- with LT	dimensionless	1.5E+02
EF3.1 - n. Water use- with LT	m3 world Eq deprived	2.8E+00
EF3.1 - o. Resource use, minerals and metals- with LT	kg Sb-Eq	6.8E-05
EF3.1 - p. Resource use, energy carrier- with LT	MJ, net calorific value	2.1E+02

B.2. Characterised results, default scenario

The characterised results of the default scenario (based on wood pellets) are summarised in Table 19 and Table 20, respectively, for the Bioenergy and BECCS default scenarios.

Table 19 The characterised results of the default Bioenergy scenario.

Name	Unit	Sum
EF3.1 - a. Climate change- with LT	kg CO2-Eq	5.0E+00
EF3.1 - b. Ozone depletion- with LT	kg CFC-11-Eq	-5.3E-07
EF3.1 - c. Human toxicity, cancer- with LT	CTUh	9.5E-09
EF3.1 - d. Human toxicity, non-carcinogenic- with LT	CTUh	2.9E-07
EF3.1 - e. Particulate matter- with LT	disease incidence	1.6E-06
EF3.1 - f. Ionising radiation- with LT	kBq U235-Eq	8.8E-02
EF3.1 - g. Photochemical ozone formation - with LT	kg NMVOC-Eq	2.2E-01
EF3.1 - h. Acidification- with LT	mol H+-Eq	1.9E-01
EF3.1 - i. Eutrophication, terrestrial - with LT	mol N-Eq	8.6E-01
EF3.1 - j. Eutrophication, freshwater - with LT	kg P-Eq	1.3E-03
EF3.1 - k. Eutrophication, marine - with LT	kg N-Eq	7.1E-02
EF3.1 - l. Ecotoxicity freshwater- with LT	CTUe	8.9E+01
EF3.1 - m. Land use- with LT	dimensionless	2.1E+03
EF3.1 - n. Water use- with LT	m3 world Eq deprived	2.3E+00
EF3.1 - o. Resource use, minerals and metals- with LT	kg Sb-Eq	-4.1E-05
EF3.1 - p. Resource use, energy carrier- with LT	MJ, net calorific value	-6.1E+00

Table 20 The characterised results of the default Bioenergy with carbon capture and storage (BECCS) scenario.

Name	Unit	Sum
EF3.1 - a. Climate change- with LT	kg CO2-Eq	-7.65E+01
EF3.1 - b. Ozone depletion- with LT	kg CFC-11-Eq	2.03E-07
EF3.1 - c. Human toxicity, cancer- with LT	CTUh	1.39E-08
EF3.1 - d. Human toxicity, non-carcinogenic- with LT	CTUh	3.10E-07
EF3.1 - e. Particulate matter- with LT	disease incidence	1.85E-06
EF3.1 - f. Ionising radiation- with LT	kBq U235-Eq	1.09E-01
EF3.1 - g. Photochemical ozone formation - with LT	kg NMVOC-Eq	2.40E-01
EF3.1 - h. Acidification- with LT	mol H+-Eq	2.59E-01
EF3.1 - i. Eutrophication, terrestrial - with LT	mol N-Eq	9.63E-01
EF3.1 - j. Eutrophication, freshwater - with LT	kg P-Eq	1.90E-03
EF3.1 - k. Eutrophication, marine - with LT	kg N-Eq	7.75E-02
EF3.1 - l. Ecotoxicity freshwater- with LT	CTUe	1.01E+02
EF3.1 - m. Land use- with LT	dimensionless	1.79E+03
EF3.1 - n. Water use- with LT	m3 world Eq deprived	3.70E+00
EF3.1 - o. Resource use, minerals and metals- with LT	kg Sb-Eq	2.91E-05
EF3.1 - p. Resource use, energy carrier- with LT	MJ, net calorific value	1.98E+02

B.3. Normalised results, default scenario

This section details the normalised impacts of the default modelling. The abbreviations used are summarised in Table 21. A heat map of the normalised results of the two default scenarios is placed in Table 22.

Table 21 Overview of the impact categories in Environmental Footprint 3.1 and the abbreviations used in this study.

Full name, impact category	Abbreviation
EF3.1 - a. Climate change- with LT	CCI
EF3.1 - b. Ozone depletion- with LT	OD
EF3.1 - c. Human toxicity, cancer- with LT	HTC
EF3.1 - d. Human toxicity, non-carcinogenic- with LT	HTnC
EF3.1 - e. Particulate matter- with LT	PM
EF3.1 - f. Ionising radiation- with LT	IR
EF3.1 - g. Photochemical ozone formation - with LT	POF
EF3.1 - h. Acidification- with LT	A
EF3.1 - i. Eutrophication, terrestrial - with LT	EuT
EF3.1 - j. Eutrophication, freshwater - with LT	EuF
EF3.1 - k. Eutrophication, marine - with LT	EuM
EF3.1 - l. Ecotoxicity freshwater- with LT	EtF
EF3.1 - m. Land use- with LT	LU
EF3.1 - n. Water use- with LT	WU
EF3.1 - o. Resource use, minerals and metals- with LT	RUM
EF3.1 - p. Resource use, energy carrier- with LT	RUE

Table 22 Normalised results of the Bioenergy and Bioenergy with carbon capture and storage (BECCS) default scenarios.

Full name	Bioenergy	Bioenergy with carbon capture and storage
EF3.1 - a.Climate change- with LT	6.6E-04	-1.0E-02
EF3.1 - b. Ozone depletion- with LT	-1.0E-05	3.9E-06
EF3.1 - c. Human toxicity, cancer- with LT	5.5E-04	8.0E-04
EF3.1 - d. Human toxicity, non-carcinogenic- with LT	2.3E-03	2.4E-03
EF3.1 - e. Particulate matter- with LT	2.7E-03	3.1E-03
EF3.1 - f. Ionising radiation- with LT	2.1E-05	2.6E-05
EF3.1 - g. Photochemical ozone formation - with LT	5.4E-03	5.9E-03
EF3.1 - h. Acidification- with LT	3.5E-03	4.7E-03
EF3.1 - i. Eutrophication, terrestrial - with LT	4.9E-03	5.4E-03
EF3.1 - j. Eutrophication, freshwater - with LT	8.3E-04	1.2E-03
EF3.1 - k. Eutrophication, marine - with LT	3.7E-03	4.0E-03
EF3.1 - l. Ecotoxicity freshwater- with LT	1.6E-03	1.8E-03
EF3.1 - m. Land use- with LT	2.6E-03	2.2E-03
EF3.1 - n. Water use- with LT	2.0E-04	3.2E-04
EF3.1 - o. Resource use, minerals and metals- with LT	-6.5E-04	4.6E-04
EF3.1 - p. Resource use, energy carrier- with LT	-9.4E-05	3.0E-03

References

[1] Evald A, Hansen MT. Biomass Statistics : Wood pellets. Copenhagen, Denmark: 2018.

[2] Evald A, Hansen MT. Biomass Statistics : Wood chips. Copenhagen, Denmark: 2018.

[3] Röder M, Whittaker C, Thornley P. How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. Biomass and Bioenergy 2015;79:50–63. https://doi.org/10.1016/j.biombioe.2015.03.030.

[4] Nielsen AT, Bentsen NS, Nord-Larsen T. CO2 emissions from biomass use in district heating and combined heat and power plants in Denmark. Copenhagen: 2023.

[5] Christensen TH, Bisinella V. Climate change impacts of introducing carbon capture and utilisation (CCU) in waste incineration. Waste Manag 2021;126:754–70. https://doi.org/10.1016/j.wasman.2021.03.046.

[6] NIRAS. Konkretisering af Carbon Capture på Amager Bakke. 2020.

[7] Svendsen JB. Personal communication - Meeting 25/11/2021. Topic: The Greensand CCS project. From INEOS DK. Lyngby, Denmark. 2021.

[8] Rambøll. CO2 fangst på danske affaldsenergianlæg. Copenhagen: 2020.

[9] Danish Energy Agency, Energinet. Technology Data for Carbon Capture, Transport and Storage. Copenhagen, Denmark: 2021.

[10] Northern Lights. Accelerating decarbonisation: Northern Lights delivers CO2 transport and storage as a service. 2021.

[11] Greensand Secretariat. First Carbon Storage 2023. https://www.projectgreensand.com/first-carbon-storage.

[12] Intergovernmental Panel on Climate Change. IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2005. https://doi.org/10.1002/9783527818488.ch15.

[13] Taniguchi I, Itaoka K. CO2 Capture, Transportation, and Storage Technology. Energy Technol. Roadmaps Japan Futur. Energy Syst. Based Feasible Technol. Beyond 2030, 2016, p. 1–573. https://doi.org/10.1007/978-4-431-55951-1.

[14] Núñez-López V, Gil-Egui R, Hosseini S. Environmental and Operational Performance of CO2-EOR as a CCUS Technology: A Cranfield Example with Dynamic LCA Considerations. Energies 2019;12:448. https://doi.org/10.3390/en12030448.

[15] Pour N, Webley PA, Cook PJ. Potential for using municipal solid waste as a resource for bioenergy with carbon capture and storage (BECCS). Int J Greenh Gas Control 2018;68:1–15. https://doi.org/10.1016/j.ijggc.2017.11.007.

[16] Bisinella V, Hulgaard T, Riber C, Damgaard A, Christensen TH. Environmental assessment of carbon capture and storage (CCS) as a post-treatment technology in waste incineration. Waste Manag 2021;128:99–113. https://doi.org/10.1016/j.wasman.2021.04.046.

[17] Bisinella V, Conradsen K, Christensen TH, Astrup TF. A global approach for sparse representation of uncertainty in Life Cycle Assessments of waste management systems. Int J Life Cycle Assess 2016;21:378–94. https://doi.org/10.1007/s11367-015-1014-4.

[18] Hasan S, Abbas AJ, Nasr GG. Improving the carbon capture efficiency for gas power plants through amine-based absorbents. Sustain 2021;13:1–28. https://doi.org/10.3390/su13010072.

[19] Matin NS, Flanagan WP. Life cycle assessment of amine-based versus ammonia-based post combustion CO2 capture in coal-fired power plants. Int J Greenh Gas Control 2022;113:103535. https://doi.org/10.1016/j.ijggc.2021.103535.

[20] Li G, Shen X, Jiao X, Xie F, Hua J, Lin H, et al. Novel tri-solvent amines absorption for flue gas CO2 capture: Efficient absorption and regeneration with low energy consumption. Chem Eng J 2024;493:152699. https://doi.org/10.1016/j.cej.2024.152699.

[21] Kalina J. Integrated biomass gasification combined cycle distributed generation plant with reciprocating gas engine and ORC. Appl Therm Eng 2011;31:2829–40. https://doi.org/10.1016/j.applthermaleng.2011.05.008.

[22] Vera D, Jurado F, Carpio J, Kamel S. Biomass gasification coupled to an EFGT-ORC combined system to maximize the electrical energy generation: A case applied to the olive oil industry. Energy 2018;144:41–53. https://doi.org/10.1016/j.energy.2017.11.152.

[23] Roy D, Samanta S, Ghosh S. Performance assessment of a biomass fuelled advanced hybrid power generation system. Renew Energy 2020;162:639–61. https://doi.org/10.1016/j.renene.2020.07.030.

[24] Li K, Leigh W, Feron P, Yu H, Tade M. Systematic study of aqueous monoethanolamine (MEA)-based CO2 capture process: Techno-economic assessment of the MEA process and its improvements. Appl Energy 2016;165:648–59. https://doi.org/10.1016/j.apenergy.2015.12.109.

[25] Emborg M, Tan GLX, Zhao Y, Thonemann N, Ho EHZ, Tan DZL, et al. Environmental impacts and scale-up efficiency of four carbon capture and storage scenarios. J Clean Prod 2024;472:143506. https://doi.org/10.1016/j.jclepro.2024.143506.

[26] Edmonson A, Lin Y, Mba-Wright M, Byrne D, Ding L, Shi J. Comparative life cycle assessment of woody biomass processing: air classification, drying, and size reduction powered by bioelectricity versus grid electricity. Biomass Convers Biorefinery 2024:11793–802. https://doi.org/10.1007/s13399-024-06038-7.

[27] Havlík J, Dlouhý T. Improving the energy effectivity of biomass drying for utilisation in energy systems by combining convective and contact drying. Dry Technol 2024;42:622–35. https://doi.org/10.1080/07373937.2023.2295524.

[28] Sacchi R, Terlouw T, Siala K, Dirnaichner A, Bauer C, Cox B, et al. PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renew Sustain Energy Rev 2022;160:112311. https://doi.org/10.1016/j.rser.2022.112311.

[29] Andreasi Bassi S, Biganzoli F, Ferrara N, Amadei A, Valente A, Sala S, et al. Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method. vol. JRC130796. 2023. https://doi.org/10.2760/798894.