Life Cycle Assessment (LCA) of Carbon Capture and Storage (CCS) on Biomass-to-Energy (BECCS)

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CARBON LIMITS

This report was prepared by Carbon Limits AS for Växjö Energi AB

Project title:

Life Cycle Assessment (LCA) of Carbon Capture and Storage (CCS) on Biomass-to-Energy (BECCS)

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Carbon Limits works with public authorities, private companies, finance institutions and non-governmental organisations to reduce greenhouse gas emissions from a range of sectors. Our team supports clients in the identification, development, and financing of projects that mitigate climate change and generate economic value, in addition to providing advice on the design and implementation of climate and energy policies and regulations.

Executive Summary

Växjö Energi AB (VEAB) operates the cogeneration plant of Sandviksverket in Växjö, Sweden, supplying heat and power to the Växjö municipality. The main feedstock is composed of branches, treetops and other harvesting residues from the forests of Småland that would otherwise have gone to waste. VEAB plans to install a carbon capture system on the cogeneration plant to reduce carbon dioxide (CO_2) emissions to air by 115,000 tons per year. The captured CO_2 will be transported and permanently stored in one of the storage sites of Northern Europe.

All the CO_2 emitted by the combustion process at Sandviksverket plant comes from biogenic sources. This means that if the amount of CO_2 stored exceeds the impacts generated by the project, the CCS project on VEAB's plant can generate "negative" CO_2 emissions, also called CO_2 removals (CDRs). CDR credits can in principle be sold in the carbon markets, thus providing additional revenue streams to project developers. In order to robustly evaluate the net removals generated by CDR projects (*i.e.*, removals once emissions due to the project itself are subtracted), VEAB commissioned Carbon Limits to conduct a life-cycle assessment (LCA) of their value chain. The assessment aims to determine the carbon footprint of energy production without and with CCS, thereby assessing the emission reduction brought by the implementation of the CCS chain. Thus, three different systems are studied:

(1) the electricity and heat generation system without CCS following an attributional method,
(2) the electricity and heat generation system with CCS following an attributional method,
(3) the CCS project itself following a consequential method.

To achieve the objectives outlined above, Carbon Limits followed the steps laid out in ISO standards 14040, «Life Cycle Analysis – principles and framework», and 14044, «Life Cycle Analysis – requirements and guidelines» to carry out the Life Cycle Assessment. Carbon Limits used a dedicated LCA software (OpenLCA) to perform the impact assessment coupled to an extensive database of reference of emission factors (ecoinvent 3.11).

Note that this LCA study is performed on a CCS chain where some elements are not firmly defined. Some conservative assumptions were made regarding the technologies and logistics involved in the chain. Based on the final CCS chain the results of this study may be refined at a later stage.

Goal and scope definition

The goal of the assessment is to quantify the life cycle greenhouse gas (GHG) emissions (carbon footprint) along the bioenergy production and the CCS value chain over the lifetime of the project. The results of this assessment will be used to showcase the GHG emissions reduction reached by applying CCS to the bioenergy production system and to develop structured documentation for determination of net carbon removals through CCS. Three different systems were assessed within this study:

1. Bioenergy system without CCS: Sandviksverket combined heat and power (CHP) plant without CCS (also called "Original CHP")
2. Bioenergy system without CCS: Sandviksverket combined heat and power (CHP) plant with CCS (also called "BECCS system")
3. CCS chain: the CCS project including the impacts on the bioenergy plant and on the energy delivered.

The function of the two first systems is to produce heat and electricity by burning biomass and to send the heat to the local district heating system and the electricity to the grid. The functional unit used in the LCA is

1 MWh of heat equivalent ($MWh_{heat-eq}$) exiting the plant. The function of the third system is to capture, transport and store CO_2 from the bioenergy plant while still delivering the same amount of heat and electricity to the grid from the bioenergy plant. The functional unit used in the LCA is 1 ton of CO_2 stored. The environmental impact indicator assessed in the LCA is the Global Warming Potential at 100 years (henceforth "GWP"). The IPCC 2021 impact method has been selected to compute the GWP100 indicator. The assessment provides results on the amount of CO_2 equivalent emitted per functional unit.

The system boundaries for the original CHP and the BECCS system are represented on Figure 1 and Figure 2 respectively. Those systems give a static view of bioenergy production in two configurations and follow an attributional modelling. The system boundaries for the CCS chain are represented on Figure 3. The assessment follows a consequential approach: it quantifies all the changes induced by the implementation of CCS. This includes: (i) all greenhouse gas (GHG) emissions due to adding the capture, transport and storage processes to the bioenergy chain, (ii) all GHG emissions due to increasing the input of biomass to the plant, (iii) all GHG emissions due to compensating the reduction in electricity production. All emissions that were already occurring before implementation of the CCS project are not accounted in this system.

Figure 1: System boundaries – Original CHP plant

Figure 2: System boundaries – Bioenergy system with CCS

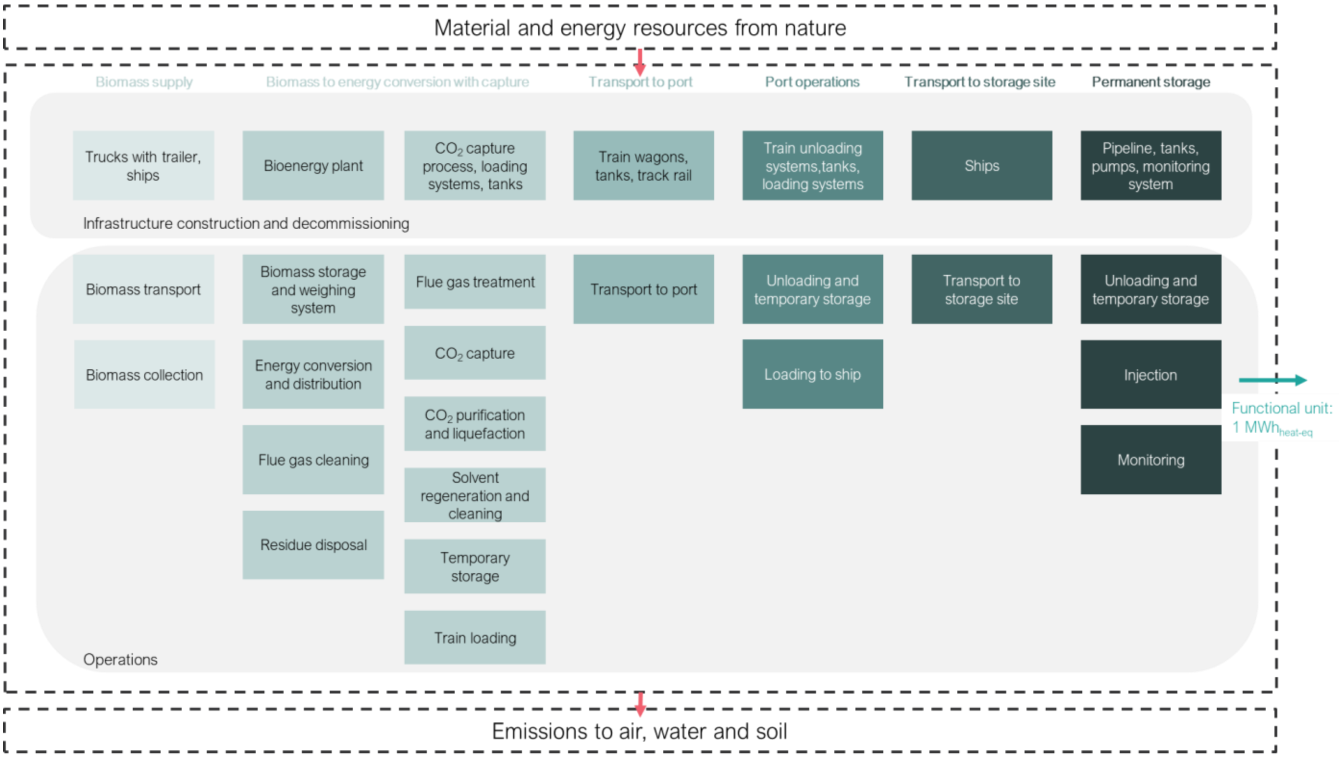
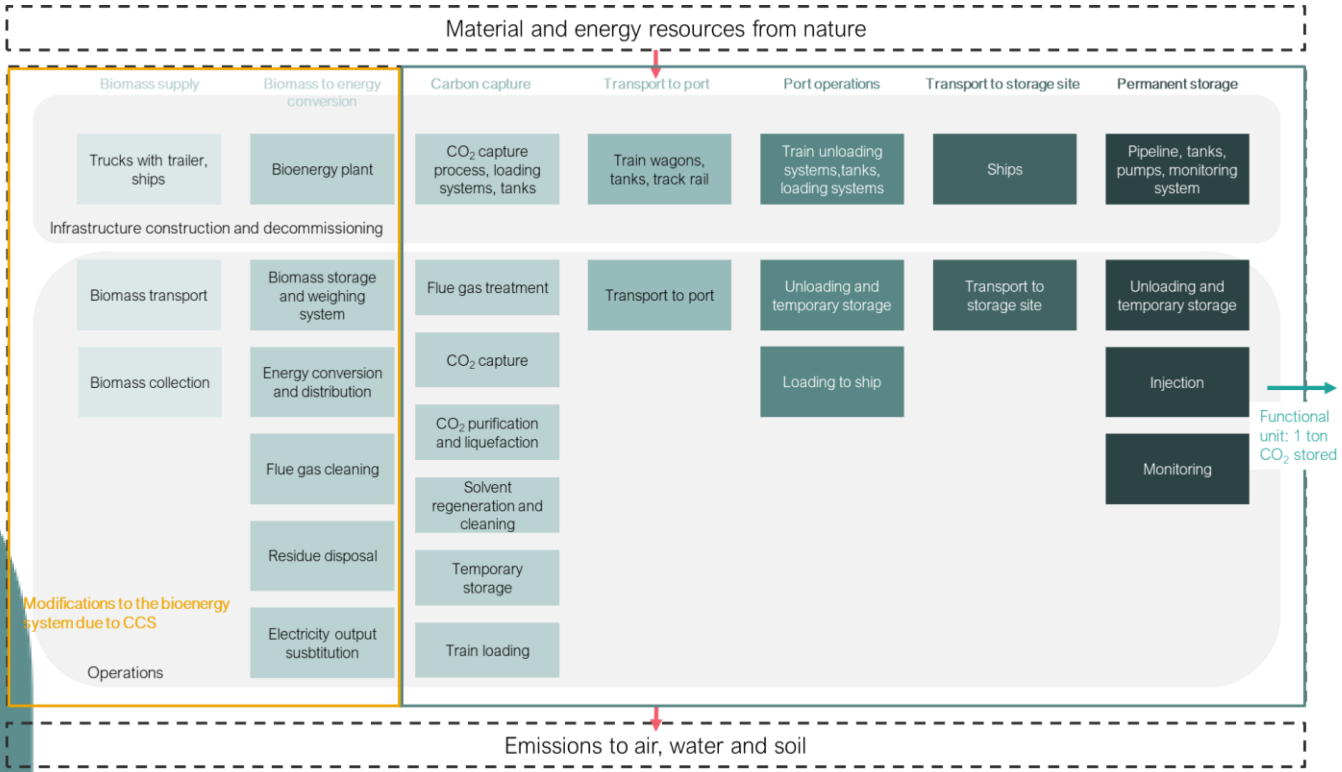


Figure 3: System boundaries – CCS chain



Life cycle inventory

Input data were collected for the existing CHP plant at Sandviksverket (“biomass supply” and “biomass-to-energy conversion”) and for the prospective CCS chain between Sandviksverket, Malmö (export port in Sweden) and Øygarden terminal from where CO_2 is injected under the surface for permanent storage (storage site location in Norway related to Northern Lights project). For each process, activity data and emission factors related to energy, chemical, material and transport requirements, as well as waste disposal, wastewater management and other direct emissions caused by the process were collected when relevant and available. System boundaries are “cradle-to gate” meaning that all upstream emissions linked to the inputs to the system are included.

For collection of activity data, information from technical documents and expert estimation was preferred whenever available. In case of missing data for key activities, assumptions were taken based on external data or best estimates. The main data providers are:

- VEAB’s databases and business models based on existing measurements for the “biomass supply” and “biomass-to-energy conversion” processes.
- Technology suppliers for the “carbon capture” process, based on pre-FEED studies.
- Transport provider (GreenCargo) for the “transport to port” process.
- Potential CO_2 hub operator at Malmö port for the “port operations” process.
- Northern Lights JV through their published carbon footprint report[1] for the “transport to storage site” and “geological storage” processes

The input data for the biomass supply and the biomass-to-energy conversion was, for the most part, provided by VEAB based on previous year measurements and data records. The results for these processes therefore have a high level of confidence. The input data for the capture and liquefaction unit, and for CO_2 transport to port was provided by potential technology and transport providers. As this information is prospective, the associated level of confidence is moderate. The input data for port operation has a low level of confidence. Estimates for the transport to storage site and the storage activities are derived average values from the NL carbon footprint. These estimates have a moderate level of confidence.

Impact assessment and results interpretation

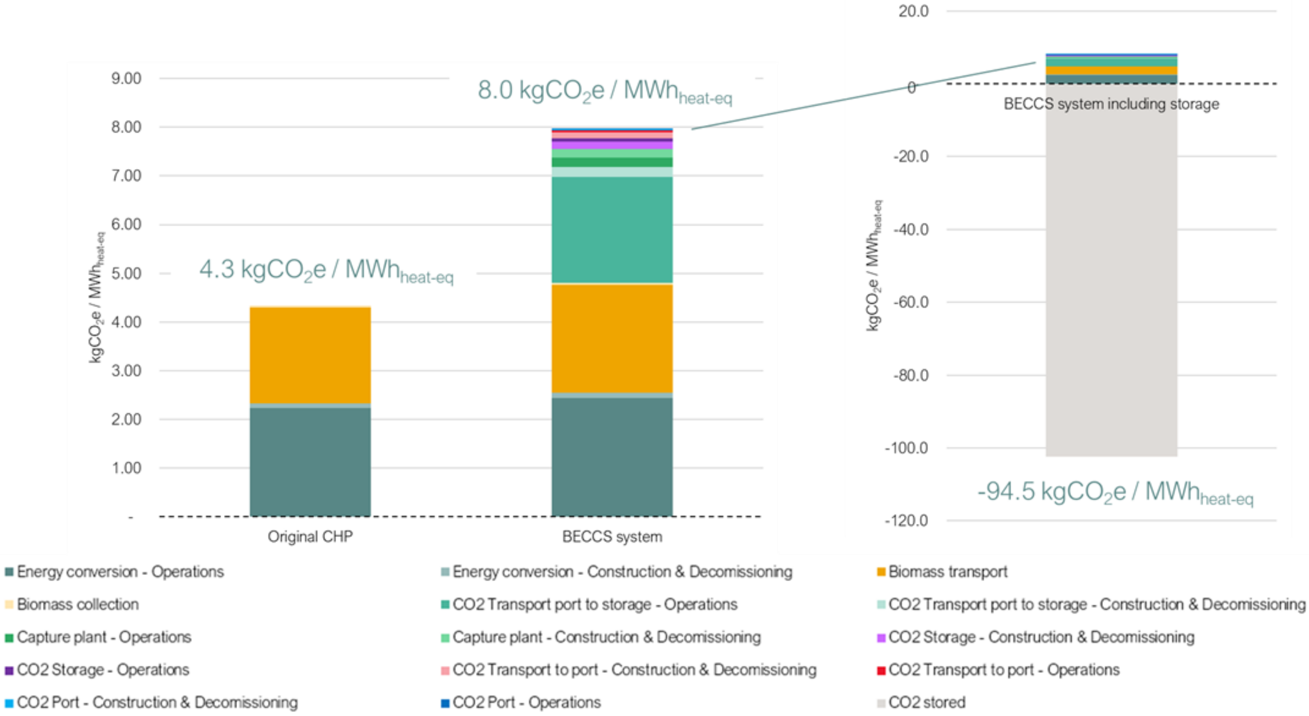
Systems 1 and 2: Original CHP and BECCS system – functional unit: 1 $MWh_{heat\text{-}eq}$

The total GWP of the original CHP without CCS is 4.3 $kgCO_2e$ / $MWh_{heat\text{-}eq}$. About half of the carbon footprint (52%) is due to the operation of the biomass-to-energy conversion system. Transport of biomass represents most of the rest of the impact (45%).

The total GWP of the BECCS system is 8.0 $kgCO_2e$ / $MWh_{heat\text{-}eq}$ before accounting for the climate benefit achieved by storing biogenic CO_2. The main contributors are the operation of the biomass-to-energy conversion system (31%), biomass transport (28%) and CO_2 shipping to storage site (27%). When accounting for the fact that biogenic CO_2 is permanently stored, the total GWP of the BECCS system is - 94.5 $kgCO_2e$ / $MWh_{heat\text{-}eq}$.

[1] Gentile et al., *Carbon footprint of the Northern Lights JV CO2 transport and storage value chain*, 2023. Accessible at: https://norlights.com/wp-content/uploads/2023/11/Report-Carbon-footprint-of-the-Northern-Lights-JV-co2-transport-and-storage-value-chain.pdf

Figure 4: GWP of the original CHP (left), BECCS system without accounting for CO_2 stored (center), and BECCS system with discount of CO_2 stored (right) – per 1 $MWh_{heat-eq}$



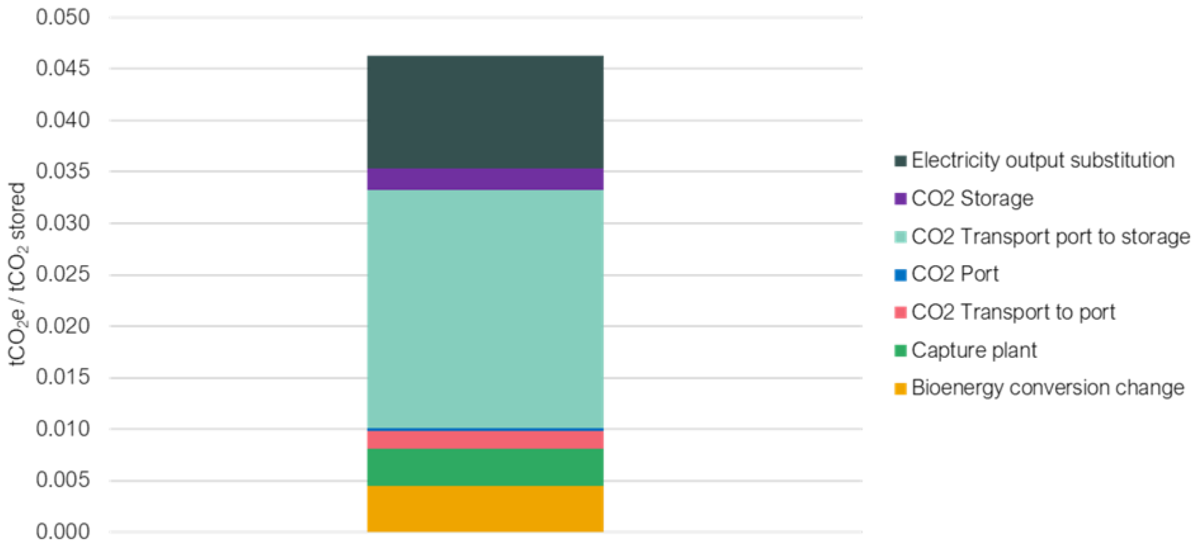
System 3: CCS chain – functional unit: 1 tCO_2 stored

The total GWP of the CCS chain is 0.046 tCO_2e / tCO_2 stored. This means the GWP impacts caused by the implementation of CCS are equivalent to about 5% of the quantity of biogenic CO_2 stored. The main contributor to the GWP of the CCS chain is the CO_2 shipping from Malmö to Øygarden, representing about 50% of the carbon footprint. The second largest contributor is the electricity substitution representing 24% of the total GWP. The change in the bioenergy system, including biomass supply and biomass-to-energy conversion represents 10% of the total GWP. The capture and liquefaction process at Sandviksverket represents 8% of the total GWP. The CO_2 storage, CO_2 transport to port and port processes respectively represent 4.5%, 3.6% and 0.5%.

As CO_2 transport to storage site is the main contributor to the carbon footprint of the CCS chain, the results are sensitive to the estimate of fuel consumption. Based on the analysis of volumes and locations considered in the first phase of the NL project, the average estimate of impacts derived from the NL carbon footprint seems appropriate for the Malmö to Øygarden route. However, the results could be consolidated if NL (or another transport and storage provider if relevant) provided data for the specific route and ships in use.

Due to the consequential modelling, the decrease of electricity output from the CHP plant causes an additional impact added to the carbon footprint of the CCS chain. The results are therefore sensitive to the choice of emission factor used to quantify the impact of electricity substitution. With the emission factors examined in the sensitivity analysis, the results range from -19% to +262% compared to the carbon footprint calculated using the market emission factor for Sweden from ecoinvent 3.11. The choice of emission factor for market leakage is an important assumption in the calculation of net removals, and, as such, should be clarified with the considered registry.

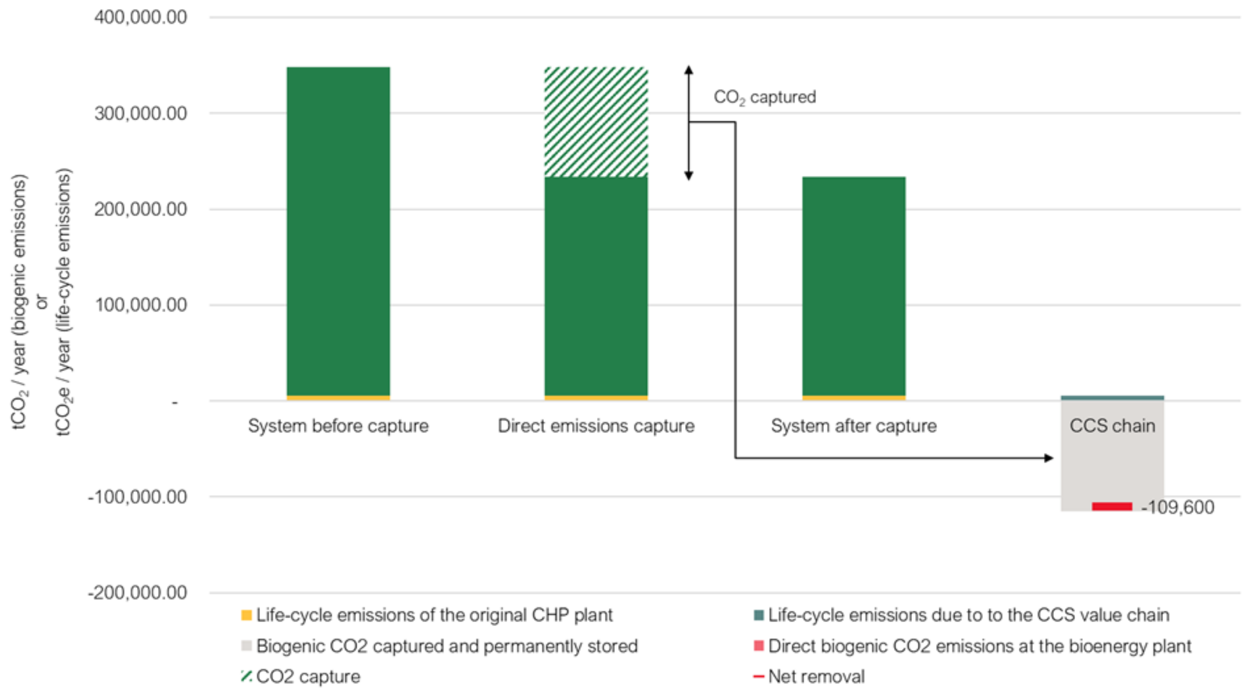
Figure 5: GWP of the CCS chain – per ton CO_2 stored



Based on the results of the LCA, the yearly net CO_2 removals are estimated to 109,600 tCO_2. Figure 6 summarises annual emissions before and after implementation of CCS and illustrates how the GWP of the CCS chain compares to stored emissions.[2]

[2] Please note that the estimate of net removals is based on the assumptions outlined in this report. Results may vary slightly depending on the methodologies used by individual registries. Therefore, Carbon Limits does not guarantee the exact quantity of credits that may be awarded.

Figure 6: Summary of emissions in the system with and without CCS – per year



Note: according to the impact assessment used, biogenic CO_2 emissions to air in tCO_{2e} are equal to 0. To make them appear on the graph, biogenic CO_2 emissions are represented in tCO_2 unit. The captured and permanently stored biogenic CO_2 is represented in tCO_2e.

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Abbreviations

BECCS	Bioenergy with carbon capture and storage
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CHP	Combined Heat and Power
CH_4	methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
ETS	Emissions Trading System
FEED	Front End Engineering and Design
GHG	Greenhouse gas
GWP	Global Warming Potential
heat-eq	Heat equivalent
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
ktpa	kilotons per year
kWh	kilowatt hours
LCA	Life Cycle Assessment
LNG	Liquefied Natural Gas
MWh	Megawatt hours
m^3	cubic meter
NL	Northern Lights JV DA also called "Northern Lights" in the report
N_2O	Nitrous oxide
PCR	Product Category Rule
RER	Region of Europe
RoW	Rest of the World
SE	Sweden
t	ton
tkm	Ton kilometer
VEAB	Växjö Energi AB

1 Introduction

Växjö Energi AB (VEAB) operates the cogeneration plant of Sandviksverket in Växjö, Sweden, supplying heat and power to the Växjö municipality. Since December 2019, all fuel used in the cogeneration plant is of biogenic origin. The main feedstock is composed of branches, treetops and other harvesting residues from the forests of Småland that would otherwise have gone to waste. This is complemented by bio-oil used for start-up burners and backup boilers.[3] VEAB now ambitions to install a carbon capture system on the cogeneration plant to reduce carbon dioxide (CO_2) emissions to air by 115,000 tons per year. The captured CO_2 will be transported and permanently stored in one of the storage sites of Northern Europe. The transportation route and storage sites are yet to be defined.

All the CO_2 emitted by the combustion process at Sandviksverket plant comes from biogenic sources. This means that if the amount of CO_2 stored exceeds the impacts generated by the project, the CCS project on VEAB's plant can generate "negative" CO_2 emissions, also called CO_2 removals (CDRs). CDR credits can in principle be sold in the carbon markets, thus providing additional revenue streams to project developers. It is therefore important to estimate the life cycle emissions of the CCS project at VEAB's plant, to ensure that the carbon impact from the development, design and implementation of the project is as limited as possible and to estimate net CO_2 removals generated by the project, which is an important step for VEAB to sell CDR credits. In this context, VEAB commissioned Carbon Limits AS to conduct a LCA to evaluate the carbon footprint of their future BECSS value chain.

The assessment presented in this report aims to determine the carbon footprint of energy production without and with CCS, thereby assessing the emission reduction brought by the implementation of the CCS chain. Thus, three different systems are studied:

(1) the electricity and heat generation system without CCS following an attributional method,
(2) the electricity and heat generation system with CCS following an attributional method,
(3) the CCS project itself following a consequential method.

To achieve the objectives outlined above, Carbon Limits followed the steps laid out in ISO standards 14040, «Life Cycle Analysis – principles and framework», and 14044, «Life Cycle Analysis – requirements and guidelines» for carrying out a Life Cycle Assessment. These steps are represented on Figure 7.

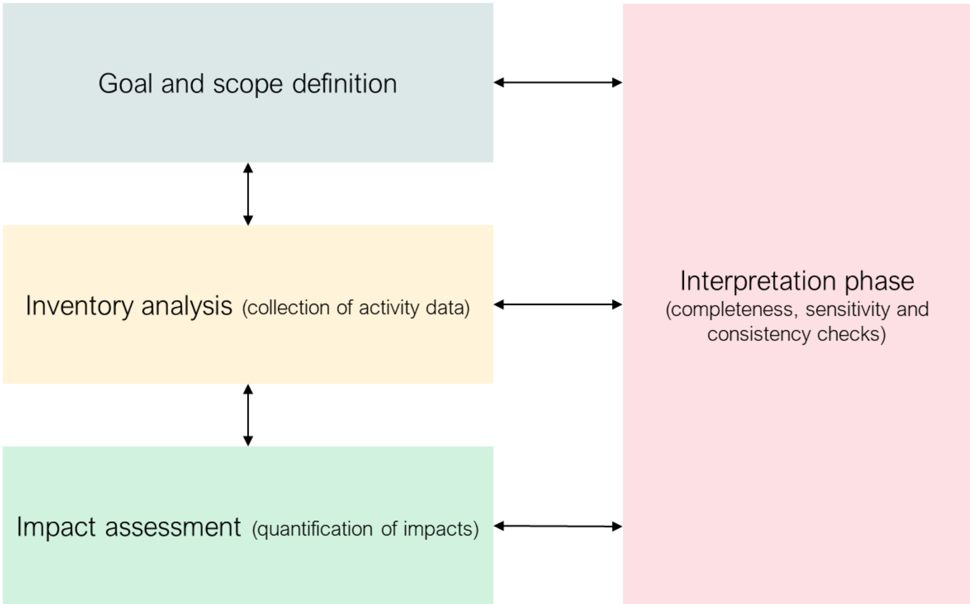
Note that this LCA study is performed on a CCS chain where some elements are not firmly defined. Some conservative assumptions were made regarding the technologies and logistics involved in the chain. Based on the final CCS chain the results of this study may be refined at a later stage.

This report is structured according to the standards:

- Goal and scope definition
- Inventory analysis
- Impact assessment and results interpretation

[3] Växjö Energi website, accessed April 2025, https://www.veab.se/en/about/the-company/plants/

Figure 7: Life cycle analysis framework as described by ISO 14040/14044



2 Goal and scope definition

2.1 Goal of the assessment

The goal of the assessment is to quantify the life cycle greenhouse gas (GHG) emissions (carbon footprint) along the bioenergy production and the CCS value chain over the lifetime of the project. The results of this assessment will be used to showcase the GHG emissions reduction reached by applying CCS to the bioenergy production system and to develop structured documentation for determination of net carbon removals through CCS.

The main intended audience of the study is carbon removal registries and potential buyers of carbon removal credits. The assessment is not intended to be used in comparative assertions with other value chains.

2.2 Scope of the assessment

2.2.1 Systems and functional units

Three different systems were assessed within this study:

1. Bioenergy system without CCS: Sandviksverket combined heat and power (CHP) plant without CCS (also called "Original CHP")
2. Bioenergy system without CCS: Sandviksverket combined heat and power (CHP) plant with CCS (also called "BECCS system")
3. CCS chain: the CCS project including the impacts on the bioenergy plant and on the energy delivered.

The function of the two first systems is to produce heat and electricity by burning biomass and to send the heat to the local district heating system and the electricity to the grid. The functional unit used in the LCA is 1 MWh of heat equivalent ($MWh_{heat\text{-}eq}$) exiting the plant.

The function of the third system is to capture, transport and store CO_2 from the bioenergy plant while still delivering the same amount of heat and electricity to the grid from the bioenergy plant. The functional unit used in the LCA is 1 ton of CO_2 stored.

2.2.2 Impact categories, indicators and methods

The environmental impact indicator assessed in the LCA is the Global Warming Potential at 100 years (henceforth "GWP"), which provides a common measurement unit for all GHG in kg of CO_2 equivalent. This indicator informs on the amount of energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of CO_2.[4] The IPCC 2021 impact method has been selected to compute the GWP indicator.[5] The assessment will provide results on the amount of CO_2 equivalent emitted per functional unit: $kgCO_2e$ / $MWh_{heat\text{-}eq}$ for systems 1 and 2 and tCO_2e / tCO_2 stored for system 3.

Other impacts were not assessed as part of this LCA as some of the input data are taken from results of previous LCAs only focusing on carbon footprint and for which the activity data cannot be accessed (*e.g.* for the storage part).

2.2.3 Allocation procedures

The CHP plant jointly produces heat and electricity. To allocate impacts between the two energy products and determine the total output as heat-equivalent, this study follows the rules set out by the Product Category Rules (PCR) for "Electricity, steam and hot/cold water generation and distribution".[6] The PCR specifies: "the environmental impacts connected to combined heat and power generation, are distributed between the two products – electricity and heat – in the same proportion as the fuel needed for separate electricity and heat generation processes." As shown by Figure 8, the combustion of biomass is first used to produce high-pressure steam with an energy efficiency of about 90%. The steam is fed into a turbine to produce electricity with an energy conversion efficiency of about 33%. All the energy carried by the steam that is not converted to electricity is recovered through a heat exchanger and sent to the district heating network (heat losses in the steam turbines are negligible). Therefore, the quantity of electricity output is converted to heat equivalent based on the conversion efficiency:

$$1\ MWh_{elec} = 1\ /\ 33\%\ MWh_{heat\text{-}eq} = 3.03\ MWh_{heat\text{-}eq}$$

The production of the Sandviksverket plant is primarily dictated by the local demand for district heating. Therefore, the implementation of CCS must not alter the heat output. However, as depicted in the energy balance on Figure 8, operating the capture and liquefaction system requires consuming some of the heat and electricity produced by the CHP plant. Consequently, the implementation of CCS causes an increase in the amount of biomass consumed in order to maintain the heat output. The electricity output to the grid, on the other hand, decreases with the implementation of CCS. Therefore, the allocation of impacts between heat and electricity differs between the system with and without CCS. The energy output in both cases, as well as the allocation factors are displayed in Table 1.

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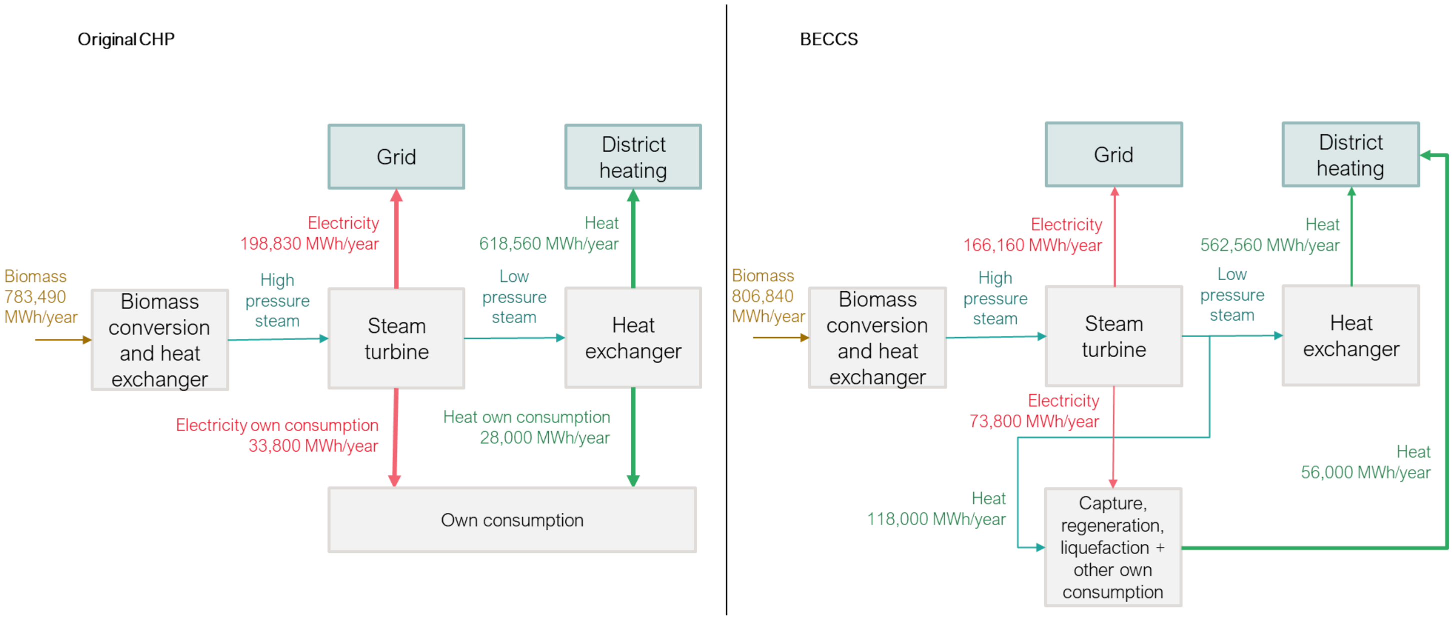
[4] United States Environmental Protection Agency, Understanding Global Warming Potentials, accessed October 2025, https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

[5] The Intergovernmental Panel on Climate Change by the United Nations regularly releases Assessment Reports containing emissions metrics for Global Warming Potential and Global Temperature Change Potential. These numbers are implemented in "IPCC" methods. More information about IPCC 2021 can be found in AR6 here.

[6] EPD International AB, *Electricity, steam and hot/cold water generation and distribution*, PCR 2007:08, version 5.0.1, last revision: 02/12/2024, valid until: 02/07/2028. https://www.environdec.com/pcr-library/pcr2007-08

Figure 8: Energy balance of the CHP plant before (left) and after (right) the implementation of CCS.



Note: the energy input in MWh appears lower than the total energy output. This is due to the convention that biomass input is quantified as Lower Heating value (LHV). However, the system being equipped with flue gas condensation, part of the energy contained in evaporated water is recovered, leading to a higher effective energy input.

Table 1: Energy output to the grid and district heating with and without CCS in heat equivalent

	Original CHP	BECCS system
Heat output to district heating [MWh_{heat}]	618,560.00	618,560.00
Electricity output to the grid [MWh_{elec}]	198,830.00	166,160.00
Heat output to district heating [$MWh_{heat\text{-}eq}$]	618,560.00	618,560.00
Electricity output to the grid [$MWh_{heat\text{-}eq}$]	602,515.15	503,515.15
Total energy output [$MWh_{heat\text{-}eq}$]	1,221,075.15	1,122,075.15
Impact allocation to heat	51%	55%
Impact allocation to electricity	49%	41%

2.2.4 Attributional and consequential modelling

The assessment of systems 1 and 2 (bioenergy system without and with CCS) follows an attributional modelling. This modelling principle “inventories the inputs and output flows of all processes of a system as they occur for a specified reference period based on historical data”. [7] The goal is to analyse the average operation of a system. In this case, the study gives a static view of bioenergy production in two configurations (without and with CCS) and answers the question “what is the carbon footprint of producing 1 MWh of

[7] EUCAR, Attributional vs. Consequential LCA Methodology Overview, Review and Recommendations with focus on Well-to-Tank and Well-to-Wheel Assessments, 2020, Study commissioned by EUCAR to IFP Energies Nouvelles and Sphera, https://horizoneuropencpportal.eu/sites/default/files/2024-05/eucar-lca-in-well-to-tank-and-well-to-well-2020.pdf

energy?". The results may typically be used to benchmark the impacts of bioenergy production against other means of production.

On the other hand, the assessment of system 3 (the CCS chain) follows a consequential approach. This modelling principle "aims at identifying the consequences that a decision in the foreground system has for other processes and systems of the economy, both in the analysed system's background system and on other systems".[5] The goal is to analyse the changes in operation. In this case, the study quantifies all the changes induced by the implementation of CCS. This includes: (i) all greenhouse gas (GHG) emissions due to adding the capture, transport and storage processes to the bioenergy chain, (ii) all GHG emissions due to increasing the input of biomass to the plant, (iii) all GHG emissions due to compensating the reduction in electricity production (as mentioned in the previous section). On the contrary, all emissions that were already occurring before implementation of the CCS project and that are not altered by the project are not accounted for in this system. This part of the study answers the question "what is the carbon footprint of implementing CCS on the existing bioenergy chain, per ton of CO_2 stored?".

2.3 System boundaries

The system boundaries cover the bioenergy value chain from biomass harvesting and transport to energy conversion and the CCS chain from capture to geological storage. The Sandviksverket CHP plant in Växjö burns branches, treetops and other harvesting residues mostly from the forests of Småland, Sweden, and supplies heat and power to the Växjö municipality. VEAB plans to install a carbon capture system on the cogeneration plant to capture 115,000 tCO_2 per year. After capture, CO_2 will be compressed, dehydrated, and liquefied before being temporarily stored in storage tanks at Sandviksverket. At this stage, the transportation route and storage site studied consist of the following:

1. CO_2 will be loaded on trains and transported to the Malmö port. VEAB is in contact with GreenCargo, a potential provider of train transportation.
2. At Malmö port, CO_2 will be transferred to temporary storage tanks and then loaded to ships. CO_2 coming from the VEAB facility will be gathered with CO_2 coming from other industrial sites in Sweden as part of the development of a CO_2 hub in Malmö, which may export about 650,000 tCO_2 per year in a first phase, and up to 2,000,000 tCO_2 per year in longer term.
3. CO_2 will be shipped to the Northern Lights storage site in Øygarden.
4. At the Øygarden terminal, CO_2 will be temporarily stored before being transported by pipeline and injected under the surface for permanent storage.

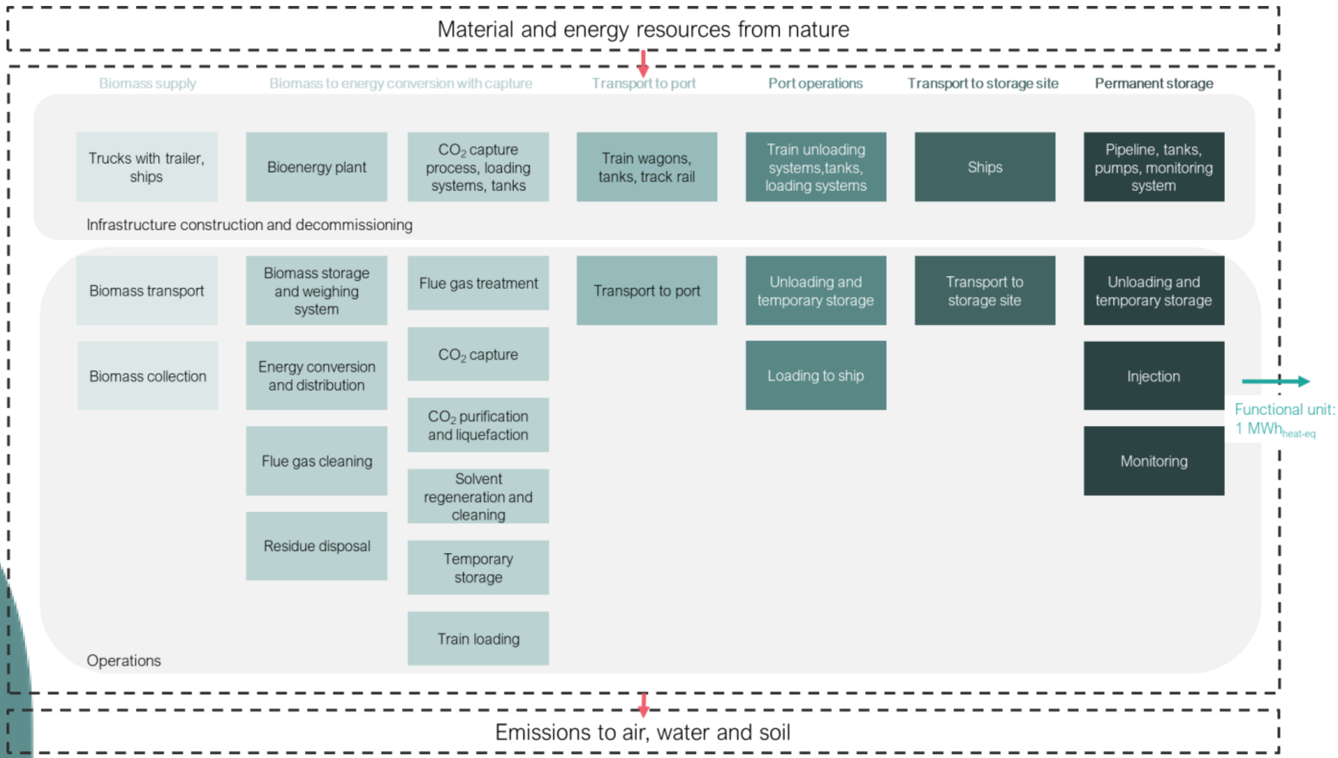
This LCA study is performed on a CCS chain where some elements are not firmly defined. Some conservative assumptions were made regarding the technologies and logistics involved in the chain. Based on the final CCS chain the results of this study may be refined at a later stage.

The heat and electricity used to operate the capture and liquefaction units will be provided by the bioenergy plant's own production. This energy consumed on site will lead to a decrease of the electricity sent to the grid, while there will be an increase in biomass intake to maintain the heat output.

The system boundaries for the bioenergy plant without CCS and the bioenergy plant with CCS are presented on Figure 9 and Figure 10 respectively. The system boundaries for the CCS chain are represented on Figure 11. As previously described, the system "CCS chain" aims at analysing all modifications brought to the bioenergy value chain due to the implementation of CCS. Therefore, for the processes that are already in place before the implementation of CCS, such as biomass supply and biomass-to-energy conversion, only the impacts due to the modification of those processes are accounted for.

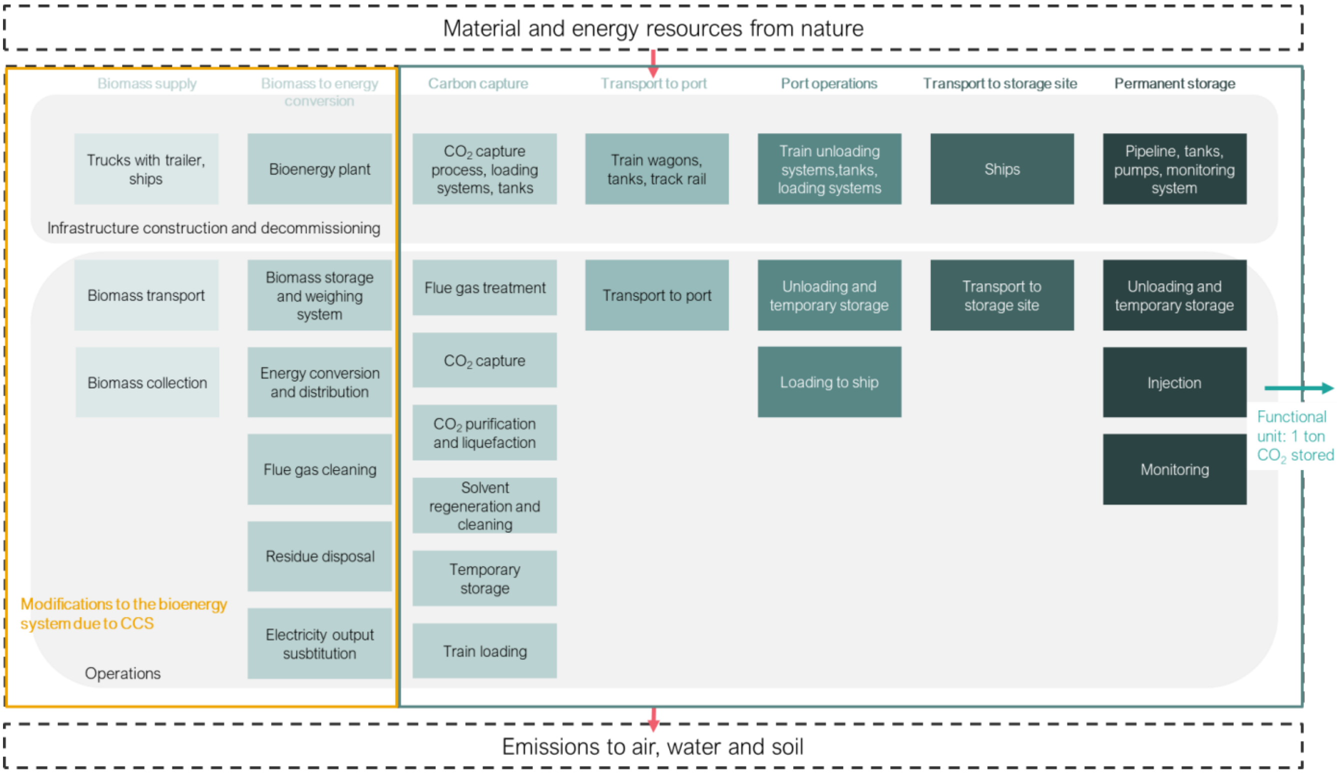
Figure 9: System boundaries – Original CHP plant

Figure 10: System boundaries – Bioenergy system with CCS



Informationsklassning: Intern

Figure 11: System boundaries – CCS chain



2.3.1 Biomass supply

The function of this process is to collect biomass and transport it to the Sandviksverket plant to supply energy production. This process includes biomass collection, with spreading of ashes in forest, and transportation from the collection points to the CHP plant.

All the biomass intake is composed of residual products such as:

- tops and branches/slash (residues from the forest industry)
- damaged wood in form of wood chips (residues from the forest industry)
- saw dust (residues from the wood industry)
- bark (residues from the wood industry and pulp and paper production)
- untreated wood chips (residues from the wood industry)

As a result, any environmental impacts associated with growing, harvesting, or processing biomass, prior to it becoming residues, are not included in the system boundaries

Most biomass is sourced from forests in Sweden. A small share is imported from European countries: from Norway and Latvia in 2023 and 2024. Transport from the biomass collection sites in Sweden to Växjö is done by trucks with a mix of diesel and biodiesel. For imported biomass, transport is done either by truck or by a combination of ship and truck.

Construction and end-of-life of trucks and ships are included in the system boundaries.

2.3.2 Biomass-to-energy conversion

The function of this process is to generate heat and electricity by burning biomass. This process starts with biomass entering the Sandviksverket plant and ends with energy exiting the plant (electricity sent to the grid and heat sent to a district heating network), and with combustion residues being sent to treatment. Activities included in this process are the temporary storage of biomass; the sorting, weighing and processing of biomass; the operation of furnaces, heat exchangers and steam turbines; the flue gas cleaning and the disposal of combustion residues. Construction and decommissioning of the CHP plant are included in the system boundaries.

When evaluating the carbon footprint of the CCS chain, the substitution of electricity output is also included in the system boundaries. It is assumed that the electricity demand remains the same and, therefore, the decrease in electricity output from the CHP must be compensated by an increase in supply from other sources.

2.3.3 Carbon capture and liquefaction

The function of this process is to capture CO_2 from the flue gas and liquefy it for transport. The process starts with part of the produced flue gas entering the capture unit and ends with liquid CO2 being loaded on trains. Activities included in this process are flue gas treatment; CO_2 capture with an amine-based solvent; amine regeneration; CO_2 compression, purification, and liquefaction (using a technology with ammonia as the cooling medium); CO_2 temporary storage; and loading into wagons. Construction and decommissioning of all equipment needed for those activities are included in the system boundaries.

2.3.4 Transport to port

The function of this process is to transport CO_2 to port. This process starts with liquid CO_2 being loaded on train wagons and ends with CO_2 being ready to be transferred to tanks at the Malmö port. Activities included in this process are transport of liquid CO_2 by electric-driven trains between Växjö and Malmö port, in the South of Sweden. Construction and end-of-life of the wagons and tracks are included in the system boundaries. Construction and end-of-life of the locomotives are excluded as it is assumed, from transport provider's information, that there are existing locomotives that have already been amortised.

2.3.5 Port operation

The function of this process is to temporarily store CO_2 and to load it into ships. The process starts with CO_2 unloading from the train wagons and loading into storage tanks and ends with CO_2 being loaded on ships. Activities included in this process are CO_2 unloading from wagons to tanks (pumps), temporary storage in tanks with cooling systems, and loading from tanks to ships (pumps). Construction and decommissioning of all equipment needed for those activities are included in the system boundaries.

2.3.6 Transport to storage site

The function of this process is transport liquid CO_2 from Malmö to the storage site in Øygarden, on the West coast of Norway. This process starts with CO_2 being loaded on ships and ends with CO_2 being ready for unloading from ships at the onshore terminal in Øygarden. Construction and decommissioning of the ships, as well as testing of the ship tanks, are included in the system boundaries.

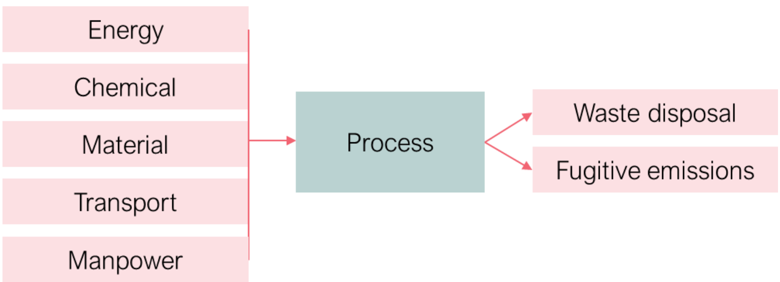
2.3.7 Geological storage

The function of this process is to permanently store CO_2 in a deep saline aquifer. This process starts with CO_2 being unloaded from ships at the Øygarden terminal and ends with CO_2 being stored under the seabed. Activities included in this process are unloading and temporary storage of liquid CO_2 in onshore tanks, injection of CO_2 in the aquifer and monitoring of the storage site during and post-injection. Construction and decommissioning of the equipment and infrastructure at the Northern Lights storage site are included in the system boundaries.

The carbon footprint of products is calculated by multiplying activity data by emission factors. Activity data quantify the physical flows linked to the production (*e.g.,* consumption of electricity), while emission factors correspond to the GWP associated with the physical flows, here expressed in $kgCO_2e$ / unit of activity data: $Carbon\ footprint\ = \sum Activity\ data\ \times\ Emission\ factor$

For each process, activity data and emission factors related to energy, chemical, material and transport requirements, as well as waste disposal, wastewater management and other direct emissions caused by the process were collected (Figure 12). System boundaries are "cradle-to gate" meaning that all upstream emissions linked to the inputs to the system are included.

Figure 12: Data collected per process



2.4 Data sources

For collection of activity data, information from technical documents and expert estimation was preferred whenever available. In case of missing data for key activities, assumptions were taken based on external data or best guess. The main data providers are:

- VEAB's databases and business models based on existing measurements for the "biomass supply" and "biomass-to-energy conversion" processes.
- Technology suppliers for the "carbon capture" process, based on pre-FEED studies.
- Transport provider (GreenCargo) for the "transport to port" process.
- Potential CO_2 hub operator at Malmö port for the "port operations" process.
- Northern Lights JV through their published carbon footprint report[8] for the "transport to storage site" and "geological storage" processes.

Levels of confidence in the input data were defined to model the level of uncertainty of the results obtained. The levels are defined as follows:

- High confidence: data from design documents
- Moderate confidence: data deduced from the design documents

[8] Gentile et al., *Carbon footprint of the Northern Lights JV CO2 transport and storage value chain*, 2023. Accessible at: https://norlights.com/wp-content/uploads/2023/11/Report-Carbon-footprint-of-the-Northern-Lights-JV-co2-transport-and-storage-value-chain.pdf

- Low confidence: guesstimates

The sources of information used for each activity data point, as well as the associated level of confidence are detailed in Section 2.

Emission factors for direct emissions from fuel consumption were taken from the International Maritime Organisation (IMO) Fourth GHG Study[9-10]. All other emission factors were taken from the ecoinvent 3.11 database. All emission factors have a high level of confidence.

2.5 Geography and time coverage

Input data were collected for the existing bioenergy plant at Sandviksverket ("biomass supply" and "biomass-to-energy conversion") and specifically for the prospective CCS chain between Växjö, Malmö and Øygarden. The most specific emission factors available in ecoinvent 3.11 were used (e.g., market for low-voltage electricity in Sweden). Whenever possible, the location where equipment is produced was identified and the most relevant emission factor was applied (*e.g.*, steel production in Europe). When not known, the emission factors for global average production were used. To account for transport of equipment to Växjö, "market" emission factors were used.[11] Specific information was provided by VEAB about location and process for the treatment of combustion residues. For all other waste flows coming out of the different processes, including flows modelling the end-of-life of equipment, market emission factors representing average treatment types per material were used.

Data providers communicated data based on the latest documentation available:

- Biomass supply: data records from 2022, 2023 and 2024
- Biomass-to-energy conversion: data records from 2022, 2023 and 2024
- Carbon capture and liquefaction: pre-FEED design documents available as of September 2025
- Transport to port: transport provider's estimates based on 2024 data records
- Port operation: port operator's estimates as of December 2025
- Transport to storage site and geological storage: carbon footprint report from 2023, based on data from 2022.

For the "biomass supply" and "biomass-to-energy conversion" processes, VEAB used data records from years 2022, 2023 and 2024 to derive normalised input and output data for normal operation years in the future. Based on records from previous years, some of the data was scaled up to account for the increase in biomass intake, while some other data points do not vary with the quantity of biomass intake.

The results are applicable for the entirety of the project's lifetime (25 years) as long as there is no major change in operating conditions and no mishap occurs. In particular, the assessment relies on the assumptions that:

- The electricity mix does not change during the lifetime of the project.
- The fuel mixes used for transport do not change during the lifetime of the project.
- The requirements for decommissioning equipment and infrastructure at the end-of-life of the project are similar as in 2025 conditions.

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[9] International Maritime Organization, *Fourth IMO Greenhouse Gas Study*, 2020. Accessible at: https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

[10] Values from the IMO report were used for both maritime and land transport. Indeed, the emission factors for diesel and LNG combustion are similar to the ones published by IPCC (2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy, Chapter 3: Mobile combustion). The values from IMO fall within the range of values given in the IPCC report and are more conservative (+1% to +8%) than the default values from IPCC.

[11] "A market activity represents the consumption mix of a product for a given region, accounting for the trade between the producer and consumer, and, when needed, for product losses that occur during the product's transportation". ecoinvent website, Last accessed: 6.11.2025. https://support.ecoinvent.org/market-activities

2.6 Cut-off criteria

If appropriate data were available, they were included in the LCA. If not, then conservative assumptions were made, and documented. In LCA, cut-off criteria refer to the omission of non-relevant life cycle stages, activity types, specific processes and products and elementary flows from the system model. However, it is difficult to set cut-off criteria beforehand, as one must know the result of the LCA to be able to know which processes, elementary flows etc. that can be left out. This paradox is solved through iterative processes. Cut-off criteria can be based on:

(1) Mass (all inputs that cumulatively contribute more than a defined percentage to the mass input of the product system being modelled)
(2) Energy (all inputs that cumulatively contribute more than a defined percentage of the product system's energy inputs)
(3) Environmental significance.

The following assumptions were made in this analysis:

- Mass cut-off criteria:
  - Construction and decommissioning (all processes): the assessment was limited to the equipment identified as significant by the data providers filling out the data collection templates (e.g. representing a large mass of steel).
- Environmental significance cut-off:
  - Manpower (all processes): emissions associated with commuting (during operation as well as construction) are considered negligible compared to the transport of biomass.
  - Construction and decommissioning (all processes): it is assumed that the assembly and the installation steps are significantly less energy intensive than the production of the material itself. Therefore, emissions associated with the production of a piece of equipment (*e.g.*, an absorption column) are assumed equal to the emissions associated with the production of the material composing that piece of equipment (*e.g.*, steel).

3 Life cycle inventory

This chapter discusses the input data used in the life cycle assessment.

3.1 General data requirements

All emission factors used in the model (cement production, steel, different fuels, chemicals etc.) are based on emission factors available as of October 2025. No assumption was made regarding potential evolution regarding the production of certain inputs during the lifetime of the project.

Data was provided as yearly values, for a typical operation year in the future between 2026 and 2050. Results were then normalised per $MWh_{heat\text{-}eq}$ produced and per tCO_2 stored.

In the following sections, main inputs per steps and their references are described. The complete inventory (available in Annex A), used for calculations in the tool, could be made available to a verifier but is not disclosed in the core of this report due to confidentiality reasons.

3.2 Biomass supply

3.2.1 Biomass collection

As the biomass used by VEAB is residues from the wood and forest industry, fuel consumption due to collecting the primary wood products (eg, trunks) and transporting it to the processing factory (eg, sawmills) is out of scope. Branches and treetops are collected from the ground as part of normal wood collection process. Following cutoff rules, impacts from local transport of residues are allocated to the wood products and are therefore out of scope. VEAB however provided information about fuel consumption used during ash spreading in the forest, which acts as a fertiliser. The upstream emissions due to the procurement of biodiesel are derived from the emissions reported by the supplier of bio-based heavy fuel oil to Sandviksverket, in its 2023 sustainability declarations.[12] Type of activity data, their associated confidence level, the reference for the data and emission factors are summarised in Table 2.

Table 2: Type of activity data and emission factors used for biomass collection

Flow	Sub-flow – activity data	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Energy	Diesel used for ash spreading	Moderate	Biomass supplier	market for diesel | diesel | Cutoff, S - Europe without Switzerland
Energy	Biodiesel used for ash spreading			Emission factor derived from Heavy Fuel Oil supplier's 2023 sustainability declaration (proxy)

3.2.2 Biomass transport

VEAB provided data from their biomass deliveries database for the tonnage sent to the bioenergy plant in 2022, 2023 and 2024. Data records detail for each supplier the type of biomass, the yearly tonnage, the number of deliveries, the transport distance, the means of transportation and the type of fuel (with the share of fossil-based and bio-based fuel). The upstream emissions due to the procurement of biodiesel are derived from the emissions reported by the supplier of bio-based heavy fuel oil to Sandviksverket, in its 2023 sustainability declarations.[12] Type of activity data, their associated confidence level, the reference for the data and emission factors are summarised in Table 3.

Table 3: Type of activity data and emission factors used for biomass transport

Flow	Sub-flow – activity data	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Transport	Biomass transported by truck - diesel	High	VEAB's data records for 2022, 2023 and 2024. Average values.	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, S - RER
Transport	Biomass transported by truck - biodiesel			Emission factor derived from Heavy Fuel Oil supplier's 2023 sustainability declaration (proxy)
Transport	Biomass transported by ship			market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, S - GLO

[12] The upstream emissions for biodiesel are very dependent on the type of feedstock used for biodiesel production and are therefore location dependent. Consequently, the emissions associated with the bio-based heavy fuel oil supplied to Sandviksverket are deemed to be a better proxy for the emissions associated with biodiesel in Sweden and Northern Europe, than the global average emission factor "market for fatty acid methyl ester" in ecoinvent 3.11.

3.3 Biomass-to-energy conversion

3.3.1 Construction and decommissioning

The lifetime of the plant is assumed to be 40 years, based on VEAB's estimate. No data on input required for construction of the plant was available. As such, the global emission factor available in ecoinvent 3.11 to represent the construction of a gas power plant was used as a proxy: "gas power plant construction, 100MW electrical | gas power plant, 100MW electrical | Cutoff, S – RER". This emission factor represents an average 100 MW gas power plant in Europe, assuming 180,000-hour lifetime. The decommissioning of the plant was estimated by adding waste flows corresponding to the materials used as inputs to the ecoinvent process.

3.3.2 Operation

VEAB provided data for all inflows and outflows for a typical operation year, based on historical data. In addition to biogenic CO_2 emissions due to combustion, VEAB provided estimates for other GHG emissions, based on their Emissions Trading System (ETS) reporting. All fuels used locally are bio-based. The upstream emissions due to the procurement of bio-based heavy fuel oil are based on the sustainability declaration of the supplier for the year 2023. VEAB also provided estimates for the mass of different combustion residues, the type of treatment they are sent to, and the distance to the corresponding treatment location. Type of activity data, their associated confidence level, the reference for the data and emission factors are summarised in Table 4.

Table 4: Type of activity data and emission factors used for operation of the CHP plant

Flow	Sub-flow – activity data	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Energy	Heating oil – bio-based	High	VEAB's records: Measurement, internal transportation of biomass + invoices, from chipping of fuel logs	Emission factor derived from Heavy Fuel Oil supplier's 2023 sustainability declaration.
Chemical	Ammonia 24.5%	High	VEAB's measurements (2022, 2023, 2024)	market for ammonia, anhydrous, liquid | ammonia, anhydrous, liquid | Cutoff, S - RER
Chemical	Ammonium sulphate 40%			market for ammonium sulphtae | ammonium sulphate | Cutoff, S - RER
Chemical	Sodium chloride			market for sodium chloride, powder | sodium chloride, powder | Cutoff, S - GLO
Chemical	Tap water			market for tap water | tap water | Cutoff, S - Europe without Switzerland
Chemical	Sodium hydroxide 25%			market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, S - RER
Chemical	Sulphur granules			market for sulphur | sulphur | Cutoff, S - GLO
Chemical	Hydrochloric acid 34%			market for hydrochloric acid, without water, in 30% solution state | hydrochloric acid, without water, in 30% solution state | Cutoff, S - RER

Material	Steel for maintenance	Moderate	VEAB's records from the project department	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Cutoff, S - GLO
Material	Sand	High	VEAB's measurements	market for sand | sand | Cutoff, S - RoW
Direct emissions	Biogenic CO_2	Moderate	VEAB's calculations based on emission factors from the Swedish environmental protection agency used in EU ETS.	Characterisation factor from IPCC 2021
Direct emissions	Refrigerants (R410A, R407c and R32)	High	Leakage from cooling machines, measured by a certified personal.	Characterisation factors of the different components (R32, R125 and R134a) provided by The Swedish Environmental agency.
Direct emissions	Nitrous oxide (N_2O)	High	VEAB's measurement in the flue gas.	Characterisation factor from IPCC 2021
Waste	Fly ash treatment – spread in forest[13]	High	VEAB's measurements (2022, 2023, 2024)	market for transport, freight, lorry 28 metric ton, fatty acid methyl ester 100% | transport, freight, lorry 28 metric ton, fatty acid methyl ester 100% | Cutoff, S - RoW
Waste	Bottom ash – used for construction material			treatment of bottom ash, MSWI-WWT-SLF, wood ash mixture, pure, slag compartment | bottom ash, MSWI-WWT-SLF, wood ash mixture, pure | Cutoff, S - Europe without Switzerland
Waste	Cleaned wastewater – to municipal wastewater treatment			treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, S - Europe without Switzerland
Waste	Metals – to recycling	High	Data from waste transport and treatment company (2022, 2023, 2024)	market for ferrous metal, in mixed metal scrap | ferrous metal, in mixed metal scrap | Cutoff, S - Europe without Switzerland
Waste	Paper – to recycling			treatment of waste paper, unsorted, sorting | waste paper, sorted | Cutoff, S - Europe without Switzerland
Waste	Mixed waste – to landfill			treatment of municipal solid waste, sanitary landfill | municipal solid waste | Cutoff, S - SE
Waste	Mixed waste – to energy production			treatment of municipal solid waste, municipal incineration | municipal solid waste | Cutoff, S - SE
Waste	Hazardous waste[14] – to recycling			treatment of waste emulsion paint on wall, sorting plant | waste emulsion paint, on wall | Cutoff, S – RoW

[13] The input in this process corresponds to the transport from Växjö to the location where ash is spread, while diesel consumption the "biomass collection" process corresponds to local transport while on site. There is therefore no double counting, and both are in scope since the impacts of waste treatment (here ash spreading) should be allocated to the activity generating the waste (here bioenergy production).
[14] VEAB provided a detailed inventory of the hazardous waste for year 2024. The main components were oils and oil-contaminated waste (which treatment in approximated by the treatment of paint) and electronic waste.

				market for electronics scrap | electronics scrap | Cutoff, S - GLO
Waste	Hazardous waste – to energy production			treatment of hazardous waste, hazardous waste incineration | hazardous waste, for incineration | Cutoff, S - Europe without Switzerland
Waste	Polluted water – to recycling			treatment of sewage sludge, 70% water, WWT, WW, average, municipal incineration | sewage sludge, 70% water, WWT, WW, average | Cutoff, S - Europe without Switzerland
Transport	Waste transport by truck - biodiesel			Emission factor derived from Heavy Fuel Oil supplier's 2023 sustainability declaration (proxy)

3.3.3 Electricity substitution

As presented in section 2.2.3, the implementation of CCS on the biomass-to-energy conversion system leads to a decrease of the electricity output from the plant. The consequential modelling thus includes an impact from "market leakage": assuming that the electricity demand remains the same, the decrease in energy output must be compensated by an increase from another production mean.

To quantify this impact, the difference in electricity output between the system with and without CCS is deduced from the energy balances communicated by VEAB (see Figure 8). As it is not possible to identify a specific source of electricity that would replace the decreased output of the CHP plant, it is assumed that the electricity supply would be provided following the average consumption mix in Sweden. The corresponding emission factor is shown in Table 5. A sensitivity analysis on this emission factor to use for the substituted electricity is presented in section 4.3.1.

Table 5: Activity data and emission factors used for the substitution of electricity – for 1 year

Flow	Sub-flow – activity data	Activity data	Unit	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Energy	Electricity substitution	32,670	MWh	High	VEAB's energy balances	market for electricity, low voltage | electricity, medium voltage | Cutoff, S SE

3.4 Carbon capture

VEAB provided information regarding the CO_2 capture, purification, liquefaction and storage units, based on studies, at pre-FEED level, carried out previously.

3.4.1 Construction and decommissioning

At this stage, the only data available to represent the construction of the capture and liquefaction units and storage tanks are the materials used in construction of these units. The lifetime of the CCS chain is estimated to 25 years. Type of activity data, their associated confidence level, the reference for the data and emission factors are summarised in Table 6.

Table 6: Type of activity data and emission factors used for construction and decommissioning of the carbon capture system

Flow	Sub-flow – activity data	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Material	Steel	Moderate	Data from technology provider (pre-FEED report)	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Cutoff, S
Material	Stainless steel			market for steel, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | Cutoff, S - GLO
Material	Concrete			market for concrete, normal strength | concrete, normal strength | Cutoff, S - RoW
Waste	Steel - decommissioning			market for waste steel | waste steel | Cutoff, S - Europe without Switzerland
Waste	Concrete - decommissioning			market for waste concrete | waste concrete | Cutoff, S - Europe without Switzerland

3.4.2 Operation

The energy required for the capture and liquefaction process comes from VEAB's own production. Therefore, the energy requirement of the capture unit does not show as an input to the system but materialises as a reduction of the energy output from the CHP. Type of activity data, their associated confidence level, the reference for the data and emission factors are summarised in Table 7.

Table 7: Type of activity data and emission factors used for capture, liquefaction and storage tanks operation

Flow	Sub-flow – activity data	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Chemical	Amine solution	Moderate	Data from technology provider (pre-FEED report)	market for monoethanolamine | monoethanolamine | Cutoff, S - GLO
Chemical	Sodium hydroxide	Moderate		market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, S - RER
Chemical	Desiccant	High		market for activated carbon, granular | activated carbon, granular | Cutoff, S - GLO
Waste	Amine solution waste – hazardous waste destruction	Moderate		treatment of hazardous waste, hazardous waste incineration | hazardous waste, for incineration | Cutoff, S - Europe without Switzerland
Waste	Desiccant waste – waste destruction	High		treatment of municipal solid waste, municipal incineration | municipal solid waste | Cutoff, S - RU
Transport	Waste transport by truck - biodiesel	Moderate	VEAB's estimation	Emission factor derived from Heavy Fuel Oil supplier's 2023 sustainability declaration (proxy)

3.5 Transport to port

VEAB provided estimates for the transport of liquid CO_2 by train to Malmö port, based on information provided by a potential transport provider.

3.5.1 Construction and decommissioning

At this stage, the only data available to represent the construction of the trains and railway tracks are the materials used in construction of this equipment. The Sandviksverket plant will be connected to an existing railway connecting Växjö to Malmö. Only the new portion of the track, which distance has been estimated by VEAB, is accounted for. Type of activity data, their associated confidence level, the reference for the data and emission factors are summarised in Table 8.

Table 8: Type of activity data and emission factors used for construction and decommissioning of equipment for transport to the port

Flow	Sub-flow – activity data	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Material	Wagons - steel	Moderate	Transport provider	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Cutoff, S
Material	Wagons – stainless steel			market for steel, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | Cutoff, S - GLO
Material	Train tracks	Moderate	VEAB preliminary design	market for railway track | railway track | Cutoff, S - GLO
Waste	Wagons - decommissioning	Moderate	Transport provider	market for waste steel | waste steel | Cutoff, S - Europe without Switzerland

3.5.2 Operation

The trains will be driven by electric locomotives. The potential transport provider GreenCargo publishes the average GHG emissions, and the average electricity consumption associated with its operations across Scandinavia in its sustainability report.[15] The average GHG emissions per tkm was used to estimate the carbon footprint of this process in the reference case, and the average electricity consumption per tkm was used to carry out sensitivity analysis (see section 4.3.3). The factors per tkm were multiplied by the quantity of CO_2 captured and by the distance from Växjö to Malmö. Type of activity data, their associated confidence level, the reference for the data and emission factors are summarised in Table 9.

Table 9: Type of activity data and emission factors used for transport to the port operation

Flow	Sub-flow – activity data	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Energy	Electricity from the grid	Moderate	GreenCargo sustainability report 2024.	market for electricity, low voltage | electricity, medium voltage | Cutoff, S SE
GHG emissions	Total life-cycle emissions			Emission factor provided by GreenCargo

3.6 Port operation

Information about the Malmö port was provided by the operator of the future CO_2 hub in Malmö. The development of the hub is planned in two phases, with initial volumes about 650 ktpa and longer-term volumes estimated at about 2,000 ktpa. Communicated data correspond to the first phase.

3.6.1 Construction and decommissioning

The port operator communicated the number and size of the tanks expected at the Malmö port. From this input, Carbon Limits estimated the quantity of steel and concrete needed. The lifetime of the CCS project is

[15] GreenCargo, Annual and Sustainability report, 2024, https://www.greencargo.com/download/18.353d0e57195b2509ef1c4d11/1743149811984/Green%20Cargo%20%C3%A5rs-%20och%20h%C3%A5llbarhetsredovisning%202024.pdf

estimated to 25 years. Type of activity data, their associated confidence level, the reference for the data and emission factors are summarised in Table 10.

Table 10: Type of activity data and emission factors used for construction and decommissioning of the port equipment

Flow	Sub-flow – activity data	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Material	Steel	Low	Carbon Limits from port operator's estimates	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Cutoff, S - GLO
Material	Concrete			market for concrete, normal strength | concrete, normal strength | Cutoff, S - RoW
Waste	Steel - decommissioning			market for waste steel | waste steel | Cutoff, S - Europe without Switzerland
Waste	Concrete - decommissioning			market for waste concrete | waste concrete | Cutoff, S - Europe without Switzerland

3.6.2 Operation

The port operator communicated the approximate electricity consumption required for the pumping and cooling of the tanks. The port operator also provided an estimate for the maximum expected CO_2 losses due to leakage. To be conservative that maximum value was used as the estimate for yearly leakages. Type of activity data, their associated confidence level, the reference for the data and emission factors are summarised in Table 11.

Table 11: Type of activity data and emission factors used for port operations

Flow	Sub-flow – activity data	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Energy	Electricity from the grid (for all operations)	Low	Port operator's estimates	market for electricity, low voltage | electricity, medium voltage | Cutoff, S SE
Direct emissions	CO_2 losses			Characterisation factor from IPCC 2021

3.7 Transport to Northern Lights facility in Øygarden and temporary and permanent storage

It is assumed that, once loaded on ships, CO_2 will be transported to the Northern Lights (NL) storage site in Øygarden. Northern Lights JV performed in 2022 a carbon footprint of their value chain including transport by ship to permanent storage in the Norwegian North Sea. A paper documenting this footprint is available online.[16] The results of the carbon footprint assessment are presented in Table 12 below for 127.8 Megatons of CO_2 stored.

Table 12: Results of Northern Lights carbon footprint – as of 2022

Activity	Phase	Process	Total emissions (tCO2e)
Transport	Construction	Mobile vehicles for construction	2,682
		Grid electricity purchases	22,054
		Heat purchases	17,259

[16] Northern Lights, *Carbon footprint of the Northern Lights JV CO_2 transport and storage value chain*, 2022 https://norlights.com/wp-content/uploads/2023/11/Report-Carbon-footprint-of-the-Northern-Lights-JV-co2-transport-and-storage-value-chain.pdf

		Equipment / material	152,946
		Other process emissions	9,720
		Ship delivery	19,781
		Wastewater treatment	0.12
		Waste disposal	16,088
	Operation	Chemicals and utilities	3,409
		Grid electricity purchases	5,492
		Ship fuel consumption	2,638,032
		Other process emissions	124,638
	Decommissioning	Waste disposal	16,129
Storage activities	Construction	Preparation of the site	4,028
		Building/road construction	2,416
		Equipment / material	64,469
		Chemicals and utilities	978
		Use of vessels	75,741
	Operation	Chemicals and utilities	119
		Grid electricity purchases	48,329
		Other process emissions	14,848
		Injection - use of vessels	33,065
		Post-injection - use of vessels	4,406
	Decommissioning	Waste disposal	2,162
		Use of vessels	32,507

Source: Northern Lights, Carbon footprint of the Northern Lights JV CO_2 transport and storage value chain, 2022

The total emissions by phase were divided by the total amount of CO_2 stored during the NL project to derive emissions per ton stored. Those numbers were applied to the amount of CO_2 stored by the VEAB CCS value chain, as determined in section 3.8, and inputted to the model.

Carbon Limits recalculated emissions from the "other process emissions" in the transport and in the storage activities to account for the fact that the CO_2 from VEAB is biogenic. Indeed, a large part of the "other process emissions" correspond to emissions of CO_2 that is meant to be stored but is leaked or vented due to operational conditions. For the "other process emissions" in the storage activity, it is assumed that 100% of the emissions correspond to CO_2 leaks or vents. Carbon Limits therefore modelled a flow of biogenic CO_2. The "other process emissions" in the transport activity include both CO_2 leaks and vents as well as a methane slip due to incomplete combustion of liquefied natural gas (LNG) in the ship engines. As a reference case, it is assumed that 50% of the impact (in tCO2e) comes from CO_2 leaks and vents, and 50% comes from methane slip. A sensitivity analysis on this assumption is presented in section 4.3.4.

All estimates derived from the NL carbon footprint have a moderate level of confidence because (i) the LCA of the NL project was a prospective study based on design documents, (ii) the results are not specific to the shipping route between Malmö and Øygarden (see discussion in section 4.3.2). It can be noted that NL JV plans to update their carbon footprint assessment with refined fuel consumption estimates based on actual shipping operations.

3.8 Quantity of CO_2 stored

The quantity of CO_2 stored is calculated from the quantity of CO_2 captured, for which the capture system is sized, by deducting CO_2 losses along the CCS chain, as depicted in Figure 13:

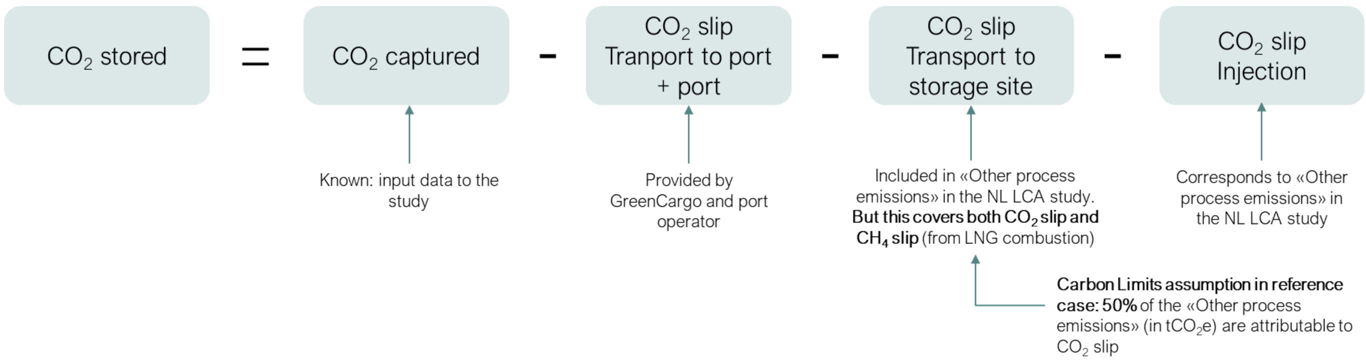
- The capture system is sized to capture 115,000 tCO_2 per year.

- CO_2 slip during transport to port are negligible as per the information provided by the transport provider
- CO_2 slip at port is estimated at 0.00001 tCO_2 / tCO_2 processed as per the maximum value communicated by the port operator
- Based on the assumption taken in section 3.7, CO_2 slip during transport to the storage site is equal to $50\% \times 124{,}638/(127.8 \times 10^6) = 0.00049$ tCO_2 / tCO_2 stored
- Based on the assumption taken in section 3.7, CO_2 slip during storage is equal to $100\% \times 14{,}848/(127.8 \times 10^6) = 0.00012$ tCO_2 / tCO_2 stored

Therefore, the quantity of CO_2 stored yearly is:

$$CO_{2,\ stored} = \frac{115{,}000 \times (1 - 0.00001)}{(1 + 0.00049 + 0.00012)} = \mathbf{114,929\ tCO_2}$$

Figure 13: Calculation of the quantity of CO_2 stored



4 Impact assessment and results interpretation

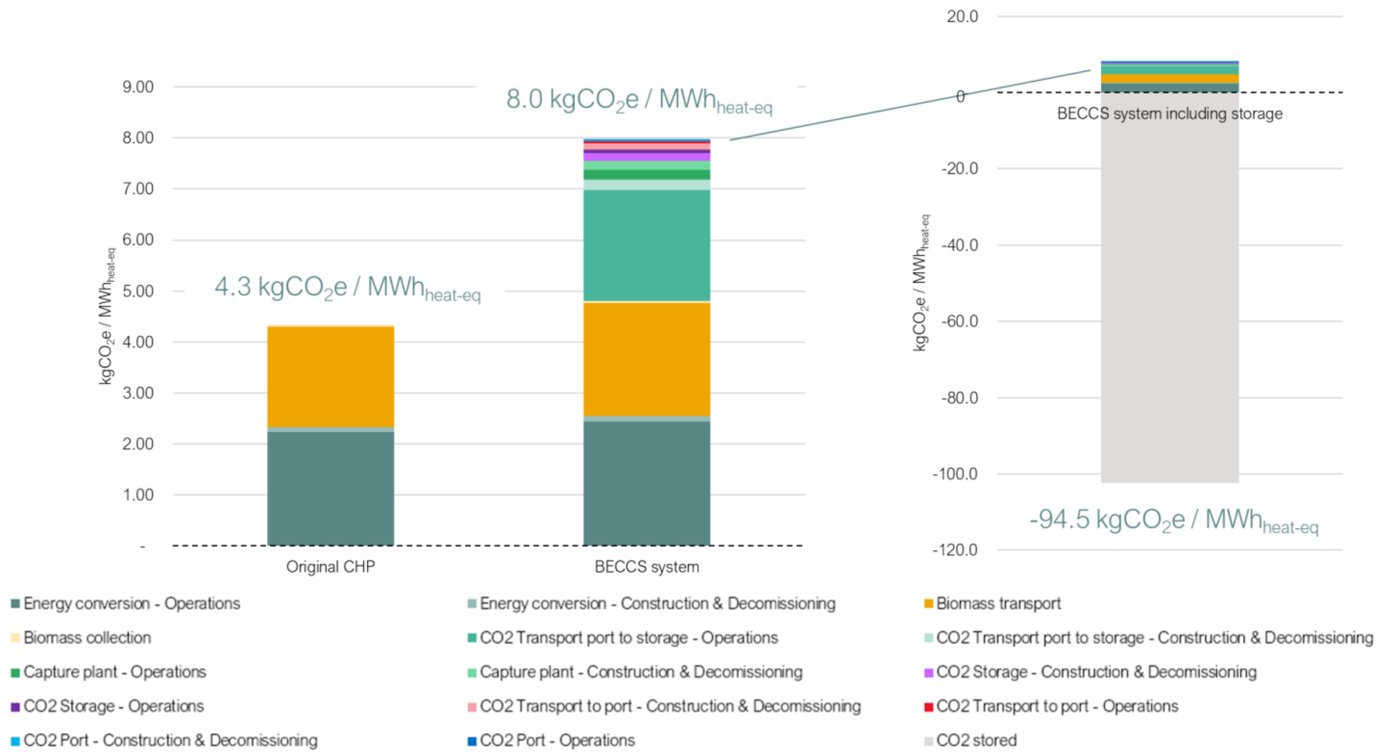
Carbon Limits modelled the systems and inputted all presented activity data in OpenLCA. This section presents the results obtained. An overview of the systems modelled are available in Annex B.

4.1 Systems 1 and 2: Original CHP and BECCS system – functional unit: 1 $MWh_{heat-eq}$

4.1.1 Results

The total GWP of the original CHP without CCS is 4.3 $kgCO_2e$ / $MWh_{heat-eq}$. About half of the carbon footprint (52%) is due to the operation of the biomass-to-energy conversion system. Transport of biomass represents most of the rest of the impact (45%). The construction and decommissioning of the CHP plant and the biomass collection process respectively represent 2% and 1% of the total impact. The split of GWP contributions per process is represented on the left-hand side of Figure 14.

Figure 14: GWP of the original CHP (left), BECCS system without accounting for CO_2 stored (center), and BECCS system with discount of CO_2 stored (right) – per 1 $MWh_{heat-eq}$

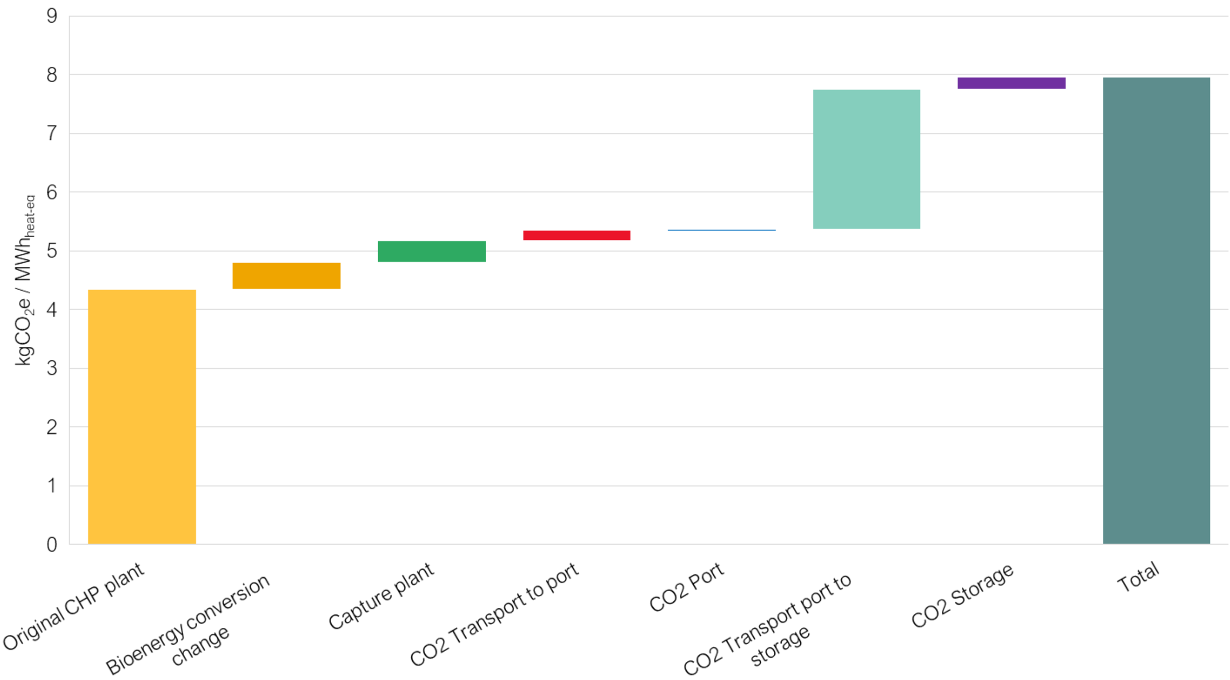


The total GWP of the BECCS system is 8.0 $kgCO_2e$ / $MWh_{heat-eq}$ before accounting for the negative contribution due to storing biogenic CO_2. The main contributors are the operation of the biomass-to-energy conversion system (31%), biomass transport (28%) and CO_2 shipping to storage site (27%). The construction and decommissioning of the ships, the construction and decommissioning of the capture and liquefaction unit, the operation of the capture and liquefaction unit, and the construction and decommissioning of the train and tracks for transport to port each represent between 2 and 3% of the total carbon footprint. The split of GWP contributions per process is represented in the middle bar of Figure 14.

When accounting for the negative contribution due to the permanent storage of biogenic CO_2, as represented on the right-hand side of Figure 14, the total GWP of the BECCS system is -94.5 $kgCO_2e$ / $MWh_{heat-eq}$.

Figure 15 depicts how the GWP of the bioenergy system is impacted by the implementation of the CCS chain, before accounting for stored biogenic CO_2. Due to the increase in biomass intake and the reduction of energy output, the implementation of CCS leads to an increase by 0.5 $kgCO_2e$ / $MWh_{heat-eq}$ in the carbon footprint of the bioenergy value chain (biomass supply and biomass-to-energy conversion). The capture plant, the CO_2 transport to port and the port processes respectively add 0.4, 0.2 and 0.03 $kgCO_2e$ / $MWh_{heat-eq}$. Finally, the CO_2 shipping and CO_2 storage processes respectively add 2.4 and 0.2 $kgCO_2e$ / $MWh_{heat-eq}$.

Figure 15: Waterfall diagram: impact of the CCS chain on the carbon footprint of the bioenergy system



GWP impacts can be allocated between heat and electricity, following the allocation factors presented in section 2.2.3, to derive separate carbon footprint for electricity sent to grid and heat sent to district heating. Table 13 details the GWP results for the original CHP and the BECCS system for the different energy products.

Table 13: Summary of the results for GWP of the original CHP and the BECCS system

Energy products	Unit	Original CHP	BECCS system – before accounting for CO_2 storage	BECCS system – after accounting for CO_2 storage
Output energy	$kgCO_2e$ / $MWh_{heat-eq}$	4.3	8.0	-94.5
Output heat	$kgCO_2e$ / MWh_{heat}	4.3	8.0	-94.5
Output electricity	$kgCO_2e$ / MWh_{elec}	13.2	24.1	-286.3

4.1.2 Confidence level of the main contributors

Table 14 and Table 15 detail the main contributors to the carbon footprint of the original CHP and the BECCS system. In this section, the main contributors are defined as the individual sub-processes that cumulatively represent at least 80% of the total GWP or individually represent at least 5% of the total GWP. The source of the activity data used for each main contributor is described in the last column.

The main contributor is the direct emissions during the CHP operations, which represent 41% of the total carbon footprint. In particular, nitrous oxide emissions (N_2O) make up more than 99% of these emissions (in $kgCO_2e$).. The supply of ammonia represents 6% of the total carbon footprint. Within the biomass transport process, 61% of the impacts come from transport by trucks running on diesel. The transport by diesel-fuelled trucks, by biodiesel-fuelled trucks and by ships respectively represents 28%, 10% and 8% of the total carbon footprint. The activity data underlying all those impacts comes from measurements and data records from previous years. The associated confidence level is estimated to be high.

Table 14: Source of the activity data for the main contributors to the GWP of the original CHP

Step	Phase	Contributor	Contribution	Source of the data	Confidence level
Biomass-to-energy conversion	Operation	Direct emissions of N_2O	41%	VEAB's measurement in the flue gas.	High
Biomass supply	Operation	Transport by diesel truck	28%	VEAB's data records for 2022, 2023 and 2024. Average values.	High
Biomass supply	Operation	Transport by biodiesel truck	10%	VEAB's data records for 2022, 2023 and 2024. Average values.	High
Biomass supply	Operation	Transport by ships	8%	VEAB's data records for 2022, 2023 and 2024. Average values.	High
Biomass-to-energy conversion	Operation	Ammonia supply	6%	VEAB's measurements (2022, 2023, 2024)	High

For the BECCS system, the main contributor is ship fuel consumption during CO_2 transport to storage site (26% of the total GWP). The corresponding input data has a moderate level of confidence as it is directly taken from the results of the NL carbon footprint. As for the original CHP, all other major contributors have a high level of confidence. It can be noted that the amount of CO_2 captured is a major parameter in the calculation of net carbon footprint (when accounting for CO_2 stored) and is associated with a moderate level of confidence.

Table 15: Source of the activity data for the main contributors to the GWP of the BECSS system

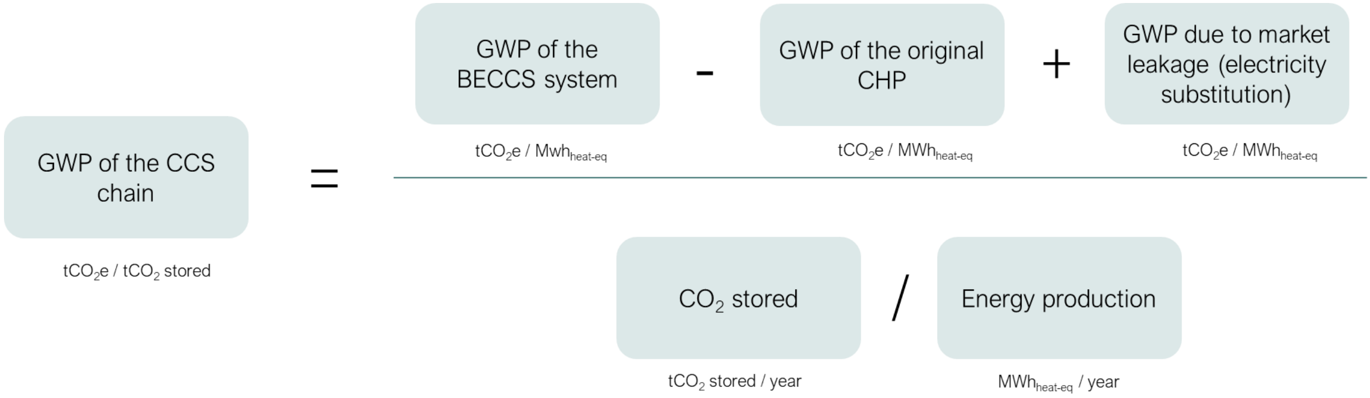
Step	Phase	Contributor	Contribution	Source of the data	Confidence level
Transport to storage site	Operation	Ship fuel consumption	26%	NL carbon footprint report, 2022	Moderate
Biomass-to-energy conversion	Operation	Direct emissions of N_2O	24%	VEAB's measurement in the flue gas.	High
Biomass supply	Operation	Transport by diesel truck	17%	VEAB's data records for 2022, 2023 and 2024. Average values.	High
Biomass supply	Operation	Transport by biodiesel truck	6%	VEAB's data records for 2022, 2023 and 2024. Average values.	High
Biomass supply	Operation	Transport by ships	5%	VEAB's data records for 2022, 2023 and 2024. Average values.	High
Biomass-to-energy conversion	Operation	Ammonia supply	3%	VEAB's measurements (2022, 2023, 2024)	High
Capture	Operation	CO_2 captured	-	VEAB's calculations based on emission factors from the Swedish environmental protection agency used in EU ETS.	Moderate

4.2 System 3: CCS chain – functional unit: 1 tCO_2 stored

4.2.1 Results

The consequential model for the CCS chain can be derived from the two attributional models by adding the impact of market leakage (electricity substitution) as depicted in Figure 16.

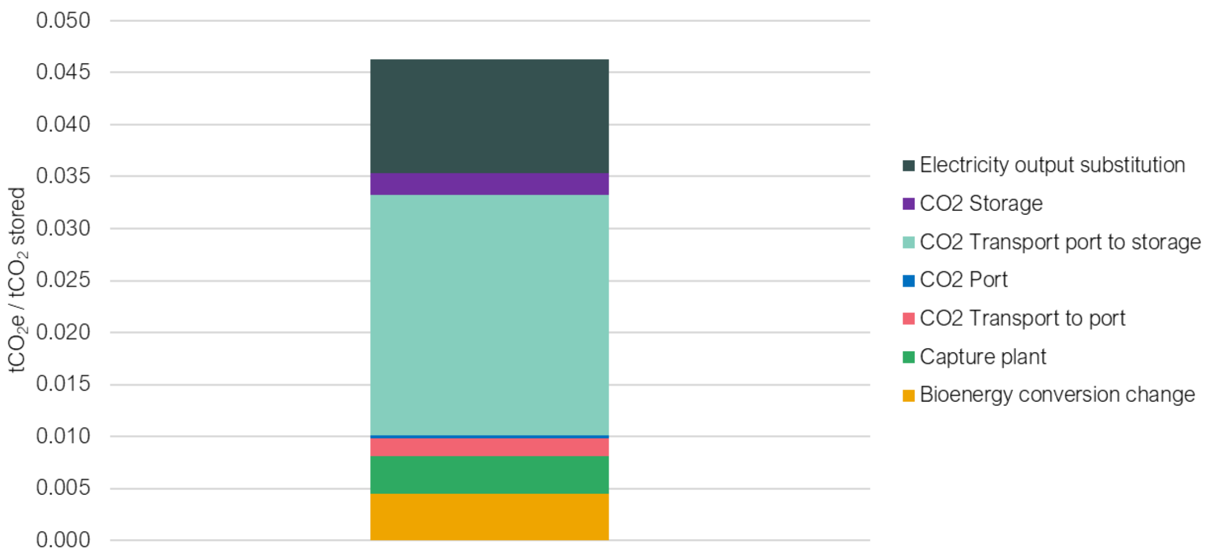
Figure 16: Relation between the consequential model for system 3 and the attributional models for systems 1 and 2



The total GWP of the CCS chain is 0.046 tCO_2e / tCO_2 stored. This means the GWP impacts caused by the implementation of CCS are equivalent to about 5% of the quantity of biogenic CO_2 stored. The contribution by process is shown on Figure 17. By simplicity, the operation, construction and decommissioning phases have been grouped for each process.

The main contributor to the GWP of the CCS chain is the CO_2 shipping from Malmö to Øygarden, representing about 50% of the carbon footprint. The second largest contributor is the electricity substitution representing 24% of the total GWP. The change in the bioenergy system, including biomass supply and biomass-to-energy conversion represents 10% of the total GWP. The capture and liquefaction process at Sandviksverket represents 8% of the total GWP. The CO_2 storage, CO_2 transport to port and port processes respectively represent 4.5%, 3.6% and 0.5%.

Figure 17: GWP of the CCS chain – per ton CO_2 stored



4.2.2 Confidence level of the main contributors

The main contributor to the GWP of the CCS chain is the transport to storage site, for which 95% of the impact comes from ship fuel consumption. As discussed in section 4.1.2, the level of confidence for this contributor is moderate. For the second and third largest contributors, the confidence level of the activity data is high because they are provided by VEAB based on measurements and data records from previous years.

Table 16: Source of the activity data for the main contributors to the GWP of the CSS chain

Process	Contribution	Source of the data	Confidence level
Transport to storage site	50%	NL carbon footprint report, 2022	Moderate
Electricity substitution	24%	VEAB's energy balances	High
Biomass-to-energy conversion change	10%	VEAB's measurement and data records.	High

4.3 Sensitivity Analysis

This section analyses how the GWP of the CCS chain is impacted by variations in the choice of certain emission factors or in certain assumptions.

4.3.1 Sensitivity to the emission factor for electricity substitution

The assessment of the GWP due to electricity substitution was carried out using the market emission factor for low voltage electricity consumption in Sweden, taken from the ecoinvent 3.11 database. This choice is based on the assumption that the decrease in electricity output from Sandviksverket will not significantly impact the national supply system. The decrease in output can be compensated by an increase in other existing production mix and existing imports, without altering existing exports.

The market emission factor uses a life-cycle perspective, including emissions due to construction and decommissioning of the production, transmission and distribution infrastructure, emissions due to the production of fuels and different losses and fugitives. A more exhaustive description of the scope of the emission factor is provided in Box 1.

This approach is consistent with what is required by Puro Earth in the guidelines for removal quantification: "For electricity, EF_i, is the average emission factor of the grid (as defined by the biding zone, or national boundaries) to which the facility is connected."[17]

However, different reporting frameworks might impose other approaches to market leakage assessment. Therefore, other emission factors for the electricity have been investigated:

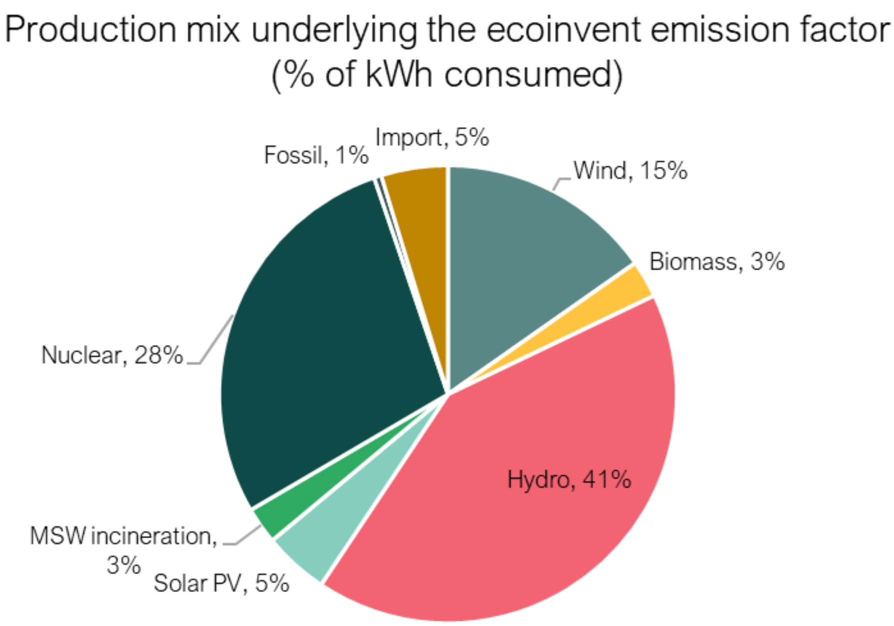
[17] Puro Earth, *Geologically Stored Carbon, Methodology for CO_2 Removal*, August 2024, section 6.3.4, https://puro.earth/geologically-stored-carbon

- the production mix emission factor published by the Nowtricity based on data from the European Network of Transmission System Operators for Electricity [18]. This emission factor accounts for life-cycles emissions (including infrastructure and supply chain emissions) for all national production.
- the emission factor corresponding to the total supplier mix published by the Association of Issuing Bodies (AIB). The emission factor only accounts for direct emissions during electricity production. It corresponds to the consumption mix in Sweden once exported guarantees of origin (GO) have been cancelled.[19]
- the emission factor corresponding to the residual mix published by the Association of Issuing Bodies (AIB). The emission factor only accounts for direct emissions during electricity production. It corresponds to the consumption mix in Sweden for consumers that do not have GO (all allocated GO are cancelled).
- the emission factor corresponding to the residual mix published by Energimarknadsinspektionen.[20] The emission factor follows the same principle as the residual mix published by AIB but yield a different result.

[18]Nowtricity, *Sweden*, Last accessed: October 2025. https://www.nowtricity.com/country/sweden/
[19] The Association of Issuing Bodies (AIB), European Residual Mixes Results of the calculation of Residual Mixes for the calendar year 2023, Version 1.0, 30/05/2024. Accessible at: https://www.aib-net.org/facts/european-residual-mix
[20] Energimarknadsinpektionen, *Residualmix*, Last accessed: October 2025, https://ei.se/bransch/ursprungsmarkning-av-el/residualmix

Box 1: Electricity in Sweden - Emission factor from ecoinvent database

Origin of the electricity in the market emission factor for low-voltage electricity in Sweden



Description, adapted from the ecoinvent documentation:[21]

- This is a **market activity**. Each market represents the **consumption mix** of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers, as well as the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant.
- Across the different steps of the value chain, the dataset includes:
  - electricity inputs produced in this country and from imports and transformed to low voltage
  - the transmission network
  - direct emissions to air (SF_6 from the insulation gas in the high voltage level switchgear are allocated to the electricity demand on medium voltage).
  - electricity losses during transmission
  - electricity losses during transformation from high to medium voltage and medium to low,
  - SF6 emissions during production and deconstruction of the switchgear

As per the information available on Energimarknadsinspektionen's website, the methodology applied is the same as the one used by AIB. However, the share of fossil energy in the residual mix is 17% according to AIB and is 68% according to Energimarknadsinpektionen. Therefore, the emission factor published by the

[21] Combination of the description given by ecoinvent on the different processes involved in the emission factor "market for electricity, low voltage | electricity, low voltage | Cutoff, S – SE". ecoinvent, *ecoQuery website*, Last accessed: October 2025.

latter is higher than the one published by AIB. With the available documentation, Carbon Limits was not able to identify the reasons behind this discrepancy. In any case, the larger range of emission factors allows to explore the sensitivity of the results to extreme cases.

Table 17: Sensitivity of the GWP of the CCS chain to the choice of emission factor for electricity substitution

	ecoinvent market emission factor	Nowtricity production mix	AIB total supplier mix	AIB residual mix	Energimarknads-inpektionen residual mix
Description of the emission factor.	Consumption mix in Sweden with an LCA approach (includes imports and exports, losses and infrastructures)	Production mix in Sweden with an LCA approach.	Refers to the electricity consumption that remains after cancelling the exported GO. Limited to direct emissions during production.	Refers to the electricity mix that remains after GO allocated to consumers are deducted. Limited to direct emissions during production.	Refers to the electricity mix that remains after GO allocated to consumers are deducted. Limited to direct emissions during production.
Reference year.	2022	2024	2024	2024	2024
Emission factor (gCO_2e / kWh).	38.4	18.0	7.5	85.5	464.8
CCS chain footprint (tCO_2e / tCO_2 stored).	0.046	0.040	0.038	0.060	0.167
Contribution of electricity substitution to the total carbon footprint %	24%	13%	6%	41%	79%

Table 17 describes the different emission factors evaluated for electricity, their values and the impact on the results when emission factor is applied to the electricity substitution. The emission factors from Nowtricity and the AIB supplier mix are lower than the one from ecoinvent. Consequently, using those emission factors would respectively lead to 13% and 19% lower total GWP. On the other hand, the residual mixes from AIB and Energimarknadsinspektionen are higher than the emission factor from ecoinvent leading to 29% and 262% higher emissions total GWP. Even in the most conservative case (emission factor from Energimarknadsinspektionen), the implementation of CCS still leads to net removals. The choice of emission factor for market leakage is an important assumption in the calculation of net removals, and, as such, should be clarified with the considered registry.

4.3.2 Sensitivity to emissions from CO_2 shipping

Transport to storage site is the main contributor to the carbon footprint of the CCS chain. However, the confidence level of the GWP estimate for this process is moderate, as the value is directly taken from the NL carbon footprint report. Therefore, this section analyses how the total GWP of the CCS chain is impacted by a variation in the emissions from CO_2 shipping, within a plausible range.

Low estimate

As it directly uses the result from the NL carbon footprint, this assessment assumes that the impact of shipping CO_2 from Malmö to Øygarden is equal to the average of the impact of all CO_2 shipping during the NL project. For the most part, emissions from shipping are linked to the distance between the export port and the Øygarden terminal. Therefore, Carbon Limits compared the distance between Malmö and Øygarden to the average distances between the export locations and Øygarden for the first phase of the NL project. Indeed, the first phase of the NL project consists of capturing around 400 ktpa from the Hafslund Celsio waste-to-energy plant near Oslo (Norway), around 400 ktpa from the Heidelberg Materials plant in Brevik (Norway), and around 800 ktpa from the Yara plant in Sluiskil (Netherlands).[22-23] The results are shown in Table 18. The distance from Malmö to Øygarden is 6% less than the average shipping distance for the first phase of the NL project, so the low estimate for the emissions from shipping is estimated at 94% of the average value taken from the NL carbon footprint. Note that the NL carbon footprint includes both phase 1 and phase 2 of the NL project, but the locations considered for the second phase are not publicly disclosed. For this assessment, it is therefore assumed that the average distance for phase 1 is representative of both phases.

Table 18: Comparisons between the distance Malmö-to-Øygarden and the shipping distances in the first phase of the NL project

Emitter	Announced CO_2 volumes (ktpa)	Distance to storage site (km) [24]
Hafslund Celsio	400	700
Heidelberg Materials	400	585
Yara	800	1180
Average distance per ton		**911**
Malmø	650	859
Difference with average		**-6%**

High estimate

For the high estimate, Carbon Limits estimated shipping emissions based on the distance between Malmö and Øygarden and generic data regarding ship fuel consumption. The input data used for this calculation

[22] Heidelberg Materials, *Brevik CCS, Facts and FAQ* [Online], Last accessed: October 2025, https://www.brevikccs.com/en/facts-and-faq

[23] The CCUS hub, *Northern Lights/Longship*, March 14, 2023, https://ccushub.ogci.com/wp-content/uploads/2023/03/Northern-Lights.pdf

[24] Distances were estimated by Carbon Limits using the sea-distance website: https://sea-distances.org/

are detailed in Table 19. From this input data, Carbon Limits calculated the emissions per ton transported due to fuel consumption, to which were added the other components extracted from the NL carbon footprint, e.g., the CO_2 and CH_4 slips during transport operations.

The emissions due to fuel consumption based on generic data are significantly larger than the ones extracted from the NL carbon footprint report. Therefore, this estimate can be considered as a high range for sensitivity analysis. However, as the fuel consumption underlying the ship fuel emissions in the NL carbon footprint report is derived from specific prospective data given by the ship provider, the average value from the NL report can be considered more accurate than the one derived from publicly available generic data.

Table 19: Input data for the calculation of ship fuel emission based on public generic data

Input parameter	Value	Unit	Source
Shipping distance	859	km	Carbon Limits based on the sea-distance website
Quantity of CO_2 to transport from Malmö	650	ktpa	CO_2 hub operator
Global average distance sailed by small liquefied-gas tankers in 2018	54,325	Nautical miles	IMO Fourth GHG Study[25]
Global average fuel consumption by small liquefied-gas tankers in 2018	3.9	kt	IMO Fourth GHG Study
Emission reduction due to wind-assisted technology and air lubrication onboard NL ships	34%		Article in Offshore Energy[26]
Capacity of the NL ships	7,500	m^3	Article in Offshore Energy
Liquid CO_2 density (-26.6˚C / 16 bar)	1060	kg / m^3	National Institute of Standards and Technology[27]
Ship filling	90%		Assumption by Carbon Limits
Emission factor for LNG (combustion + upstream)	Not disclosed		IMO Fourth GHG Study (combustion) + ecoinvent 3.11 (upstream)

Results

The results of the sensitivity analysis are shown in Table 20. Using the lower estimate for ship fuel consumption leads decreasing the total GWP of the CCS chain by 3%, to 0.045 tCO_2e / tCO_2 stored. On the other hand, the higher estimate based on generic data leads to a total GWP 39% larger than the reference case. As previously discussed, this estimate for fuel consumption is however deemed less

[25] International Maritime Organization, *Fourth IMO Greenhouse Gas Study*, 2020. Accessible at: https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

[26] Offshore Energy, *Second LNG-powered LCO2 carrier handed over to Northern Lights JV*, December 27 2024, https://www.offshore-energy.biz/second-lng-powered-lco2-carrier-handed-over-to-northern-lights-jv/

[27] National Institute of Standards and Technology, *Saturation Properties for Carbon dioxide — Temperature*, in *NIST Chemistry WebBook, SRD 69* [Online], US Department of Commerce, last accessed: December 2025, https://webbook.nist.gov/cgi/fluid.cgi?TLow=-56&THigh=30&TInc=1&Digits=5&ID=C124389&Action=Load&Type=SatP&TUnit=C&PUnit=bar&DUnit=kg%2Fm3&HUnit=kJ%2Fkg&WUnit=m%2Fs&VisUnit=uPa*s&STUnit=N%2Fm&RefState=DEF

accurate than the one derived from the NL carbon footprint report. As ship fuel emissions are the largest contributor to the GWP of the CCS chain, it may be relevant to consolidate the estimate for this process to increase the accuracy of the overall result. To do so, data regarding fuel consumption along the specific route from Malmö to Øygarden and with the specific ships in operations could be retrieved from NL or from a potential other transport and storage provider.

Table 20: Sensitivity of the GWP of the CCS chain to the ship fuel consumption

	Reference case	Low estimate	High estimate
Method for ship fuel emissions	Data from the NL carbon footprint report	Data from the NL carbon footprint -6%	Generic data from public sources
CCS chain footprint (tCO_2e / tCO_2 stored).	0.046	0.045	0.064
Contribution of CO_2 transport to port to the total carbon footprint %	50%	49%	64%

4.3.3 Sensitivity to the method to calculate emissions from CO_2 transport to port

As presented in section 3.5.2, the impact due to CO_2 transport by train from the Sandviksverket plant to Malmö is estimated using the average GHG emissions per tkm provided by GreenCargo. As an alternative, this impact can be quantified using the average electricity consumption communicated by GreenCargo and applying the emission factor corresponding to electricity supply in Sweden. The results are shown in Table 21.

Using the market emission factor for electricity in Sweden leads to a decrease by 0.2% of the total GWP of the CCS chain. Indeed, the average grid emission factor of GreenCargo, obtained by dividing the average emissions by the average consumption, is 51.7 kgCO2e / MWh, which is higher than the market emission factor from ecoinvent 3.11. This is explained by the fact that the values communicated by GreenCargo correspond to averages over their entire operations in Scandinavia. This includes different electricity mixes and a small share of diesel-fueled trips.

Using average emissions from GreenCargo is the most conservative of the two approaches. The results could be refined if GreenCargo provided the electricity mix specifically applicable for the Växjö-Malmö route, with guarantees of origin if applicable. However, as the transport to port only represents a small share of the total GWP of the CCS chain, and that applicable electricity emission factors will be in the same order of magnitude as the ones applied in the reference case, no significant difference in the results is expected.

Table 21: Sensitivity of the GWP of the CCS chain to the method to estimate emissions from CO_2 transport to port

Method for CO_2 transport emissions	GreenCargo emissions estimate (reference case)	GreenCargo consumption estimate
CCS chain footprint (tCO_2e / tCO_2 stored).	0.0463	0.0462

Contribution of CO_2 transport to port to the total carbon footprint %	3.6%	3.4%

4.3.4 Sensitivity to assumption regarding CO_2 slip during shipping

As presented in section 3.7, the reference case assumes that 50% (in tCO_2e) of the "other process emissions" in the transport-to-storage-site process come from CO_2 slip, while the rest is methane slip. To test the sensitivity of the results to this assumption, the share of CO_2 slip was also set to 25% and 75%. The results are shown in Table 22.

The share of CO_2 influences the results in two ways:

- The higher the share of CO_2 slips, the more CO_2 is lost and therefore the lower the quantity of CO_2 stored.
- The higher the share of CO_2 slips, the lower the CH_4 slip and the lower the impact of slips on the GWP (since biogenic CO_2 does not impact the total GWP, while methane emissions do)

Consequently, when the share of CO_2 in the "other process emissions" is set at 25%, more CO_2 is stored than in the reference case, but the GWP per ton stored is larger. On the contrary, when the share is set at 75%, the quantity of CO_2 stored is lower but the GWP per ton is also lower. In both cases, the variations in total GWP compared to the reference case are very small (±0.5%). The variations in net CO_2 stored yearly (see section 4.4) are negligible (±0.0007%).

Table 22: Sensitivity of the GWP of the CCS chain to the share of CO_2 slip in CO_2 shipping

Share of "Other process emissions" in shipping attributed to CO_2 slip	50% (reference case)	25%	75%
CO_2 effectively stored (tCO_2 / year)	114,929	114,957	114,901
CCS chain footprint (tCO_2e / tCO_2 stored).	0.0463	0.0465	0.0460
Net CO_2 stored (tCO_2 / year)	109,611	109,611	109,612

4.4 Summary: net removals per year

Yearly net CO_2 removals can be calculated by subtracting the GWP of the CCS chain from the quantity of CO_2 stored yearly, applying the following formula:

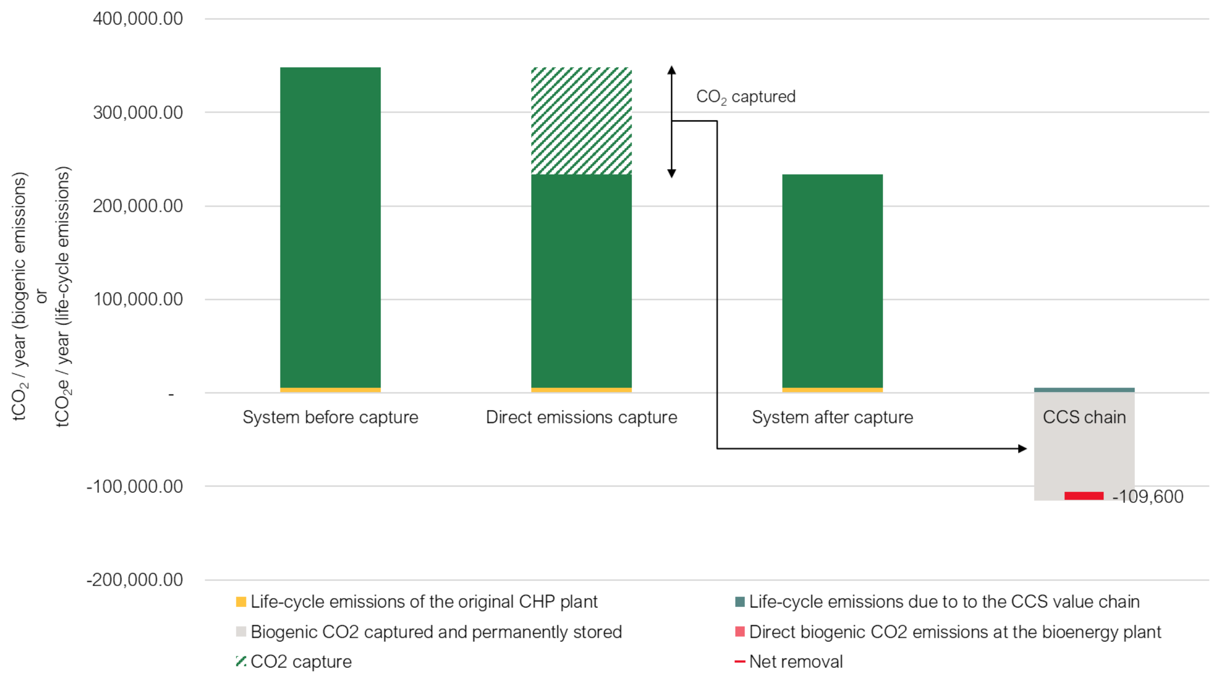
$$Net\ removals\ [tCO_2] = CO_2\ stored\ [tCO_2] \times (1 - GWP_{CCS}\ [tCO_2e/tCO_2])$$

$$Net\ removals = 114{,}929 \times (1 - 0.046) = \mathbf{109{,}611\ tCO_2e}$$

Based on the results of the LCA, conservatively rounded down to hundreds of tons, the yearly net CO_2 removals are estimated to 109,600 tCO_2. Figure 18 summarises annual emissions before and after implementation of CCS and illustrates how the GWP of the CCS chain compares to stored emissions.

Please note that this is an estimate based on the assumptions outlined in this report. Results may vary slightly depending on the methodologies used by individual registries. Therefore, Carbon Limits does not guarantee the exact quantity of credits that may be awarded.

Figure 18: Summary of emissions in the system with and without CCS – per year



Note: according to the impact assessment used, biogenic CO_2 emissions to air in tCO_{2e} are equal to 0. To make them appear on the graph, biogenic CO_2 emissions are represented in tCO_2 unit. The captured and permanently stored biogenic CO_2 is represented in tCO_2e.

5 Conclusion

The carbon footprint of the CHP plant in Sandviksverket without and with CCS was assessed by applying life-cycle analysis methodology on the whole chain from biomass supply to energy conversion to CO_2 geological storage. Results of the attributional LCA show that the carbon footprint of bioenergy production in the original CHP is 4.3 $kgCO_2e$ / $MWh_{heat\text{-}eq}$ (i.e., 4.3 $kgCO_2e$ / MWh_{heat} and 13.2 $kgCO_2e$ / MWh_{elec}). The implementation of CCS causes additional impacts, leading to a carbon footprint of 8.0 $kgCO_2e$ / $MWh_{heat\text{-}eq}$. However, when accounting for the fact that biogenic CO_2 is permanently stored, the carbon footprint of bioenergy production with CCS is - 94.5 $kgCO_2e$ / $MWh_{heat\text{-}eq}$ (i.e., - 94.5 $kgCO_2e$ / MWh_{heat} and - 286.3 $kgCO_2e$ / MWh_{elec}).

The carbon footprint of the CCS chain is calculated following consequential modelling. The carbon footprint of the CCS chain is 0.046 tCO_2e / tCO_2 stored. This means that additional emissions caused by the CCS chain represent about 5% of the volume of CO_2 stored yearly. VEAB plans to capture 115,000 tCO_2 per year, all of biogenic origin. Accounting for CO_2 losses along the CCS value chain, this means 114,929 tCO_2 could be stored per year. Subtracting the GWP of the CCS chain, net removals are estimated to 109,600 tCO_{2e} / year.

The emissions from ship fuel consumption during CO_2 transport to storage site is the main contributor to the carbon footprint of the CCS chain, representing 50% of the total GWP. The results are therefore sensitive to the estimate of fuel consumption. Based on the analysis of volumes and locations considered in the first phase of the NL project, the average estimate of impacts derived from the NL carbon footprint seems appropriate for the Malmö to Øygarden route. However, the results could be consolidated if NL (or another transport and storage provider if relevant) provided data for the specific route and ships in use.

Due to the consequential modelling, the decrease of electricity output from the CHP plant causes an additional impact added to the carbon footprint of the CCS chain. This electricity substitution represents 24% of the total GWP. The results are therefore sensitive to the choice of emission factor used to quantify the impact of electricity substitution. With the emission factors examined in the sensitivity analysis, the results range from -19% to +262% compared to the carbon footprint calculated using the market emission factor for Sweden from ecoinvent 3.11. The choice of emission factor for market leakage is an important assumption in the calculation of net removals, and, as such, should be clarified with the considered registry.

The input data for the biomass supply and the biomass-to-energy conversion was, for the most part, provided by VEAB based on previous year measurements and data records. The results for these processes therefore have a high level of confidence. The input data for the capture and liquefaction unit, and for CO_2 transport to port was provided by potential technology and transport providers. As this information is prospective, the associated level of confidence is moderate. Further studies (e.g., FEED studies for the capture unit) may improve the quality of the estimates, but the results are not likely to be significantly impacted as those processes contribute to 8% and 3.6% of the total GWP. The input data for port operation has a low level of confidence, but this process only contributes to 0.5% of the total GWP. Estimates for the transport to storage site and the storage activities are derived average values from the NL carbon footprint. These estimates have a moderate level of confidence and may be improved with more specific data. Finally, the quantity of CO_2 emitted yearly, and therefore the quantity of CO_2 captured and stored, are based on emission factors approved by Swedish authorities. They have a moderate level of confidence. As this parameter is capital for the quantification of total yearly removals, some registries may require alternative quantification methods.

Annex A. Detailed data inventory – CONFIDENTIAL

The tables in this section may only be presented to a restricted audience, as they contain confidential information related to VEAB's operations.

Table 23: Type of activity data and emission factors used for biomass collection – for 1 year

Flow	Sub-flow – activity data	Activity Data	Unit	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Energy	Diesel used for ash spreading	No CCS: 10,547 CCS: 10866.4	kg	Moderate	Biomass supplier	market for diesel | diesel | Cutoff, S - Europe without Switzerland
Energy	Biodiesel used for ash spreading	No CCS: 673 CCS: 694	kg			Emission factor derived from Heavy Fuel Oil supplier's 2023 sustainability declaration (proxy)

Table 24: Type of activity data and emission factors used for biomass transport – for 1 kg biomass intake

Flow	Sub-flow – activity data	Activity Data	Unit	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Transport	Biomass transported by truck - diesel	0.043	tkm	High	VEAB's data records for 2022, 2023 and 2024. Average values.	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, S - RER
Transport	Biomass transported by truck - biodiesel	0.022	tkm			Emission factor derived from Heavy Fuel Oil supplier's 2023 sustainability declaration (proxy).
Transport	Biomass transported by ship	0.01	tkm			market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, S - GLO

Table 25: Type of activity data and emission factors used for operation of the CHP plant – for 1 year

Flow	Sub-flow – activity data	Activity Data	Unit	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Energy	Heating oil – bio-based	No CCS: 55,250 CCS: 56,950	kg	High	VEAB's records: Measurement, internal transportation of biomass + invoices, from chipping of fuel logs	Emission factor derived from Heavy Fuel Oil supplier's 2023 sustainability declaration.
Chemical	Ammonia 24.5%	No CCS: 105,350 CCS: 108,780	kg	High	VEAB's measurements (2022, 2023, 2024)	market for ammonia, anhydrous, liquid | ammonia, anhydrous, liquid | Cutoff, S - RER
Chemical	Ammonium sulphate 40%	32,000	kg			market for ammonium sulphate | ammonium sulphate | Cutoff, S - RER

Chemical	Sodium chloride	7,000	kg			market for sodium chloride, powder | sodium chloride, powder | Cutoff, S - GLO
Chemical	Tap water	73,000,000	kg			market for tap water | tap water | Cutoff, S - Europe without Switzerland
Chemical	Sodium hydroxide 25%	18,750	kg			market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, S - RER
Chemical	Sulphur granules	23,000	kg			market for sulphur | sulphur | Cutoff, S - GLO
Chemical	Hydrochloric acid 34%	1,904	kg			market for hydrochloric acid, without water, in 30% solution state | hydrochloric acid, without water, in 30% solution state | Cutoff, S - RER
Material	Steel for maintenance	10,000	kg	Moderate	VEAB's records from the project department	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Cutoff, S - GLO
Material	Sand	2,450,000	kg	High	VEAB's measurement s	market for sand | sand | Cutoff, S - RoW
Direct emissions	Biogenic CO_2	No CCS: 333,187 CCS: 343,084 (before capture) 228,604 (after capture)	kg	Moderate	VEAB's calculations based on emission factors from the Swedish environmental protection agency used in EU ETS.	Characterisation factor from IPCC 2021
Direct emissions	Refrigerants (R410A, R407C and R32)	10	tCO_2e	High	Leakage from cooling machines, measured by a certified personal.	Characterisation factors of the different components (R32, R125 and R134a) provided by The Swedish Environmental agency.
Direct emissions	Nitrous oxide (N_2O)	7,900	kg	High	VEAB's measurement in the flue gas.	Characterisation factor from IPCC 2021
Waste	Fly ash treatment – spread in forest[28]	No CCS: 388,148 CCS: 399,739	tkm	High	VEAB's measurement s (2022, 2023, 2024)	market for transport, freight, lorry 28 metric ton, fatty acid methyl ester 100% | transport, freight, lorry 28 metric ton, fatty acid methyl ester 100% | Cutoff, S - RoW
Waste	Bottom ash – used for construction material	No CCS: 3,320,000 CCS: 3,419,000	kg			treatment of bottom ash, MSWI-WWT-SLF, wood ash mixture, pure, slag compartment | bottom ash, MSWI-WWT-SLF, wood ash mixture, pure | Cutoff, S - Europe without Switzerland
Waste	Cleaned wastewater – to	No CCS: 85,000	m^3			treatment of wastewater, average, wastewater treatment | wastewater,

[28] The input in this process corresponds to the transport from Växjö to the location where ash is spread, while diesel consumption the "biomass collection" process corresponds to local transport while on site. There is therefore no double counting, and both are in scope since the impacts of waste treatment (here ash spreading) should be allocated to the activity generating the waste (here bioenergy production).

	municipal wastewater treatment	CCS: 97,000				average | Cutoff, S - Europe without Switzerland
Waste	Metals – to recycling	73,000	kg	High	Data from waste transport and treatment company (2022, 2023, 2024)	market for ferrous metal, in mixed metal scrap | ferrous metal, in mixed metal scrap | Cutoff, S - Europe without Switzerland
Waste	Paper – to recycling	2,400	kg			treatment of waste paper, unsorted, sorting | waste paper, sorted | Cutoff, S - Europe without Switzerland
Waste	Mixed waste – to landfill	11,000	kg			treatment of municipal solid waste, sanitary landfill | municipal solid waste | Cutoff, S - SE
Waste	Mixed waste – to energy production	30,000	kg			treatment of municipal solid waste, municipal incineration | municipal solid waste | Cutoff, S - SE
Waste	Hazardous waste[29] – to recycling	5,000	kg			treatment of waste emulsion paint on wall, sorting plant | waste emulsion paint, on wall | Cutoff, S – RoW market for electronics scrap | electronics scrap | Cutoff, S - GLO
Waste	Hazardous waste – to energy production	1,000	kg			treatment of hazardous waste, hazardous waste incineration | hazardous waste, for incineration | Cutoff, S - Europe without Switzerland
Waste	Polluted water – to recycling	24,000	kg			treatment of sewage sludge, 70% water, WWT, WW, average, municipal incineration | sewage sludge, 70% water, WWT, WW, average | Cutoff, S - Europe without Switzerland
Transport	Waste transport by truck - biodiesel	1,485	tkm			market for fatty acid methyl ester | fatty acid methyl ester | Cutoff, S - RoW

Note 1: when no distinction is made between the system with and without CCS, it means the same values apply to both system (the flows do not scale with the input of biomass)

Note 2: for some chemicals, Carbon Limits re-calculated the mass to match the concentration of the emission factor

Table 26: Type of activity data and emission factors used for construction and decommissioning of the carbon capture system – for 1 system

Flow	Sub-flow – activity data	Activity data	Unit	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Material	Steel	1,350	t	Moderate	Data from technology provider (pre-FEED report)	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Cutoff, S
Material	Stainless steel	250	t			market for steel, chromium steel 18/8, hot rolled | steel, chromium

[29] VEAB provided a detailed inventory of the hazardous waste for year 2024. The main components were oils and oil-contaminated waste (which treatment in approximated by the treatment of paint) and electronic waste.

						steel 18/8, hot rolled | Cutoff, S - GLO
Material	Concrete	2,700	t			market for concrete, normal strength | concrete, normal strength | Cutoff, S - RoW
Waste	Steel - decommissioning	1,600	t			market for waste steel | waste steel | Cutoff, S - Europe without Switzerland
Waste	Concrete - decommissioning	2,700	t			market for waste concrete | waste concrete | Cutoff, S - Europe without Switzerland

Table 27: Type of activity data and emission factors used for capture, liquefaction and storage tanks operation – for 1 year

Flow	Sub-flow – activity data	Activity data	Unit	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Chemical	Amine solution	35	t	Moderate	Data from technology provider (pre-FEED report)	market for monoethanolamine | monoethanolamine | Cutoff, S - GLO
Chemical	Sodium hydroxide	1	t	Moderate		market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, S - RER
Chemical	Desiccant	2	t	High		market for activated carbon, granular | activated carbon, granular | Cutoff, S - GLO
Waste	Amine solution waste – hazardous waste destruction	35	t	Moderate		treatment of hazardous waste, hazardous waste incineration | hazardous waste, for incineration | Cutoff, S - Europe without Switzerland
Waste	Desiccant waste – waste destruction	2	t	High		treatment of municipal solid waste, municipal incineration | municipal solid waste | Cutoff, S - RU
Transport	Waste transport by truck - biodiesel	2849	tkm	Moderate	VEAB's estimation	market for fatty acid methyl ester | fatty acid methyl ester | Cutoff, S - RoW

Table 28: Type of activity data and emission factors used for construction and decommissioning of equipment for transport to the port – for 1 system

Flow	Sub-flow – activity data	Activity data	Unit	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Material	Wagons - steel	237	t	Moderate	Transport provider	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Cutoff, S
Material	Wagons – stainless steel	237	t			market for steel, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | Cutoff, S - GLO
Material	Train tracks	600	m	Moderate	VEAB preliminary design	market for railway track | railway track | Cutoff, S - GLO
Waste	Wagons - decommissioning	474	t	Moderate	Transport provider	market for waste steel | waste steel | Cutoff, S - Europe without Switzerland

Table 29: Type of activity data and emission factors used for construction and decommissioning of the port equipment – for the whole port (with a 650 ktpa capacity)

Flow	Sub-flow – activity data	Activity data	Unit	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Material	Steel	4,400	t	Low	Carbon Limits based on port operator's information	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Cutoff, S - GLO
Material	Concrete	9,856	t			market for concrete, normal strength | concrete, normal strength | Cutoff, S - RoW
Waste	Steel - decommissioning	4,400	t			market for waste steel | waste steel | Cutoff, S - Europe without Switzerland
Waste	Concrete - decommissioning	9,856	t			market for waste concrete | waste concrete | Cutoff, S - Europe without Switzerland

Table 30: Type of activity data and emission factors used for port operations – for the whole port (with a 650 ktpa capacity)

Flow	Sub-flow – activity data	Activity data	Unit	Confidence level	Reference for activity data	Emission Factor from ecoinvent
Energy	Electricity from the grid (for all operations)	1.3 [0.9 to 2.4][30]	kWh / tCO_2	Low	Port operator's estimates	market for electricity, low voltage | electricity, medium voltage | Cutoff, S SE
Direct emissions	CO_2 losses	6500	kg			Characterisation factor from IPCC 2021

[30] As the estimate is preliminary, the port operator provided a reference value of 1.3 kWh / tCO_2 and an uncertainty range of 0.9 to 2.4 kWh / tCO_2. However, as electricity consumption at port represents 0.03% of the total GWP of the CCS chain, a dedicated sensitivity analysis is not presented in this report.

Annex B. Systems modelled in OpenLCA

Figure 19 and Figure 20 show screenshots of the systems modelled in OpenLCA, for the original CHP and the BECCS system respectively.

Figure 19: System modelled – Original CHP

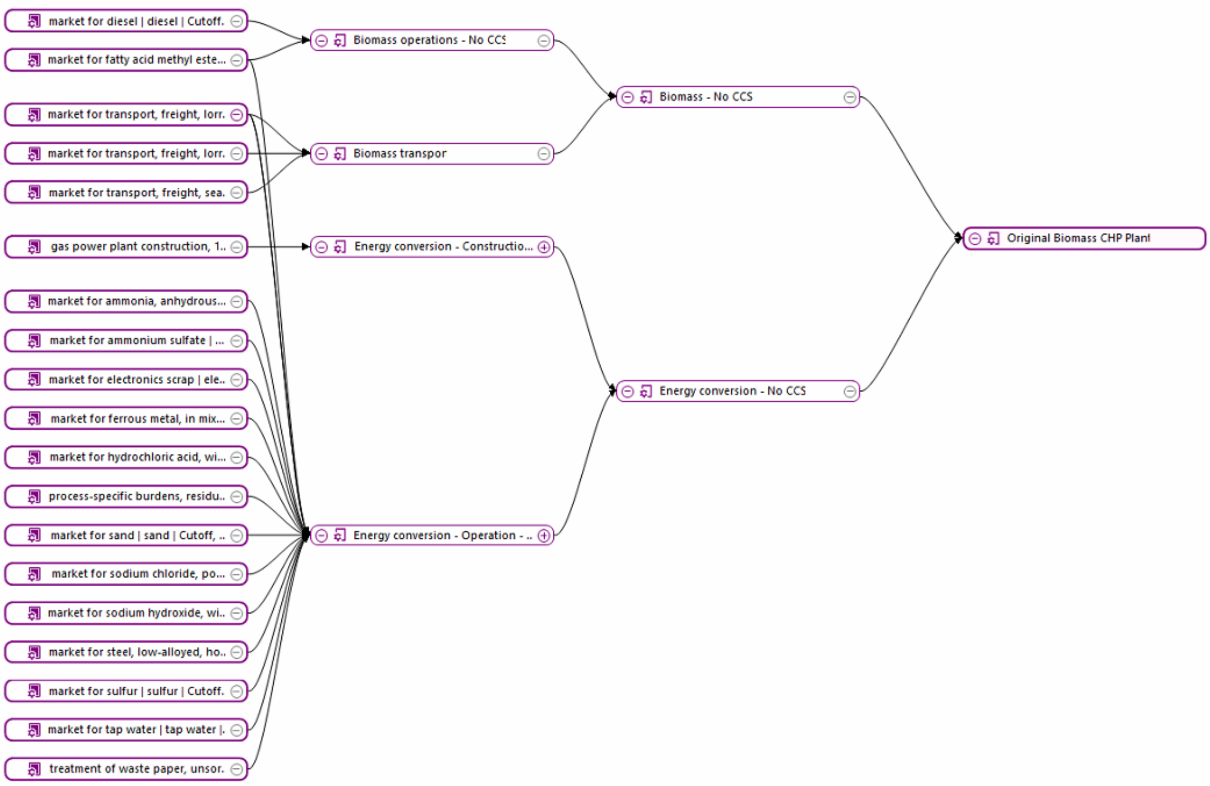
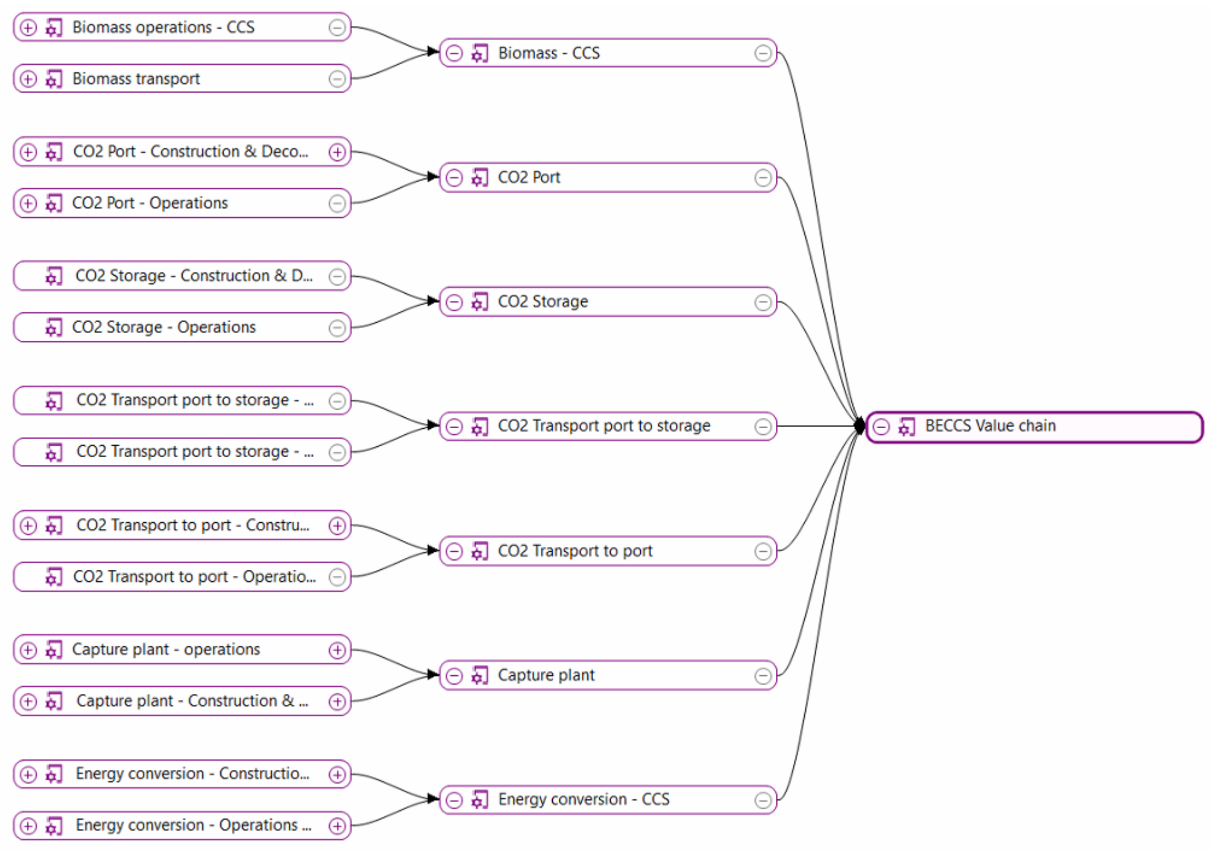


Figure 20: System modelled – BECCS system



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