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Export of bioenergy from Norway – Hydrogen or wood chips?

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ABSTRACT

This study investigates the potential of producing hydrogen based on currently unused biomass potentials in Norway and exporting the hydrogen to the European Union. Export of hydrogen via compressed hydrogen is compared with the export of wood chips via bulk shipping and the production of hydrogen from wood chips in the respective import country. A mixed-integer linear optimization model was developed to minimize total supply chain costs of the two parallel supply chain options. Results show that shipping wood chips and producing hydrogen in the importing country is more cost-effective than producing and shipping compressed hydrogen from Norway, with levelized supply chain costs of 33.4 NOK/kg$_{H_2}$ versus 47.6 NOK/kg$_{H_2}$, respectively. This arises mainly because of significantly higher investment costs for compressed hydrogen ships and lower payload. However, hydrogen production in Norway and export via compressed hydrogen shipping result in lower overall emissions due to Norway's higher renewable penetration.

Keywords: compressed hydrogen shipping, hydrogen supply chain, wood chip shipping, biomass gasification, hydrogen production, eco-techno-economic analysis

1. Introduction

In the REPowerEU plan in 2022, the European Commission presented the goal of producing 10 million tonnes and importing 10 million tonnes of renewable hydrogen by 2030 into the EU [1]. Norway could become a hydrogen-exporting country in the future to help fulfill this need. To this end, the Norwegian government's hydrogen strategy considers exporting hydrogen through both pipeline and shipping [2]. While significant effort has focused on producing renewable hydrogen via electrolysis, the electricity required for hydrogen production is expected to compete with rapidly growing demands from AI and data centers. For example, the Narvik Green Ammonia project in northern Norway would have used electricity to produce hydrogen for export in the form of green ammonia, but it was cancelled in 2025 so that available electricity would be used for a data center instead [3].

As an alternative to electrolysis, renewable hydrogen could be produced via gasification of biomass. In 2021, the growth in productive forests in Norway amounted to 22.6 million cubic meters [4], while the felling rate amounted to 11.4 million cubic meters [5]. This means that about 10 million cubic meters of timber could theoretically be sourced annually without a reduction in standing forest volume. In this study, we investigate the techno-economics of using this sustainable forest potential to supply mainland Europe with renewable hydrogen.

Many studies in the literature have looked at the techno-economics of international hydrogen trade. Commonly considered energy forms are compressed hydrogen (cH_2), liquid hydrogen (LH_2), liquid organic hydrogen carriers (LOHC) or ammonia (NH_3) [6-9]. For the export of compressed hydrogen, pipelines are commonly considered. Much work has been conducted on liquid hydrogen shipping, while compressed hydrogen shipping has received little attention. Noh *et al.* [6] found that compressed hydrogen shipping is the most energy efficient option among cH_2, LH_2, LOHC and NH_3 shipping. Saborit *et al.* [10] compared hydrogen pipeline with liquid hydrogen and compressed hydrogen shipping and found that compressed hydrogen shipping can have lower costs than liquid hydrogen shipping. Cebolla *et al.* [8] found that for short transport distances, pipeline and compressed hydrogen shipping are the most cost-effective.

Alternatively, wood chips could be exported, and hydrogen could be produced where needed or where a hydrogen pipeline network exists. The international wood chip trade is an established business, with existing ship and port infrastructure. For example, the wood chip carrier CL ACACIA is used today to export wood chips from Tasmania around the world [11]. In that manner, large-scale export of wood chip can become economically viable (e.g., Tasmanian Ports Corporation reported 2.78 million tonnes of wood chip export in 2024 [12]). The export of timber has also become an important sector of Norway's economy. In the last ten years, export of timber has been quite stable at about 3.5 Mm^3 per year, with pulpwood making up for about 50% [13].

This study addresses the question of whether it is economically and/or environmentally better to produce hydrogen in Norway and ship the hydrogen, or to ship wood chips from Norway to the EU and produce hydrogen there. To this end, we develop mathematical optimization model aiming to estimate the system cost of both options. For the first case, we only consider hydrogen shipping in the form of compressed hydrogen, since there is no hydrogen pipeline between Norway and mainland Europe as of today and building a pipeline in the near-term future is not profitable due to the prohibitive infrastructure cost.

2. Methodology

2.1. General

The aim of the study is to model the supply chain cost and emissions for supplying mainland Europe with renewable hydrogen, which is based on sustainable biomass potentials in Norway. The shipping terminal of Wilhelmshaven in Germany serves as the proxy for mainland Europe, meaning that the system boundary ends at the shipping terminal. It is assumed that hydrogen demand in Europe can be satisfied from Wilhelmshaven through inland transport infrastructure such as a pipeline network, though this is not explicitly considered within our model. On the other end of the supply chain, the system boundary starts at the primary energy potentials in Norway (see Fig 1). Here, the sustainable energy potential was calculated as the annual growth minus felling.

The time scope of the study is the present and near-term future, meaning that the costs presented in this study reflect the question "How much would it cost to build out the supply chain now?". This means that currently available infrastructure can be used without additional investment, while non-existing infrastructure must be constructed. For currently available infrastructure, we consider existing wood chip shipping terminals and assume that these have sufficient available capacity to handle the operations investigated in this study. On the other hand, compressed hydrogen shipping terminals and hydrogen production plants must be newly constructed.

2.2. Supply chain superstructure

2.2.1. General

Fig 1 describes the supply chain superstructure. On the first level, the model allows for timber transport from Norwegian forests to either biomass gasification plants in Norway to produce domestic hydrogen (i.e., these plants do not exist and have to be constructed) and timber transport to existing shipping ports, where timber is converted into wood chips. Domestically produced hydrogen must then be transported to shipping terminals for compressed hydrogen, which also must be constructed. In the next step, compressed hydrogen and wood chips are shipped to the import terminal in Germany. In the case of wood chip shipping, imported wood chips are fed to a hydrogen production plant, which is located at the import terminal in Germany.

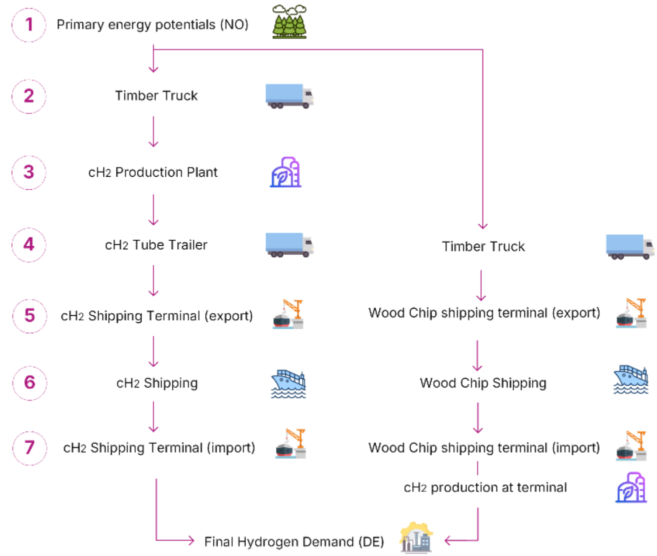

Fig 1: Supply Chain Superstructure

Table 1 describes the indices for nodes in the graph and should be understood as location indices where nodes could be constructed or existing infrastructure could be used. The subscript number of the index set states the level of the index set in the graph (see Fig 1):

Table 1: Indices sets for nodes in the graph

Set	Description
I_1	Timber production sites in Norway
I_3	Biomass gasification hubs in Norway
I_{5,cH_2}	Shipping terminals for export of cH_2
$I_{5,wc}$	Shipping terminals for export of wood chips
I_{7,cH_2}	Shipping terminals for import of cH_2
$I_{7,wc}$	Shipping terminals for import of wood chips

2.2.2. Description of nodes

2.2.2.1. Primary energy potentials

Only forest resources were considered in this study. We calculated the annual timber potential in Norway as the annual forest growth minus the current felling. The potential was calculated per county given numbers for growth and felling [4, 5]. The county-based potentials were then translated into 1000 geographically specific points distributed randomly on the map of Norway. For all nodes, the production costs were calculated based on harvester productivity and forwarder productivity. These values were estimated based on distributions for maturity classes, mean stem volumes, forest densities, terrain types and inclination classes, as well as extraction distances. We assume that the timber production operation consists of felling, transport to the closest road and roadside drying to a final moisture content of 20%. Finally, nodes with production costs exceeding the timber price in the node's county were assumed to be infeasible.

Since the allocation of county-based potentials into geographically specific points contains a random component, there is some uncertainty in production costs and potential. Fig 2 shows the mean and standard deviation of the timber production costs as a function of timber production rate for 10 different runs. It can be seen that the prediction of the production cost is very stable for low to medium production rates. The calculation which we used for further analysis yields an annual economic timber potential of 2075 kt/a. This translates to an energy potential of 31122 TJ/a using a LHV of 15 GJ/t [14] and an average "power" of 985 MW. This translates also to a maximum hydrogen export potential of 745 MW from Norway under current timber market conditions, which we use as the upper bound in this work. The detailed calculations and an analysis of production cost are given in the supplementary material.

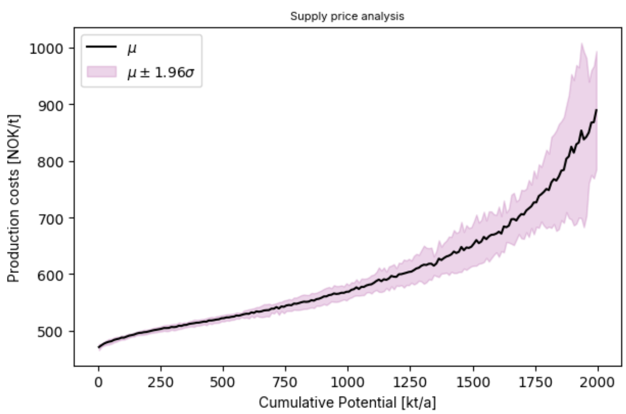

Fig 2: Timber production costs vs cumulative potential

2.2.2.2. Biomass gasification (NO)

The system for biomass gasification is based on a techno-economic analysis of a dual fluidized bed gasification process reported by Binder *et al.* [15]. The reported system has a nominal size of 50 MW, and results were scaled from 10 to 1000 MW based on the stated scaling laws. The model of the process plant was extended by a hydrogen compressor to 350 bar. Moreover, plants that export produced hydrogen via cH_2 tube trailers, a hydrogen storage vessel and a tube trailer loading unit was considered. The cost function for hydrogen production via biomass gasification is automatically generated via piecewise linear regression upon model creation based on its nonlinear cost function. The regression equation was then implemented in the cost constraints. The implemented cost functions are stated in the supplementary material.

2.2.2.3. cH_2 shipping terminals (export)

We assumed that feasible locations for terminals are towns with more than 5000 inhabitants along the coastline, of which 20 random towns were selected. The dataset for the Norwegian coastline, which was used to identify feasible nodes for shipping terminals was provided by Miljødirektoratet [16].

The design and cost data for the shipping terminals was sourced from previous work [17]. The shipping terminals for export of compressed hydrogen consists of a receiving site, where hydrogen tube trailers deliver compressed hydrogen gas, and a sending site, where compressed hydrogen carrying ships can dock and load. We assume that the minimum terminal throughput should be larger than 10 MW. The annual ship filling time times the annual trips from the terminal must thus be less than 8760h.

2.2.2.4. cH_2 shipping terminals (import)

The design and cost data for the shipping terminals was sourced from previous work [17]. The shipping terminals for the import of compressed hydrogen consists of a receiving site, where compressed hydrogen carrying ships can dock and unload and a sending site, where hydrogen is exported into a national hydrogen grid. We assumed that the minimum terminal throughput should be larger than 100 MW. We assume that the import terminal is perfectly connected to a hydrogen pipeline network operating at 80 bar, which can absorb all hydrogen imported at the import terminal at the given flow rate. Since the national pipeline infrastructure is not considered in this study, we assume that the pipeline network can handle all import mass flows from the shipping terminal. If this is not the case, intermediate storage capability would be required at the import terminal. Especially for small terminals, significant spikes in hydrogen mass flow are observed during ship unloading. We assume that the port of Wilhelmshaven could serve as an import terminal for hydrogen. The considered costs include the costs for construction and operation of the infrastructure.

2.2.2.5. Wood chip shipping terminals (export)

19 existing ports in Norway were selected for the export of wood chips: Sortland, Mandal, Larvik, Trondheim, Orkanger, Hitra, Stjørdal, Verdal, Steinkjer, Fredrikstad, Drammen, Stavanger, Haugesund, Bergen, Florø, Kristiansund, Mo i Rana, Bodø, Tromsø. Data for waterway fees, quay fees and time fees was sourced from the port operators.

At the incoming side of the export terminal, timber is received from timber trucks. The timber is unloaded and converted into wood chips using a chipper. While investment costs for the wood chipper were not calculated due to insignificance, we considered a electricity consumption of 52 kJ/kg timber [18].

2.2.2.6. Wood chip shipping terminals (import)

The import terminal for wood chips is located in Wilhelmshaven. Wood chips are sourced from the ship through a continuous unloader and are transported to a gasification plant built on site. Data for port fees are obtained from the port operator [19].

2.2.2.7. Biomass gasification (DE)

The biomass gasification plant in Germany has the same structure as the biomass gasification plants in Norway. Costs in the underlaying study from Binder *et al.* [15] are given for Germany and were only adjusted using CEPCI (CAPEX) and inflation (OPEX). After production, hydrogen is compressed to 80 bar and assumed to be injected into a hydrogen grid. We assume no compressed hydrogen storage. The biomass gasification plants are located at the import terminal for wood chips.

2.2.3. Description of edges

2.2.3.1. Timber truck

The timber truck was considered as a system consisting of a truck, trailer and a self-loader. Investment costs, lifetimes (in km and loading cycles), residual values, fuel consumptions, tire costs and repair / service costs were taken from Fjeld *et al.* [20]. The payload was assumed to be 38 t, as presented in the report as a Norwegian average. Given the regulations for timber transport in Norway for roads of the category (*i.e.*, Norwegian: Bruksklasse) BkT8 and Bk10 [21], this is an optimistic assumption, as not all roads satisfy this regulation and should be interpreted as a maximum payload.

2.2.3.2. cH_2 tube trailer

The technical specification of the system and cost calculation was sourced from previous work [17].

2.2.3.3. Truck transport (general)

Both the costs for timber trucking and cH_2 tube trailers were implemented into the model using the same logic. It was assumed that a truck can be employed on different routes throughout the year. The total annual cost per truck was calculated by a linear regression over the annual driven distance per truck (see supplementary material section 3.1.2). For all inland transport routes, the route distance and driving time was calculated and stored in matrices, which serve as input for the optimization model. The driving distance and driving time between nodes using the Norwegian road network was calculated using a custom implementation of OpenRouteService [22]. For more information, see supplementary material, section 4.1.

2.2.3.4. cH_2 pipeline

Due to the small scale and time scale of the investigated supply chains, we assume that domestic pipeline construction in Norway is not adequate. Thus, pipeline transport was not modelled as a transport option for long distance transport. However, we assumed that if a biomass gasification plant is built at the same place (*i.e.*, distance less than 5000 meters) as an export terminal for compressed hydrogen, hydrogen can be transported via a local pipeline. For that case, we implemented a pipeline transport option, but do not consider any cost.

2.2.3.5. cH_2 ship

The technical specification of the system and cost calculation was sourced from previous work [17]. The cost calculation considers investment cost for the bare ship and the modules, fixed operating costs (i.e., staff, maintenance and insurance) as well as variable operating costs (i.e., fuel costs).

2.2.3.6. Wood chip ship

The vessel for shipping of wood chips is based on a real vessel, the CL ACACIA, with a deadweight tonnage of 71 kt [11]. The cost calculation considers investment cost for the ship, fixed operating costs (*i.e.*, staff, maintenance and insurance) as well as variable operating costs (*i.e.*, fuel costs). For more information, see supplementary material.

2.2.3.7. Ship transport (general)

For all shipping routes, the shipping distance was calculated and stored in a shipping distance matrix, which serves as input for the optimization model. The shipping route on open sea was approximated using the Searoute python package [23]. The route from the Norwegian port to the route on open sea was calculated using custom python code and is an approximate estimation of the actual route. The practical feasibility of the shipping routes is not considered, as the calculation does not take depth data into consideration. Actual shipping routes might thus differ.

2.3. Model description

The model is presented piece by piece in the following section. A tabular overview of all the decision variables, parameters and constraints is given in the supplementary material. The source code of the model is made available to the public, see section Data Transparency.

The supply chain model receives a set of meta parameters and general supply chain data upon generation. The meta parameters include 71 values for cost and technical design data and is declared in an external file, which is given as supplementary material. Before the supply chain model is declared, the set of meta parameters is extended by values for cH_2 ship size, cH_2 ship filling time and cH_2 ship emptying time. These are calculated based on the relations reported in [17], which showed that there is a relationship between amount of transported hydrogen, average shipping distance and optimal cH_2 ship size as well as optimal transfer times for cH_2 shipping terminals. Herein, we assume an average expected one-way shipping distance of 600km, which is typical for southern Norway to northern Europe. All cH_2 shipping terminals receive the same transfer times. The set of meta parameters is given as supplementary material.

2.3.1. Description of nodes

2.3.1.1. Timber production

The timber production is described by the variables for timber production amount at site i $m_i^{timber\ 01}$ [kt timber p.a.], annual cost at timber production site i $c_i^{\text{timber 01}}$ [kNOK2024 p.a.], and annual CO_2 emissions from timber production $e^{\text{timber 01}}$ [tCO_{2eq} p.a.]. The timber production amount at site i is linked to the transport edges for timber trucking from site i to biomass gasification hub j $m_{ij}^{\text{timber truck 02}}$ [kt timber p.a.] and timber trucking from site i to the export wood chip shipping terminal j $m_{ij}^{\text{timber truck 04}}$ [kt timber p.a.].

$$m_i^{\text{timber 01}} = \sum_{j \in I_3} m_{ij}^{\text{timber truck 02}} + \sum_{j \in I_{5,wc}} m_{ij}^{\text{timber truck 04}} \; \forall i \in I_1$$

The timber production in each node i must be lower than or equal to the timber potential in the node i $m_i^{\text{timber,pot 01}}$ [kt timber p.a.]. For the calculation of timber potentials, see section 2.2.2.1.

$$m_i^{\text{timber 01}} \leq m_i^{\text{timber,pot 01}} \; \forall i \in I_1$$

The annual costs for timber production were calculated based on the local timber price of the production site i $c_i^{\text{timber,price 01}}$ [NOK2024/kg] times the annual production volume.

$$c_i^{\text{timber 01}} = m_i^{\text{timber 01}} \cdot c_i^{\text{timber,price 01}} \cdot 1000 \; [t/kt] \; \forall i \in I_1$$

The CO_2 emissions for timber production are calculated based on the diesel consumption for timber production in the site i $m_i^{\text{diesel 01}}$ [kg diesel / kg timber] and the emission factor e^{diesel} [kg CO_{2eq} / kg diesel] for diesel.

$$e^{\text{timber 01}} = \sum_{i \in I_1} m_i^{\text{timber 01}} \cdot m_i^{\text{diesel 01}} \cdot e^{\text{diesel}} \cdot 1000 \; [t/kt]$$

2.3.1.2. Biomass gasification (NO)

The biomass gasification plants for hydrogen production are described by the variables for expansion decision of plant i $z_i^{\text{gasification 03}}$ [binary], expansion size of plant i $m_i^{\text{gasification 03}}$ [kt cH_2 p.a.], expansion decision of a terminal for hydrogen tube trailers at plant i $z_i^{\text{gasification,ttt 03}}$ [binary], size of the tube trailer terminal at the plant i $m_i^{\text{gasification,ttt 03}}$ [kt cH_2 p.a.], annualized costs of the plant i $c_i^{\text{gasification 03}}$ [kNOK2024 p.a.], and annual CO_2 emissions from all biomass gasification hubs in Norway $e^{\text{gasification 03}}$ [tCO_{2eq} p.a.]. The upper bound ub and lower bound lb of the expansion size were chosen as reasonable engineering values.

$$m_i^{\text{gasification 03}} \geq lb \cdot z_i^{\text{gasification 03}} \; \forall i \in I_3$$

$$m_i^{\text{gasification 03}} \leq ub \cdot z_i^{\text{gasification 03}} \; \forall i \in I_3$$

The expansion size of the plant i is linked to the transport edges for inflow and outflow. On the inflow side, timber is received and converted to hydrogen with the conversion rate $m^{\text{gasification,conv}}$ [kg cH_2 / kg timber].

$$m_i^{\text{gasification 03}} = \sum_{j \in I_1} m_{ji}^{\text{timber truck 02}} \cdot m^{\text{gasification,conv}} \; \forall i \in I_3$$

On the outflow side, the produced hydrogen is transported via compressed hydrogen tube trailers $m_{ij}^{cH_2 \text{ tube trailer 04}}$ [kt cH_2 p.a.] or hydrogen pipeline $m_{ij}^{cH_2 \text{ pipeline 04}}$ [kt cH_2 p.a.]. Hydrogen pipeline transport is assumed feasible only if the source and destination are in the same place (i.e., distance <= 5km), see section 2.2.3.4.

$$m_i^{\text{gasification 03}} = \sum_{j \in I_{5,cH_2}} m_{ij}^{cH_2 \text{ tube trailer 04}} + m_{ij}^{cH_2 \text{ pipeline 04}} \; \forall i \in I_3$$

The expansion size of the compressed hydrogen tube trailer terminal is given by the size of the tube trailer transport edge.

$$m_i^{\text{gasification,ttt 03}} = \sum_{j \in I_{5,cH_2}} m_{ij}^{cH_2 \text{ tube trailer 04}} \; \forall i \in I_3$$

$$m_i^{\text{gasification,ttt 03}} \leq ub \cdot z_i^{\text{gasification,ttt 03}} \; \forall i \in I_3$$

The CO_2 emissions for biomass gasification production are calculated based on the utility consumption. The only utility with significant CO_2 emissions that is considered is electricity with the utility factor $m^{\text{gasification,el cons 03}}$ [MWh/kg cH_2] for the main plant, the utility factor $m^{\text{ttt,el cons 03}}$ [MWh/kg cH_2] for the tube trailer terminal and the emission factor $e^{\text{el,NO}}$ [kg CO_{2eq} / MWh].

$$e^{\text{gasification 03}} = \sum_{i \in I_3} \Big(m_i^{\text{gasification 03}} \cdot m^{\text{gasification,el cons 03}} + m_i^{\text{gasification,ttt 03}} \cdot m^{\text{ttt,el cons 03}} \Big) \cdot e^{\text{el,NO}} \cdot 1000 \; [t/kt]$$

The cost function links the annualized plant costs to the expansion size. The cost function considers annualized investment costs as well as operating costs. The cost factor $c_i^{\text{gasification,base 03}}$ includes investment costs, maintenance costs, staff costs, and auxiliary operational costs, and is in general a non-linear function of the expansion size. A piecewise linear regression was performed on the non-linear cost function which was then used to link $c_i^{\text{gasification,base 03}}$ to the expansion size. The electricity cost scales linearly with the expansion size given the electricity price at plant i c_i^{el} [NOK2024/MWh].

$$c_i^{\text{gasification 03}} = c_i^{\text{gasification,base 03}} \cdot z_i^{\text{gasification 03}} + c_i^{\text{gasification,ttt,specific 03}} \cdot m_i^{\text{gasification,ttt 03}} \cdot z_i^{\text{gasification,ttt 03}} + m_i^{\text{gasification 03}} \cdot m^{\text{gasification,el cons 03}} \cdot c_i^{\text{el}} \cdot 1000 + m_i^{\text{gasification,ttt 03}} \cdot m^{\text{ttt,el cons 03}} \cdot c_i^{\text{el}} \cdot 1000 \; [t/kt] \; \forall i \in I_3$$

$$c_i^{\text{gasification,base 03}} = a_p \cdot m_i^{\text{gasification 03}} + b_p \; \forall i \in I_3$$

where a_p is the specific cost factor and b_p is the offset for the piece $p_{\text{lower}} \leq m_i^{\text{gasification 03}} \leq p_{\text{upper}}$. The pieces of the cost function are defined by their breakpoints p_{lower}

and p_{upper}. The values for a_p, b_p and the breakpoints can be found in the supplementary material section 3.2.5.

2.3.1.3. cH_2 shipping terminals (export)

The shipping terminals for export of compressed hydrogen are described by the variables for expansion decision of terminal i $z_i^{cH_2\ terminal\ 05}$ [binary], expansion size of terminal i $m_i^{cH_2\ terminal\ 05}$ [kt cH_2 p.a.], expansion decision of a terminal for hydrogen tube trailers at terminal i $z_i^{cH_2\ terminal,ttt\ 05}$ [binary], size of the tube trailer terminal at the terminal i $m_i^{cH_2\ terminal,ttt\ 05}$ [kt cH_2 p.a.], annualized costs of the terminal i $c_i^{cH_2\ terminal\ 05}$ [kNOK2024 p.a.], and annual CO_2 emissions from all cH_2 export shipping terminals in Norway $e^{cH_2\ terminal\ 05}$ [tCO_{2eq} p.a.].

The upper bound ub and lower bound lb of the expansion size were chosen as reasonable engineering values.

$$m_i^{cH_2\ terminal\ 05} \geq lb \cdot z_i^{cH_2\ terminal\ 05}\ \forall i \in I_{5,cH_2}$$

$$m_i^{cH_2\ terminal\ 05} \leq ub \cdot z_i^{cH_2\ terminal\ 05}\ \forall i \in I_{5,cH_2}$$

The expansion size of the terminal i is linked to the transport edges for inflow and outflow. On the inflow side, hydrogen is received either via compressed hydrogen tube trailer or hydrogen pipeline (i.e., for on-site hydrogen production).

$$m_i^{cH_2\ terminal\ 05} = \sum_{j \in I_3} m_{ji}^{cH_2\ tube\ trailer\ 04} + m_{ji}^{cH_2\ pipeline\ 04}\ \forall i \in I_{5,cH_2}$$

On the outflow side, hydrogen is exported via compressed hydrogen shipping $m_{ij}^{cH_2\ shipping\ 06}$ [kt cH_2 p.a.] on route ij to all import terminals $j \in I_{7,cH_2}$.

$$m_i^{cH_2\ terminal\ 05} = \sum_{j \in I_{7,cH_2}} m_{ij}^{cH_2\ shipping\ 06}\ \ \forall i \in I_{5,cH_2}$$

The expansion size of the compressed hydrogen tube trailer terminal is given by the size of the tube trailer transport edge.

$$m_i^{cH_2\ terminal,ttt\ 05} = \sum_{j \in I_3} m_{ji}^{cH_2\ tube\ trailer\ 04}\ \forall i \in I_{5,cH_2}$$

$$m_i^{cH_2\ terminal,ttt\ 05} \leq ub \cdot z_i^{cH_2\ terminal,ttt\ 05}\ \forall i \in I_{5,cH_2}$$

The constraint which defines the practical upper bound of the terminal throughput is the utilization constraint. The total annual time spent at the terminal i for loading compressed hydrogen ships must be less than or equal to 8760h and is given by the time spent at the terminal i for one loading operation $t^{cH_2\ ship,fill}$ [h] times the number of loading operations per year. The latter is equal to the number of outgoing trips $n_{ij}^{cH_2\ shipping\ trips\ 06}$ [-] from terminal i to all import terminals $j \in I_{7,cH_2}$. A trip is defined as one full export operation, consisting of loading at the export terminal, sailing to the import terminal, unloading at the import terminal and sailing back to the export terminal.

$$\sum_{j \in I_{7,cH_2}} n_{ij}^{cH_2\ shipping\ trips\ 06} \cdot t^{cH_2\ ship,fill} \leq 8760\ [h/a]\ \forall i \in I_{5,cH_2}$$

The CO_2 emissions for cH_2 export shipping terminals are calculated based on the utility consumption. The only utility with significant CO_2 emissions that is considered is electricity with the utility factor $m^{cH_2\ terminal,el\ cons\ 05}$ [MWh/kg cH_2] for the main plant, the utility factor $m^{cH_2\ terminal,ttt\ el\ cons\ 05}$ [MWh/kg cH_2] for the tube trailer terminal and the emission factor $e^{el,NO}$ [kg CO_{2eq} / MWh].

$$e^{cH_2\ terminal\ 05} = \sum_{i \in I_{5,cH_2}} \left(m_i^{cH_2\ terminal\ 05} \cdot m^{cH_2\ terminal,el\ cons\ 05} + \sum m_i^{cH_2\ terminal,ttt\ 05} \cdot m^{cH_2\ terminal,ttt\ el\ cons\ 05}\right) \cdot e^{el,NO} \cdot 1000\ [t/kt]$$

The costs for shipping terminals for export of compressed hydrogen include investment costs $c_i^{cH_2\ terminal,inv\ 05}$ [kNOK2024 p.a.], maintenance costs, staff costs $c_i^{cH_2\ terminal,staff\ 05}$ [kNOK2024 p.a.] and costs for the utilities electricity $c_i^{cH_2\ terminal,el\ 05}$ [kNOK2024 p.a.] and cooling water (i.e., given by the specific cost factor $c_i^{cH_2\ terminal,cw,specific\ 05}$ [NOK2024/kg cH_2]). Electricity costs are calculated based on the specific electricity consumption and the electricity price at terminal i. The cost factor $c_i^{cH_2\ terminal,inv\ 05}$ was calculated based on analysis from a previous study [17] and was annualized using the capital recovery factor $crf^{cH_2\ terminal}$, which was calculated based on a terminal lifetime of 20 years and the given WACC (see supplementary material, section 1.1). It includes the investment costs for a tube trailer terminal $c_i^{cH_2\ terminal,ttt\ inv\ 05}$ [kNOK2024 p.a.] with the expansion size $m_i^{cH_2\ terminal,ttt\ 05} = m_i^{cH_2\ terminal\ 05}$. For accurately considering the tube trailer terminal costs, the cost factor $c_i^{cH_2\ terminal,ttt\ inv\ 05}$ has to be subtracted from the cost term $c_i^{cH_2\ terminal,inv\ 05}$ first and then separately considered given the actual expansion size $m_i^{cH_2\ terminal,ttt\ 05}$. The cost $c_i^{cH_2\ terminal,ttt\ inv\ 05}$ is calculated based on the expansion size and the capital recovery factor crf^{ttt}, which was calculated based on a lifetime for hydrogen compressors of 15 years and the given WACC.

$$c_i^{cH_2\ terminal,inv\ 05} = \left(1.64 \cdot m_i^{cH_2\ terminal\ 05}/26.2975 \cdot 100\ \ [MW/kta^{-1}] + 197.1\right) \cdot crf^{cH_2\ terminal}\ \forall i \in I_{5,cH_2}$$

$$c_i^{cH_2\ terminal,ttt\ inv\ 05} = \left(0.505 \cdot m_i^{cH_2\ terminal,ttt\ 05}/26.2975 \cdot 100\ [MW/kta^{-1}] + 20.55\right) \cdot crf^{ttt}\ \forall i \in I_{5,cH_2}$$

$$c_i^{cH_2\ terminal,el\ 05} = \Big(m_i^{cH_2\ terminal\ 05} \cdot m^{cH_2\ terminal,el\ cons\ 05} + m_i^{cH_2\ terminal,ttt\ 05} \cdot m^{cH_2\ terminal,ttt\ el\ cons\ 05}\Big) \cdot c_i^{el} \cdot 1000\ [t/kt]\ \forall i \in I_{5,cH_2}$$

$$c_i^{cH_2\ terminal\ 05} = \Big(c_i^{cH_2\ terminal,inv\ 05} - \Big(0.505 \cdot m_i^{cH_2\ terminal\ 05}/26.2975 \cdot 100\ [MW/kta^{-1}] + 20.55\Big) * crf^{ttt}\Big) \cdot (1 + 0.05/1.05/1.093) \cdot z_i^{cH_2\ terminal\ 05} + c_i^{cH_2\ terminal,ttt\ inv\ 05} \cdot z_i^{cH_2\ terminal,ttt\ 05} + c_i^{cH_2\ terminal,el\ 05} + c_i^{cH_2\ terminal,staff\ 05} \cdot z_i^{cH_2\ terminal\ 05} + c_i^{cH_2\ terminal,cw,specific\ 05} \cdot m_i^{cH_2\ terminal\ 05} \cdot 1000\ [t/kt]\ \forall i \in I_{5,cH_2}$$

2.3.1.4. Wood chip shipping terminals (export)

The shipping terminals for export of wood chips are described by the variables for expansion size of terminal i $m_i^{wc\ terminal\ 05}$ [kt cH_2 p.a.], annualized costs of the terminal i $c_i^{wc\ terminal\ 05}$ [kNOK2024 p.a.], and annual CO_2 emissions from all wood chip export shipping terminals in Norway $e^{wc\ terminal\ 05}$ [tCO_{2eq} p.a.].

The expansion size of the terminal i is linked to the transport edges for inflow and outflow. On the inflow side, timber is sourced via timber trucking from forest resources.

$$m_i^{wc\ terminal\ 05} = \sum_{j \in I_1} m_{ji}^{timber\ truck\ 04}\ \forall i \in I_{5,wc}$$

At the terminal, wood chips are produced from incoming timber with a 1:1 conversion ratio. On the outflow side, wood chips are exported via bulk shipping $m_{ij}^{wc\ shipping\ 06}$ [kt wc p.a.] on route ij to all import terminals $j \in I_{7,wc}$.

$$m_i^{wc\ terminal\ 05} = \sum_{j \in I_{7,wc}} m_{ij}^{wc\ shipping\ 06}\ \forall i \in I_{5,wc}$$

The CO_2 emissions for wood chip export shipping terminals are calculated based on the electricity consumption for wood chip production.

$$e^{wc\ terminal\ 05} = \sum_{i \in I_{5,wc}} m_i^{wc\ terminal\ 05} \cdot 52\ [kJ/kg]\ /\ 3600\ [kJ/kWh] \cdot e^{el,NO}$$

The costs for wood chip export shipping terminals include utility costs for wood chip production, and terminal fees as stated by the terminal operators. Terminal fees are separated into time fees, waterway fees and quay fees. Each terminal has a different calculation logic for the specific terminal fees $c_i^{wc\ terminal,fee\ 05}$ [kNOK2024/trip]. The components for the specific terminal fees are given as supplementary material. The costs are then given by the product of the fees cost per trip times the annual number of outgoing trips $n_{ij}^{wc\ shipping\ 06}$ on each route ij to the import terminals $j \in I_{7,wc}$.

$$c_i^{wc\ terminal\ 05} = \sum_{j \in I_{7,wc}} n_{ij}^{wc\ shipping\ 06} \cdot c_i^{wc\ terminal,fee\ 05}\ \forall i \in I_{5,wc}$$

2.3.1.5. cH_2 shipping terminals (import)

The shipping terminals for import of compressed hydrogen are described by the variables for expansion decision of terminal i $z_i^{cH_2\ terminal\ 07}$ [binary], expansion size of terminal i $m_i^{cH_2\ terminal\ 07}$ [kt cH_2 p.a.], annualized costs of the terminal i $c_i^{cH_2\ terminal\ 07}$ [kNOK2024 p.a.], and annual CO_2 emissions from all cH_2 import shipping terminals $e^{cH_2\ terminal\ 07}$ [tCO_{2eq} p.a.].

The upper bound ub and lower bound lb of the expansion size were chosen as reasonable engineering values.

$$m_i^{cH_2\ terminal\ 07} \geq lb \cdot z_i^{cH_2\ terminal\ 07}\ \forall i \in I_{7,cH_2}$$

$$m_i^{cH_2\ terminal\ 07} \leq ub \cdot z_i^{cH_2\ terminal\ 07}\ \forall i \in I_{7,cH_2}$$

The expansion size of the terminal i is linked to the transport edges for inflow and outflow. On the inflow side, hydrogen is sourced via compressed hydrogen shipping from export terminals in Norway.

$$m_i^{cH_2\ terminal\ 07} = \sum_{j \in I_{5,cH_2}} m_{ji}^{cH_2\ shipping\ 06}\ \forall i \in I_{7,cH_2}$$

The constraint which defines the practical upper bound of the terminal throughput is the utilization. The total annual time spent at the terminal i for unloading compressed hydrogen ships must be less than or equal to 8760h and is given by the time spent at the terminal i for one unloading operation $t^{cH_2\ ship,empty}$ [h] times the number of unloading operations per year. The latter is equal to the number of incoming trips $n_{ji}^{cH_2\ shipping\ trips\ 06}$ [-] from all export terminals $j \in I_{5,cH_2}$ to terminal i.

$$\sum_{j \in I_{5,cH_2}} n_{ji}^{cH_2\ shipping\ trips\ 06} \cdot t^{cH_2\ ship,empty} \leq 8760\ [h/a]\ \forall i \in I_{7,cH_2}$$

The CO_2 emissions for cH_2 import shipping terminals are calculated based on the utility consumption. The only utility with significant CO_2 emissions that is considered is electricity with the utility factor $m^{cH_2\ terminal,el\ cons\ 07}$ [MWh/kg cH_2] and the emission factor $e^{el,DE}$ [kg CO_{2eq} / MWh].

$$e^{cH_2\ terminal\ 07} = \sum_{i \in I_{7,cH_2}} m_i^{cH_2\ terminal\ 07} \cdot m^{cH_2\ terminal,el\ cons\ 07} \cdot e^{el,DE} \cdot 1000\ [t/kt]$$

The costs for shipping terminals for import of compressed hydrogen include investment costs $c_i^{cH_2\ terminal,inv\ 07}$ [kNOK2024 p.a.], maintenance costs, staff costs $c_i^{cH_2\ terminal,staff\ 07}$ [kNOK2024 p.a.] and costs for electricity $c_i^{cH_2\ terminal,el\ 07}$ [kNOK2024 p.a.]. Electricity costs are calculated based on the specific electricity consumption and the electricity price at terminal i. The cost factor $c_i^{cH_2\ terminal,inv\ 07}$ was calculated based on analysis from a previous study [17] given the terminal expansion size and the number of modules per cH_2 ship $n^{cH_2\ ship,modules}$ [-] and was annualized using the capital recovery factor $crf^{cH_2\ terminal}$.

$$c_i^{cH_2\ terminal,inv\ 07} = \left(0.694 \cdot m_i^{cH_2\ terminal\ 07}/26.2975 \cdot 100\ [MW/kta^{-1}] + 0.24 \cdot n^{cH_2\ ship,modules}\right) \cdot crf^{cH_2\ terminal}\ \forall i \in I_{7,cH_2}$$

$$c_i^{cH_2\ terminal,el\ 07} = m_i^{cH_2\ terminal\ 07} \cdot m^{cH_2\ terminal,el\ cons\ 07} \cdot c_i^{el} \cdot 1000\ [t/kt]\ \forall i \in I_{7,cH_2}$$

$$c_i^{cH_2\ terminal\ 07} = c_i^{cH_2\ terminal,inv\ 07} \cdot z_i^{cH_2\ terminal\ 07} \cdot (1 + 0.05/1.05/1.093) + c_i^{cH_2\ terminal,el\ 07} + c_i^{cH_2\ terminal,staff\ 07} \cdot z_i^{cH_2\ terminal\ 07}\ \forall i \in I_{7,cH_2}$$

2.3.1.6. Wood chip shipping terminals (import)

The shipping terminals for import of wood chips are described by the variable for annualized costs of the terminal i $c_i^{wc\ terminal\ 07}$ [kNOK2024 p.a.]. The annualized costs are linked to the number of incoming trips $n_{ji}^{wc\ shipping\ trips\ 06}$ [-] from all export terminals $j \in I_{5,wc}$ to terminal i. The specific costs $c_i^{wc\ terminal,fee\ 07}$ [kNOK2024/Trip] consider time fees and quay fees and are calculated from the deadweight of the wood chip ship $m^{wc\ ship,dwt}$ [tonnes] and the gross tonnage of the wood chip ship $m^{wc\ ship,gt}$ [-].

$$c_i^{wc\ terminal,fee\ 07} = 0.598 \cdot m^{wc\ ship,dwt} \cdot \frac{11.63}{1000}\left[\frac{tNOK2024}{EUR2024}\right] + 0.2716 \cdot m^{wc\ ship,gt} \cdot \frac{11.63}{1000}\left[\frac{tNOK2024}{EUR2024}\right]$$

$$c_i^{wc\ terminal\ 07} = \sum_{j \in I_{5,wc}} n_{ji}^{wc\ shipping\ 06} \cdot c_i^{wc\ terminal,fee\ 07}\ \forall i \in I_{7,wc}$$

2.3.1.7. Biomass gasification (DE)

The biomass gasification plants for hydrogen production in Germany are located at the import terminals for wood chips and have thus the same indices. They are described by the variables for expansion decision of plant i $z_i^{gasification\ 07}$ [binary], expansion size of plant i $m_i^{gasification\ 07}$ [kt cH_2 p.a.], annualized costs of the plant i $c_i^{gasification\ 07}$ [kNOK2024 p.a.], and annual CO_2 emissions from all biomass gasification hubs in Germany $e^{gasification\ 07}$ [tCO_{2eq} p.a.]. The upper bound ub and lower bound lb of the expansion size were chosen as reasonable engineering values.

$$m_i^{gasification\ 07} \geq lb \cdot z_i^{gasification\ 07}\ \forall i \in I_{7,wc}$$

$$m_i^{gasification\ 07} \leq ub \cdot z_i^{gasification\ 07}\ \forall i \in I_{7,wc}$$

The expansion size of the plant i is linked to the transport edges for inflow. On the inflow side, timber is received and converted to hydrogen with the conversion rate $m^{gasification,conv}$ [kg cH_2 / kg timber].

$$m_i^{gasification\ 07} = \sum_{j \in I_{5,wc}} n_{ji}^{wc\ shipping\ 06} \cdot m^{gasification,conv}\ \forall i \in I_{7,wc}$$

The CO_2 emissions for biomass gasification production are calculated based on the utility consumption. The considered utilities are electricity with the utility factor $m^{gasification,el\ cons\ 07}$ [MWh/kg cH_2] and the emission factor $e^{el,DE}$ [kg CO_{2eq} / MWh] as well as natural gas for heating with the utility factor $m^{gasification,heat\ cons\ 07}$ [MWh/kg cH_2] and the emission factor $e^{ng,DE}$ [kg CO_{2eq} / MWh].

$$e^{gasification\ 07} = \sum_{i \in I_{7,wc}} m_i^{gasification\ 07} \cdot \left(m^{gasification,el\ cons\ 07} \cdot e^{el,DE} + m^{gasification,heat\ cons\ 07} \cdot e^{ng,DE}\right) \cdot 1000\ [t/kt]$$

The cost function links the annualized plant costs to the expansion size. The cost function considers annualized investment costs as well as operating costs. A linear regression was performed on the non-linear cost function which was then used to link $c_i^{gasification\ 07}$ to the expansion size. For more details on the regression, see supplementary material section 3.3.

$$c_i^{gasification\ 07} = \left(4.33 \cdot m_i^{gasification\ 07}/26.2975 \cdot 100\ [MW/kta^{-1}] + 229\right) \cdot 1000\ \left[\frac{tNOK}{MNOK}\right] \cdot z_i^{gasification\ 07}\ \forall i \in I_{7,wc}$$

2.3.1.8. Demand node

A demand node was added to the model which ensures that the imported hydrogen and the hydrogen produced at import wood chip shipping terminals sum up to the final hydrogen demand $m^{cH_2,demand}$.

$$m^{cH_2,demand} = \sum_{i \in I_{5,cH_2}} m_i^{cH_2\ terminal\ 05} + \sum_{i \in I_{7,wc}} m_i^{gasification\ 07}$$

2.3.2. Description of edges

2.3.2.1. Timber trucking

The timber trucking edges connect the nodes for timber resources $i \in I_1$ with the nodes for biomass gasification $i \in I_3$ and wood chip shipping terminals $i \in I_{5,wc}$. The edges are described by the variables for timber trucking amount from timber resources to biomass gasification hubs $m_{ij}^{timber\ truck\ 02} \mid i \in I_1, j \in I_3$ [kt timber p.a.], timber trucking amount from timber resources to wood chip shipping terminals $m_{ij}^{timber\ truck\ 04} \mid i \in I_1, j \in I_{5,wc}$ [kt timber p.a.], annual costs of the timber fleet $c^{timber\ truck}$

[kNOK2024 p.a.], number of trucks in the timber fleet $n^{\text{timber truck}}$ [-], annual CO_2 emissions from all timber trucking operations $e^{\text{timber truck}}$ [tCO_{2eq} p.a.]. The costs consider annualized capital costs, annual fixed costs as well as variable driving costs as described in the supplementary material section 4.1.2. The annualized capital costs are calculated based on a regression on annual driven distance by the fleet $d^{\text{timber truck}}$ [Mm p.a.] and number of trucks in the fleet. The fixed operational costs are based on the specific cost factor $c^{\text{timber truck,fixed opex}}$ [kNOK2024 p.a. and truck]. The variable operational costs are based on the specific cost factor $c^{\text{timber truck,variable opex}}$ [NOK2024/km].

$$c^{\text{timber truck}} = 1.641 \cdot d^{\text{timber truck}} + 722.25 \cdot n^{\text{timber truck}} + c^{\text{timber truck,fixed opex}} \cdot n^{\text{timber truck}} + c^{\text{timber truck,variable opex}} \cdot d^{\text{timber truck}}$$

The annual driven distance by the fleet is calculated based on the transport distance (i.e., twice the distance between source and destination since we assume driving back empty) times the transport amount divided by the payload of the timber truck $m^{\text{timber truck,payload}}$ [tonnes]. The transport distances through the road network from timber resources to biomass gasification hubs $d_{ij}^{\text{timber transport 02}} \mid i \in I_1, j \in I_3$ [km] and from timber resources to wood chip shipping terminals $d_{ij}^{\text{timber transport 04}} \mid i \in I_1, j \in I_{5,wc}$ [km] were pre-calculated as described in section 2.2.3.3.

$$d^{\text{timber truck}} = \sum_{i \in I_1} \sum_{j \in I_3} d_{ij}^{\text{timber transport 02}} \cdot 2 \cdot m_{ij}^{\text{timber truck 02}} / m^{\text{timber truck,payload}} \cdot 1000\ [t/kt] + \sum_{i \in I_1} \sum_{j \in I_{5,wc}} d_{ij}^{\text{timber transport 04}} \cdot 2 \cdot m_{ij}^{\text{timber truck 04}} / m^{\text{timber truck,payload}} \cdot 1000\ [t/kt]$$

The number of trucks in the fleet is calculated as the sum of the operational time required on each route divided by the utilization of a timber truck per year $t^{\text{timber truck,annual}}$ [h/a]. The driving times through the road network from timber resources to biomass gasification hubs $t_{ij}^{\text{timber transport 02}} \mid i \in I_1, j \in I_3$ [h] and from timber resources to wood chip shipping terminals $t_{ij}^{\text{timber transport 04}} \mid i \in I_1, j \in I_{5,wc}$ [h] were pre-calculated as described in section 2.2.3.3. The total trip time is calculated as the sum of driving time from source to destination and back to the source plus the terminal times for loading and unloading $t^{\text{timber truck,terminal}}$ [h/trip].

$$n^{\text{timber truck}} \geq \sum_{i \in I_1} \sum_{j \in I_3} t_{ij}^{\text{timber transport 02}} \cdot 2 \cdot m_{ij}^{\text{timber truck 02}} / m^{\text{timber truck,payload}} \cdot 1000\ [t/kt] / t^{\text{timber truck,annual}} + \sum_{i \in I_1} \sum_{j \in I_{5,wc}} t_{ij}^{\text{timber transport 04}} \cdot 2 \cdot m_{ij}^{\text{timber truck 04}} / m^{\text{timber truck,payload}} \cdot 1000\ [t/kt] / t^{\text{timber truck,annual}}$$

The annual fleet emissions are calculated as the sum of specific emissions per trip on each route times the number of trips on route ij. The specific emissions for routes from timber resources to biomass gasification hubs $e_{ij}^{\text{timber transport 02}} \mid i \in I_1, j \in I_3$ [tCO_{2eq}/trip] and the specific emissions for routes from timber resources to wood chip shipping terminals $e_{ij}^{\text{timber transport 04}} \mid i \in I_1, j \in I_{5,wc}$ [tCO_{2eq}/trip] consider emissions from driving as well as emissions from the loading and unloading operation. The specific emissions are calculated from the specific fuel consumption during driving (empty) $m^{\text{timber truck,fc,empty}}$ [l/100km], the specific fuel consumption during driving (fully loaded) $m^{\text{timber truck,fc,full}}$ [l/100km], and the specific fuel consumption during terminal $m^{\text{timber truck,fc,terminal}}$ [l/h].

$$e^{\text{timber truck}} = \sum_{i \in I_1} \sum_{j \in I_3} m_{ij}^{\text{timber truck 02}} / m^{\text{timber truck,payload}} \cdot 1000\ [t/kt] \cdot e_{ij}^{\text{timber transport 02}} + \sum_{i \in I_1} \sum_{j \in I_{5,wc}} m_{ij}^{\text{timber truck 04}} / m^{\text{timber truck,payload}} \cdot 1000\ [t/kt] \cdot e_{ij}^{\text{timber transport 04}}$$

$$e_{ij}^{\text{timber transport 02}} = \left(\left(m^{\text{timber truck,fc,full}} / 100 \cdot d_{ij}^{\text{timber transport 02}} + m^{\text{timber truck,fc,empty}} / 100 \cdot d_{ij}^{\text{timber transport 02}} + m^{\text{timber truck,fc,terminal}} \cdot t^{\text{timber truck,terminal}} \right) / 1000\ [m^3 l^{-1}] \cdot \text{diesel density}\ [kgm^{-3}] \right) \cdot e^{\text{diesel}} \ \forall i \in I_1, \forall j \in I_3$$

$$e_{ij}^{\text{timber transport 04}} = \left(\left(m^{\text{timber truck,fc,full}} / 100 \cdot d_{ij}^{\text{timber transport 04}} + m^{\text{timber truck,fc,empty}} / 100 \cdot d_{ij}^{\text{timber transport 04}} + m^{\text{timber truck,fc,terminal}} \cdot t^{\text{timber truck,terminal}} \right) / 1000\ [m^3 l^{-1}] \cdot \text{diesel density}\ [kgm^{-3}] \right) \cdot e^{\text{diesel}} \ \forall i \in I_1, \forall j \in I_{5,wc}$$

2.3.2.2. cH_2 pipeline

The model does not consider pipeline transport for compressed hydrogen transport between two different places. However, the model allows for pipeline transport from biomass gasification hubs to cH_2 shipping terminals (export) if both nodes are located at the same place (i.e., less than 5km apart). In that case, we assume that there are zero costs and emissions for pipeline transport. The transport distances through the road network from biomass gasification hubs to cH_2 shipping terminals $d_{ij}^{cH_2\text{ tube trailer }04} \mid i \in I_3, j \in I_{5,cH_2}$ [km] were pre-calculated as described in section 2.2.3.3.

$$m_{ij}^{cH_2\text{ pipeline }04} \leq \left(d_{ij}^{cH_2\text{ tube trailer }04} < 5\right) \cdot \text{bigM} \; \forall i \in I_3 \; \forall j \in I_{5,cH_2}$$

2.3.2.3. cH_2 tube trailer

The cH_2 tube trailer edges connect the nodes for biomass gasification $i \in I_3$ with the nodes for cH_2 shipping terminals $i \in I_{5,cH_2}$. The edges are described by the variables for cH_2 tube trailer transport amount $m_{ij}^{cH_2\text{ tube trailer }04} \mid i \in I_3, j \in I_{5,cH_2}$ [kt cH_2 p.a.], annual costs of the fleet $c^{cH_2\text{ tube trailer }04}$ [kNOK2024 p.a.], number of trucks in the fleet $n^{cH_2\text{ tube trailer }04}$ [-], annual CO_2 emissions from all cH_2 tube trailer operations $e^{cH_2\text{ tube trailer }04}$ [tCO_{2eq} p.a.]. The annual cost for the cH_2 tube trailer fleet is calculated using a regression on the annual driven distance by the fleet $d^{cH_2\text{ tube trailer }04}$ [Mm p.a.] and the number of trucks in the fleet from a previous study [17]. The annual driven distance by the fleet is calculated based on the transport distance (i.e., twice the distance between source and destination since we assume driving back empty) times the transport amount divided by the payload of the cH_2 tube trailer $m^{cH_2\text{ tube trailer,payload}}$ [tonnes].

$$c^{cH_2\text{ tube trailer }04} = 4.9808 \cdot d^{cH_2\text{ tube trailer }04} + 9078.4 \cdot n^{cH_2\text{ tube trailer }04}$$

$$d^{cH_2\text{ tube trailer }04} = \sum_{i\in I_3} \sum_{j\in I_{5,cH_2}} d_{ij}^{cH_2\text{ tube trailer }04} \cdot 2 \cdot m_{ij}^{cH_2\text{ tube trailer }04} / m^{cH_2\text{ tube trailer,payload}} \cdot 1000\,[\text{t/kt}]$$

The number of trucks in the fleet is calculated as the sum of the operational time required on each route divided by the utilization of a cH_2 tube trailer per year $t^{cH_2\text{ tube trailer,annual}}$ [h/a]. The driving times through the road network from biomass gasification hubs to cH_2 shipping terminals (export) $t_{ij}^{cH_2\text{ tube trailer }04} \mid i \in I_3, j \in I_{5,cH_2}$ [h] were pre-calculated as described in section 2.2.3.3. The total trip time is calculated as the sum of driving time from source to destination and back to the source plus the terminal time $t^{cH_2\text{ tube trailer,terminal}}$ [h/trip]. The terminal time is the sum of required loading and unloading time plus 15 minutes for driving in and out of the terminal.

$$n^{cH_2\text{ tube trailer }04} \geq \sum_{i\in I_3} \sum_{j\in I_{5,cH_2}} t_{ij}^{cH_2\text{ tube trailer }04} \cdot 2 \cdot m_{ij}^{cH_2\text{ tube trailer }04} / m^{cH_2\text{ tube trailer,payload}} \cdot 1000\,[\text{t/kt}] / t^{cH_2\text{ tube trailer,terminal}}$$

The annual fleet emissions are calculated as the sum of specific emissions per trip on each route times the number of trips on route ij. The specific emissions $e_{ij}^{cH_2\text{ tube trailer }04} \mid i \in I_3, j \in I_{5,cH_2}$ [tCO_{2eq}/trip] consider emissions from driving and are calculated from the specific fuel consumption during driving $m^{cH_2\text{ tube trailer,fc}}$ [l/100km].

$$e^{cH_2\text{ tube trailer }04} = \sum_{i\in I_3} \sum_{j\in I_{5,cH_2}} m_{ij}^{cH_2\text{ tube trailer }04} / m^{cH_2\text{ tube trailer,payload}} \cdot 1000\,[\text{t/kt}] \cdot e_{ij}^{cH_2\text{ tube trailer }04}$$

$$e_{ij}^{cH_2\text{ tube trailer }04} = \left(\left(m^{cH_2\text{ tube trailer,fc}}/100 \cdot d_{ij}^{cH_2\text{ tube trailer }04} \cdot 2\right)/1000\,[\text{m}^3\text{l}^{-1}] \cdot \text{diesel density}\,[\text{kgm}^{-3}]\right) \cdot e^{\text{diesel}} \; \forall i \in I_3, \forall\, j \in I_{5,cH_2}$$

2.3.2.4. cH_2 shipping

The cH_2 shipping edges connect the nodes for cH_2 shipping terminals (export) $i \in I_{5,cH_2}$ with the nodes for cH_2 shipping terminals (import) $i \in I_{7,cH_2}$. The edges are described by the variables for cH_2 shipping amount $m_{ij}^{cH_2\text{ shipping }06} \mid i \in I_{5,cH_2}, j \in I_{7,cH_2}$ [kt cH_2 p.a.], number of annual trips on the route ij $n_{ij}^{cH_2\text{ shipping trips }06} \mid i \in I_{5,cH_2}, j \in I_{7,cH_2}$ [-], variable cost on the route ij $c_{ij}^{cH_2\text{ shipping,var }06} \mid i \in I_{5,cH_2}, j \in I_{7,cH_2}$ [kNOK2024 p.a.], number of cH_2 ships in the fleet $n^{cH_2\text{ shipping ships }06}$ [-], fixed annual costs of the fleet $c^{cH_2\text{ shipping,fixed }06}$ [kNOK2024 p.a.], annual CO_2 emissions from cH_2 shipping $e^{cH_2\text{ shipping }06}$ [tCO_{2eq} p.a.].

The number of ships in the fleet must be greater than the required number of ships (float) in the fleet. The number of ships required in the fleet is calculated as the sum of ships required on each route. We assume that one ship can sail different routes throughout the year. The number of ships required on route ij is calculated as the number of trips required on the route ij divided by number of trips a ship can do per year on route ij. The number of trips required on the route ij is defined as the shipping amount $m_{ij}^{cH_2\text{ shipping }06}$ divided by the payload of the ship $m^{cH_2\text{ ship,payload}}$ [tonnes cH_2]. The number of trips a ship can do per year on route ij is calculated as the maximum annual ship utilization $t^{cH_2\text{ ship,annual}}$ [h/a] divided by the trip time. The trip time is calculated as the time for sailing on route ij from the export terminal to the import terminal and back to the export terminal given the distance $d_{ij}^{cH_2\text{ shipping }06}$ [km] and a speed of $v^{cH_2\text{ ship}}$ [km/day] plus the time spent at terminal $t^{cH_2\text{ shipping,terminal}}$ [h/trip]. The time spent at terminal is the sum of ship loading time, ship unloading time and 30 minutes for docking and undocking for each terminal. The shipping distances $d_{ij}^{cH_2\ shipping\ 06}$ [km] were pre-calculated, see section 2.2.3.3.

$$n^{cH_2\ shipping\ ships\ 06} \geq \sum_{i \in I_{5,cH_2}} \sum_{j \in I_{7,cH_2}} m_{ij}^{cH_2\ shipping\ 06} / (m^{cH_2\ ship,payload} \cdot t^{cH_2\ ship,annual}) \cdot 1000\ [t/kt] \cdot (d_{ij}^{cH_2\ shipping\ 06} \cdot 2 \cdot 24\ [h/day] / v^{cH_2\ ship} + t^{cH_2\ shipping,terminal})$$

The number of trips conducted on route ij (integer) must be greater than the number of trips required on route ij.

$$n_{ij}^{cH_2\ shipping\ trips\ 06} \geq m_{ij}^{cH_2\ shipping\ 06} / m^{cH_2\ ship,payload} \cdot 1000\ [t/kt]\ \forall i \in I_{5,cH_2}, \forall\ j \in I_{7,cH_2}$$

The variable cost on route ij is calculated as the product of the number of trips conducted on route ij and the specific trip cost on route ij $c_{ij}^{cH_2\ shipping,trip\ 06}$ [kNOK2024/trip]. The specific trip costs are calculated as the fuel costs during sailing $c^{cH_2\ shipping,fuel\ 06}$ [kNOK2024/day] times the sailing time on route ij $t_{ij}^{cH_2\ shipping,sailing\ 06}$ [days/trip] plus the fuel costs during terminal. The fuel cost during sailing is calculated as the product of specific fuel consumption during sailing $m^{cH_2\ shipping\ fuel}$ [tonnes/day] and the cost for ship fuel. The specific fuel consumption during sailing is based on a previous study and considers the ship deadweight tonnage and ship speed [17]. The fuel consumption at terminal is assumed to be 5% of the fuel consumption during sailing. The sailing time on route ij $t_{ij}^{cH_2\ shipping,sailing\ 06}$ is calculated based on the trip distance and ship speed.

$$c_{ij}^{cH_2\ shipping,var\ 06} = n_{ij}^{cH_2\ shipping\ trips\ 06} \cdot c_{ij}^{cH_2\ shipping,trip\ 06}\ \forall i \in I_{5,cH_2}, \forall\ j \in I_{7,cH_2}$$

$$c_{ij}^{cH_2\ shipping,trip\ 06} = c^{cH_2\ shipping,fuel\ 06} \cdot t_{ij}^{cH_2\ shipping,sailing\ 06} + c^{cH_2\ shipping,fuel\ 06} \cdot 0.05/24\ [h/day] \cdot t^{cH_2\ shipping,terminal}\ \forall i \in I_{5,cH_2}, \forall\ j \in I_{7,cH_2}$$

$$t_{ij}^{cH_2\ shipping,sailing\ 06} = d_{ij}^{cH_2\ shipping\ 06} \cdot 2 / v^{cH_2\ ship} \forall i \in I_{5,cH_2}, \forall\ j \in I_{7,cH_2}$$

The fixed annual costs of the fleet are calculated as the product of the number of ships in the fleet times the fixed annual costs per cH_2 ship $c^{cH_2\ shipping,fixed,ship\ 06}$ [kNOK2024/a]. This cost factor includes investment costs, staff costs, insurance and maintenance costs and is based on a previous study [17].

$$c^{cH_2\ shipping,fixed\ 06} = n^{cH_2\ shipping\ ships\ 06} \cdot c^{cH_2\ shipping,fixed,ship\ 06}$$

The annual CO_2 emissions from cH_2 shipping are calculated as the product of annual fuel consumption on all cH_2 shipping routes times the emission factor for very low sulfur fuel oil (VLSFO) e^{VLSFO} [$kgCO_{2eq}$/kg].

$$e^{cH_2\ shipping\ 06} = \sum_{i \in I_{5,cH_2}} \sum_{j \in I_{7,cH_2}} (t_{ij}^{cH_2\ shipping,sailing\ 06} \cdot m^{cH_2\ shipping\ fuel} + t^{cH_2\ shipping,terminal} \cdot m^{cH_2\ shipping\ fuel} \cdot 0.05) \cdot n_{ij}^{cH_2\ shipping\ trips\ 06} \cdot e^{VLSFO}$$

2.3.2.5. Wood chip shipping

The wood chip shipping edges connect the nodes for wood chip shipping terminals (export) $i \in I_{5,wc}$ with the nodes for wood chip shipping terminals (import) $i \in I_{7,wc}$. The edges are described by the variables for wood chip shipping amount $m_{ij}^{wc\ shipping\ 06} \mid i \in I_{5,wc}, j \in I_{7,wc}$ [kt wood chips p.a.], number of annual trips on the route ij $n_{ij}^{wc\ shipping\ trips\ 06} \mid i \in I_{5,wc}, j \in I_{7,wc}$ [-], variable cost on the route ij $c_{ij}^{wc\ shipping,var\ 06} \mid i \in I_{5,wc}, j \in I_{7,wc}$ [kNOK2024 p.a.], number of wood chip ships in the fleet $n^{wc\ shipping\ ships\ 06}$ [-], fixed annual costs of the fleet $c^{wc\ shipping,fixed\ 06}$ [kNOK2024 p.a.], annual CO_2 emissions from wood chip shipping $e^{wc\ shipping\ 06}$ [tCO_{2eq} p.a.].

The number of ships in the fleet must be greater than the required number of ships (float) in the fleet. The number of ships required in the fleet is calculated as the sum of ships required on each route. We assume that one ship can sail different routes throughout the year. The number of ships required on route ij is calculated as the number of trips required on the route ij divided by number of trips a ship can do per year on route ij. The number of trips required on the route ij is defined as the shipping amount $m_{ij}^{wc\ shipping\ 06}$ divided by the payload of the ship $m^{wc\ ship,dwt}$ [tonnes wood chips]. The number of trips a ship can do per year on route ij is calculated as the maximum annual ship utilization $t^{wc\ ship,annual}$ [h/a] divided by the trip time. The trip time is calculated as the time for sailing on route ij from the export terminal to the import terminal and back to the export terminal given the distance $d_{ij}^{wc\ shipping\ 06}$ [km] and a speed of $v^{wc\ ship}$ [km/day] plus the time spent at terminal $t^{wc\ shipping,terminal}$ [h/trip]. The time spent at terminal is the sum of ship loading time and ship unloading time. The shipping distances $d_{ij}^{wc\ shipping\ 06}$ [km] were pre-calculated, see section 2.2.3.7.

$$n^{wc\ shipping\ ships\ 06} \geq \sum_{i \in I_{5,wc}} \sum_{j \in I_{7,wc}} m_{ij}^{wc\ shipping\ 06} / (m^{wc\ ship,dwt} \cdot t^{wc\ ship,annual}) \cdot 1000\ [t/kt] \cdot (d_{ij}^{wc\ shipping\ 06} \cdot 2 \cdot 24 / v^{wc\ ship} + t^{wc\ shipping,terminal})$$

The number of trips conducted on route ij (integer) must be greater than the number of trips required on route ij.

$$n_{ij}^{\text{wc shipping trips 06}} \geq m_{ij}^{\text{wc shipping 06}}/m^{\text{wc ship,dwt}} \cdot 1000\ [\text{t/kt}]\ \forall i \in I_{5,wc}, \forall j \in I_{7,wc}$$

The variable cost on route ij is calculated as the product of the number of trips conducted on route ij and the specific trip cost on route ij $c_{ij}^{\text{wc shipping,trip 06}}$ [kNOK2024/trip]. The specific trip costs are calculated as the fuel costs during sailing $c^{\text{wc shipping,fuel 06}}$ [kNOK2024/day] times the sailing time on route ij $t_{ij}^{\text{wc shipping,sailing 06}}$ [days/trip] plus the fuel costs during terminal. The fuel cost during sailing is calculated as the product of specific fuel consumption during sailing $m^{\text{wc shipping fuel}}$ [tonnes/day] and the cost for ship fuel. The specific fuel consumption during sailing is calculated using the same logic as for the cH_2 ship, see section 2.3.2.4. The sailing time on route ij $t_{ij}^{\text{wc shipping,sailing 06}}$ is calculated based on the trip distance and ship speed.

$$c_{ij}^{\text{wc shipping,var 06}} = n_{ij}^{\text{wc shipping trips 06}} \cdot c_{ij}^{\text{wc shipping,trip 06}}\ \forall i \in I_{5,wc}, \forall j \in I_{7,wc}$$

$$c_{ij}^{\text{wc shipping,trip 06}} = c^{\text{wc shipping,fuel 06}} \cdot t_{ij}^{\text{wc shipping,sailing 06}} + c^{\text{wc shipping,fuel 06}} \cdot 0.05/24\ [\text{h/day}] \cdot t^{\text{wc shipping,terminal}}\ \forall i \in I_{5,wc}, \forall j \in I_{7,wc}$$

$$t_{ij}^{\text{wc shipping,sailing 06}} = d_{ij}^{\text{wc shipping 06}} \cdot 2/v^{\text{wc ship}}\ \forall i \in I_{5,wc}, \forall j \in I_{7,wc}$$

The fixed annual costs of the fleet are calculated as the product of the number of ships in the fleet times the fixed annual costs per wood chip ship $c^{\text{wc shipping,fixed,ship 06}}$ [kNOK2024/a]. This cost factor includes investment costs, staff costs, insurance and maintenance costs and is based on a previous study, see supplementary material section 4.2.2.

$$c^{\text{wc shipping,fixed 06}} = n^{\text{wc shipping ships 06}} \cdot c^{\text{wc shipping,fixed,ship 06}}$$

The annual CO_2 emissions from wood chip shipping are calculated as the product of annual fuel consumption on all wood chip shipping routes times the emission factor for very low sulfur fuel oil (VLSFO) e^{VLSFO} [$kgCO_{2eq}$/kg].

$$e^{\text{wc shipping 06}} = \sum_{i \in I_{5,wc}} \sum_{j \in I_{7,wc}} (t_{ij}^{\text{wc shipping,sailing 06}} \cdot m^{\text{wc shipping fuel}} + t^{\text{wc shipping,terminal}} \cdot m^{\text{wc shipping fuel}} \cdot 0.05) \cdot n_{ij}^{\text{wc shipping trips 06}} \cdot e^{\text{VLSFO}}$$

2.3.3. Objective function

The objective is stated below, where θ is the set of meta parameters and X are the decision variables in the supply chain graph.

$$p_{\text{supply chain}}(\theta, m^{cH_2,\text{demand}}): \min_X f_{\text{cost}}(X, \theta, m^{cH_2,\text{demand}})$$

$$\begin{aligned} f_{\text{cost}}(X, \theta, m^{cH_2,\text{demand}}) = & \underbrace{\sum_{i \in I_1} c_i^{\text{timber 01}}}_{\text{Timber production}} + \underbrace{c^{\text{timber truck}}}_{\text{Timber truck transport}} \\ & + \underbrace{\sum_{i \in I_3} c_i^{\text{gasification 03}}}_{\text{Gasification hub (NO)}} + \underbrace{c^{cH_2\text{ tube trailer 04}}}_{cH_2\text{ tube trailer}} + \underbrace{\sum_{i \in I_{5,cH_2}} c_i^{cH_2\text{ terminal 05}}}_{cH_2\text{ shipping terminal (NO)}} \\ & + \underbrace{\sum_{i \in I_{5,wc}} c_i^{\text{wc terminal 05}}}_{\text{wc shipping terminal (NO)}} \\ & + \underbrace{\sum_{i \in I_{5,cH_2}} \sum_{j \in I_{7,cH_2}} c_{ij}^{cH_2\text{ shipping,var 06}} + c^{cH_2\text{ shipping,fixed 06}}}_{cH_2\text{ shipping}} \\ & + \underbrace{\sum_{i \in I_{5,wc}} \sum_{j \in I_{7,wc}} c_{ij}^{\text{wc shipping,var 06}} + c^{\text{wc shipping,fixed 06}}}_{\text{Wood chip shipping}} \\ & + \underbrace{\sum_{i \in I_{7,cH_2}} c_i^{cH_2\text{ terminal cost 07}}}_{cH_2\text{ shipping terminal (DE)}} + \underbrace{\sum_{i \in I_{7,wc}} c_i^{\text{wc terminal 07}}}_{\text{wc shipping terminal (DE)}} + \underbrace{\sum_{i \in I_{7,wc}} c_i^{\text{gasification 07}}}_{\text{Gasification hub (DE)}} \end{aligned}$$

2.4. Model summary

The supply chain superstructure model is formulated as a mixed-integer linear problem (MILP) using Pyomo [24] and solved using the commercial solver Gurobi [25]. The decision variables of the supply chain graph (e.g., expansion size of nodes, thickness of transport edges) are implemented as nonnegative float, integer or binary variables. All variables are connected to each other via node or edge constraints. The objective is to minimize the total annualized supply chain costs given a final hydrogen demand at the end node. In that manner, the supply chain superstructure is represented as a MILP problem with 35909 continuous variables, 122 binary variables and 43 integer variables.

3. Model Results

3.1. Base case

The base case is defined as the optimal solution to the optimization problem for a hydrogen demand of 400 MW (LHV). The hydrogen throughput in MW should be understood as an average annual throughput with the conversion factor of 100 MW = 26.2975 kt/a. The solution shows that forest resources along the coast in counties with cheap timber prices are used, all the way up to Tromsø. Further, wood chips are shipped from 15 different Norwegian shipping terminals to Wilhelmshaven, where hydrogen is produced. The operation requires 24 trucks to transport timber to the terminals and 1 ship to ship the wood chips. No hydrogen is produced in Norway and shipping of cH_2 is omitted. Levelized costs of hydrogen of 33.4 NOK/kg_{H2} are achieved.

3.2. Hydrogen shipping case

Since no compressed hydrogen shipping was observed in the base case result, a second hydrogen shipping case was defined. Herein, an additional constraint was added to the optimization model. The constraint sets the expansion decision of the biomass gasification plant

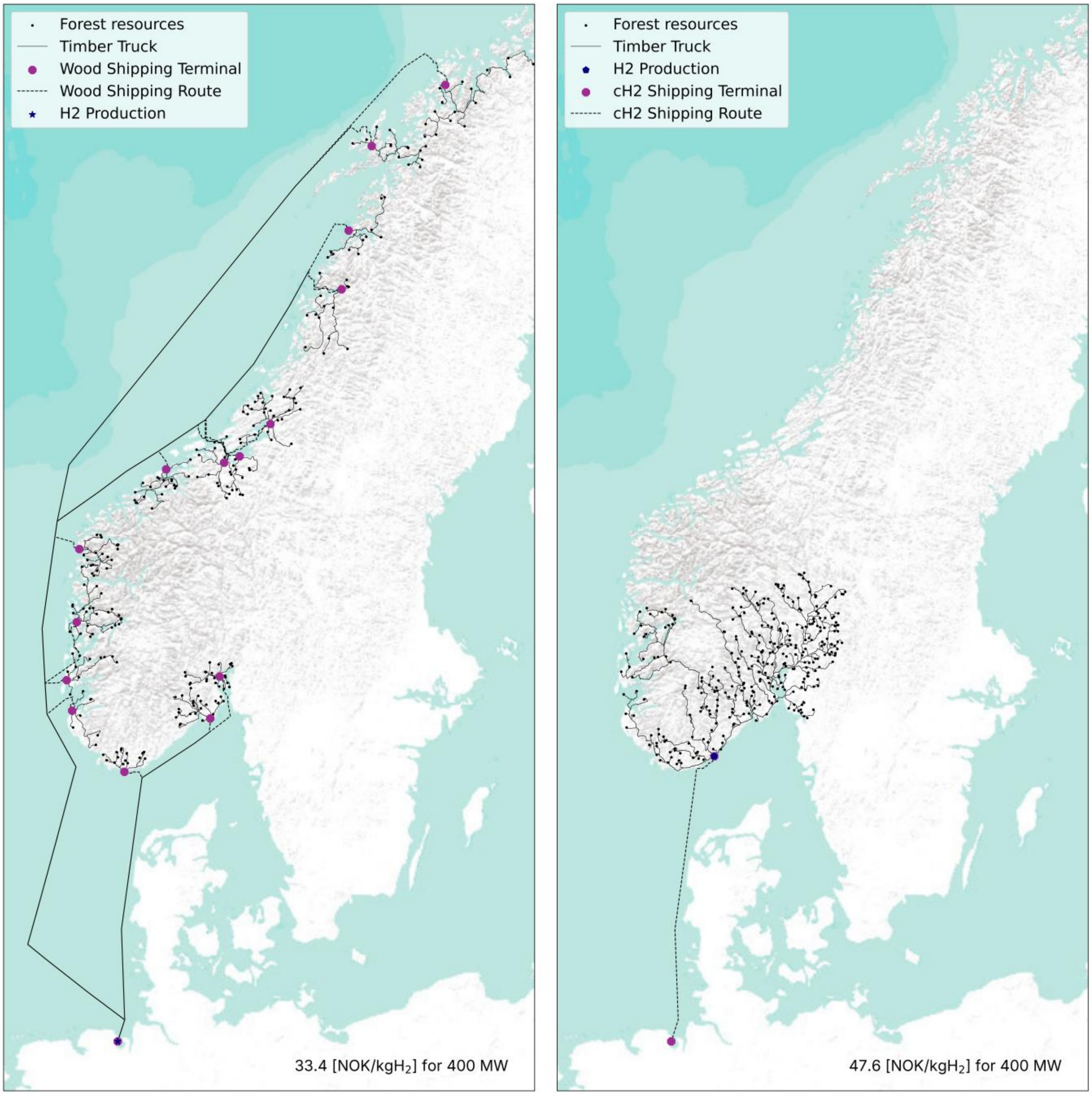

Fig 3: Supply chain for 400MW for the base case (left) and for cH_2 shipping (right)

in Germany $z_i^{\text{gasification 07}} = 0 \, \forall i \in I_{7,wc}$. Hence, hydrogen production in Norway and compressed hydrogen shipping is enforced. The optimal solution of the model then obtained by solving for a hydrogen demand of 400MW. Only one cH_2 shipping terminal is built (i.e., Grimstad) and timber is sourced regionally around that terminal (see Fig 3). Compressed hydrogen is shipped from Grimstad to Wilhelmshaven, requiring 4 ships on 612 trips. Levelized costs of hydrogen of 47.6 NOK/kg_{H2} are achieved.

3.3. Comparison of cases

In the following section, the two cases defined above are compared (see Fig 1). The term "wood chip shipping" case is used synonymously with the term base case, since the base case only shows wood chip shipping.

Fig 4 shows the specific costs of both cases for a variable hydrogen demand. It can be seen that the levelized costs of supplied hydrogen are a function of hydrogen demand in both cases. Higher hydrogen demands bring specific investment costs down due to economies of scale and increase the utilization of equipment. As hydrogen demand grows, the remaining options become increasingly scarce, leading to higher marginal costs of production. Specifically, as hydrogen demand increases, timber needs to be sourced in less lucrative areas. This is especially prominent in the cH_2 shipping case, leading to a slight increase in specific costs despite economies of scale. By increasing the hydrogen demand from 400 MW to 700 MW, the average one-way distance for timber trucking increases from 260 km to 500 km for the cH_2 shipping case, while it only increases from 70 to 100 km for the wood chip shipping case. This is because wood chip shipping is much cheaper, meaning that routes all along the coast of Norway are expanded in the wood chip shipping case, while only shipping routes from the south of Norway (e.g., Grimstad, Halden) are expanded in the cH_2 shipping case.

At 295 MW, the number of required cH_2 ships jumps from 3 to 4 in the cH_2 shipping case, leading to a discontinuity in specific costs. For all investigated hydrogen demands, wood chip shipping is economically advantageous over hydrogen shipping.

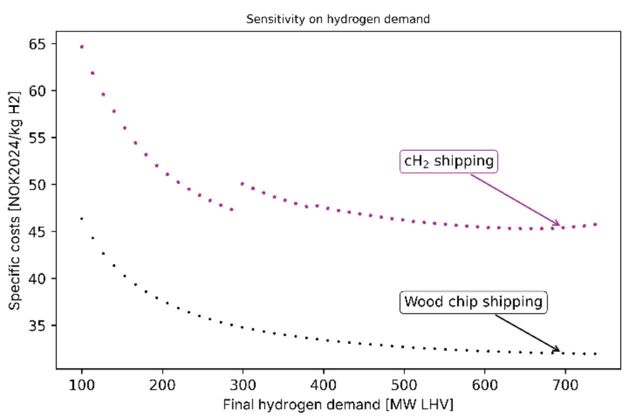

Fig 4: Dependency of LCOH on hydrogen demand.

Fig 5 shows the levelized costs of hydrogen for both cases for a final hydrogen demand of 400 MW. It is evident that the wood chip case is economically advantageous at all supply chain levels apart from gasification plants. Here, cheap electricity prices in Norway compared to Germany can be leveraged to reduce hydrogen production costs. There is a significant difference in cost between shipping terminals for wood chips and compressed hydrogen. As for wood chip shipping terminals, the considered costs include fees paid at the terminal (i.e., waterway fees, time fees and quay fees) as well as operating costs for wood chip production. The terminal fees reflect the total costs of the shipping terminal operator, which are distributed among many different customers. We hereby assume that the wood chip shipping terminals have sufficient capacity to handle the operations investigated in this study, which is a reasonable assumption given the low required annual operational time (see Fig 8). Moreover, wood chip shipping terminals rely on cheap, simple infrastructure for bulk shipping (i.e., continuous ship loaders and unloaders).

On the other hand, shipping terminals for cH_2 require investment costs for construction, compressed hydrogen storage as well as hydrogen loading and unloading equipment (i.e., booster compressors and hydrogen precooling units). Furthermore, they require additional energy to power the equipment.

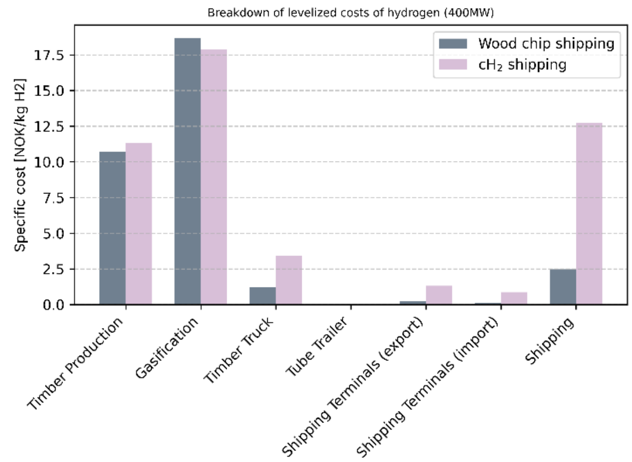

Fig 5: LCOH for cH_2 and wood chip route for 400 MW

As for shipping, the costs for compressed hydrogen shipping are much higher than the costs for wood chip shipping. This arises from generally lower specific ship investment costs of a bulk ship than of a complex pressure vessel ship, higher payload and thus lower specific operating costs. This is illustrated in Fig 6, which compares shipping cost for both cases. In the wood chip shipping case, one wood chip ship is sufficient to transport all wood chips. The ship travels 40 thousand km on 18 trips with an average one-way distance of 1247 km, transporting 1110 kt/a of wood chips. In fact, the ship is underutilized in this case (i.e., actual utilization of 2270 h/a), meaning that the ship could in theory be rented out to decrease costs further. In contrast, four cH_2 ships are required in the compressed hydrogen shipping case. The ships travel 630 thousand km on 612 trips with an average one-way distance of 518 km, transporting 105 kt/a of hydrogen. This leads to higher investment costs and higher fixed operational costs such as salary costs and maintenance, as 4 times as many ships are needed. As the payload of the wood chip ship is higher than the compressed hydrogen ship much fewer trips are required, leading to lower fuel costs. The wood chip ship has a payload of 70 kilotons wood chips, while the payload of the compressed hydrogen ship is 172 tonnes hydrogen in the investigated case. This value comes from an optimal ship size of 541 modules for a shipping route size of 400 MW [17].

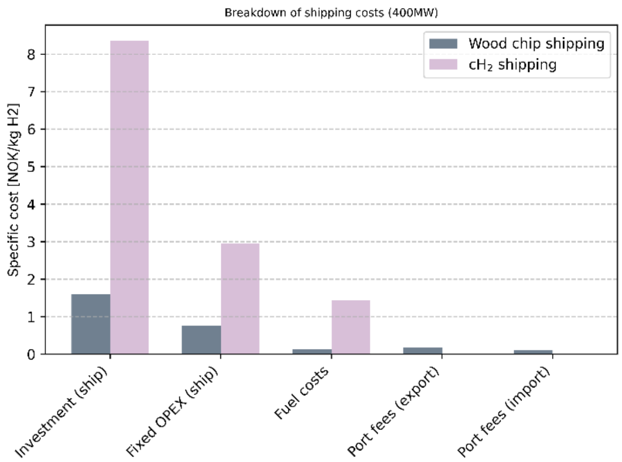

Fig 6: Shipping cost for cH_2 and wood chip case for 400 MW

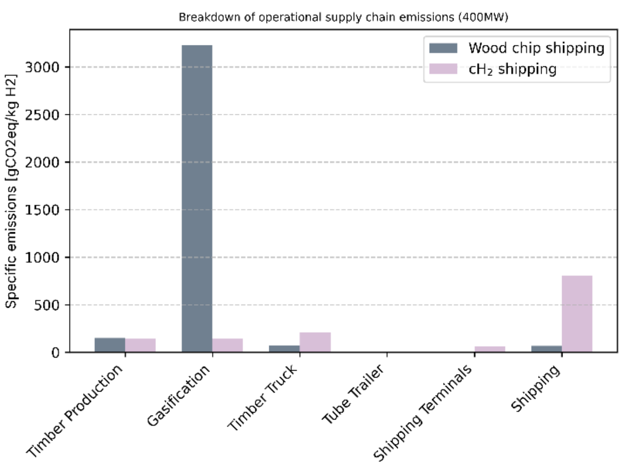

Fig 7: Emissions for cH_2 and wood chip case for 400 MW

Fig 7 shows the specific emissions for both cases for a final hydrogen demand of 400 MW. The emissions are dominated by two main contributors, which are hydrogen production through gasification and shipping. In terms of shipping, the fuel consumption for shipping is directly proportional to the sailed distance. Due to the large distance sailed in the cH_2 case, the emissions for shipping are much higher than in the wood chip shipping case. On the other hand, hydrogen production in Germany has a significantly higher environmental impact than in Norway. This has two reasons. First of all, the hydrogen production plants require electricity and heat as an input. For plants in Norway, we assume that heat can be supplied through electric heating due to low cost and low emissions of electricity. This leads to an electricity demand of 9.33 kWh/kg_{H2} (excluding an eventual loading terminal for hydrogen tube trailers) and no natural gas demand and thus low overall emissions. For plants in Germany, we assume that the heat demand is covered by natural gas, which leads to higher emissions. Secondly, while the electricity demand for plants in Germany is lower than for plants in Norway due to less compression requirements (i.e., 6.5 kWh/kg hydrogen), the specific emissions from electricity are 30 times as high. This leads to a stark difference in overall emissions. The emission factors used in this work are stated in the supplementary material.

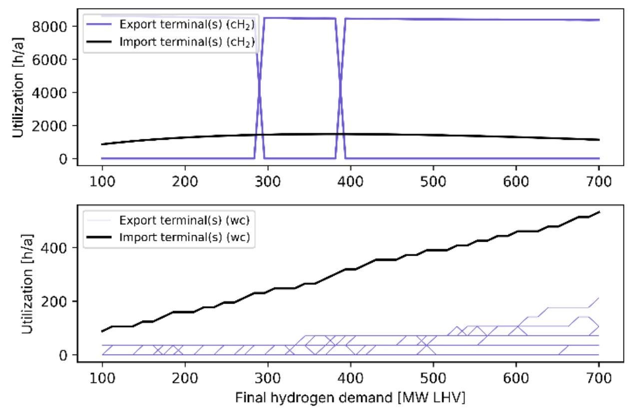

Fig 8: Utilization of shipping terminals (top: cH_2 terminals, bottom: wood chip terminals)

Another inherent disadvantage of compressed hydrogen shipping terminals compared to wood chip shipping terminals is utilization, which is illustrated in Fig 8. Bulk shipping terminals are used by an existing shipping industry, which leads to high terminal utilization and thus low costs. While the utilization of wood chip terminals due to the operations investigated in this study is very low, the equipment used (i.e., continuous loaders and unloaders) is general equipment that is also used by other bulk shipping industry. As the hydrogen demand is increased, more wood chip terminals are utilized. On the other hand, there is no current industry for compressed hydrogen export via shipping in Norway, meaning that the equipment at the shipping terminals has to be specifically built for the compressed hydrogen shipping operation and might not be used by any other party.

Utilization of shipping terminals for compressed hydrogen export is not strongly correlated with terminal throughput, using the relations reported by Maier et al. [17]. Due to expensive intermediate storage, the loading time and thus the terminal utilization is maximized. On the import side, utilization remains under 2000 h/year for all investigated terminal throughputs, which arises because of cheaper unloading equipment compared to ship dead time costs. Here, the import terminal could be rented out to other companies to bring down costs.

4. Discussion

4.1. Comparison with other alternative hydrogen production sources

Fig 9 shows a comparison of hydrogen supply from Norway to Germany using the two routes described in this study with domestic hydrogen production in

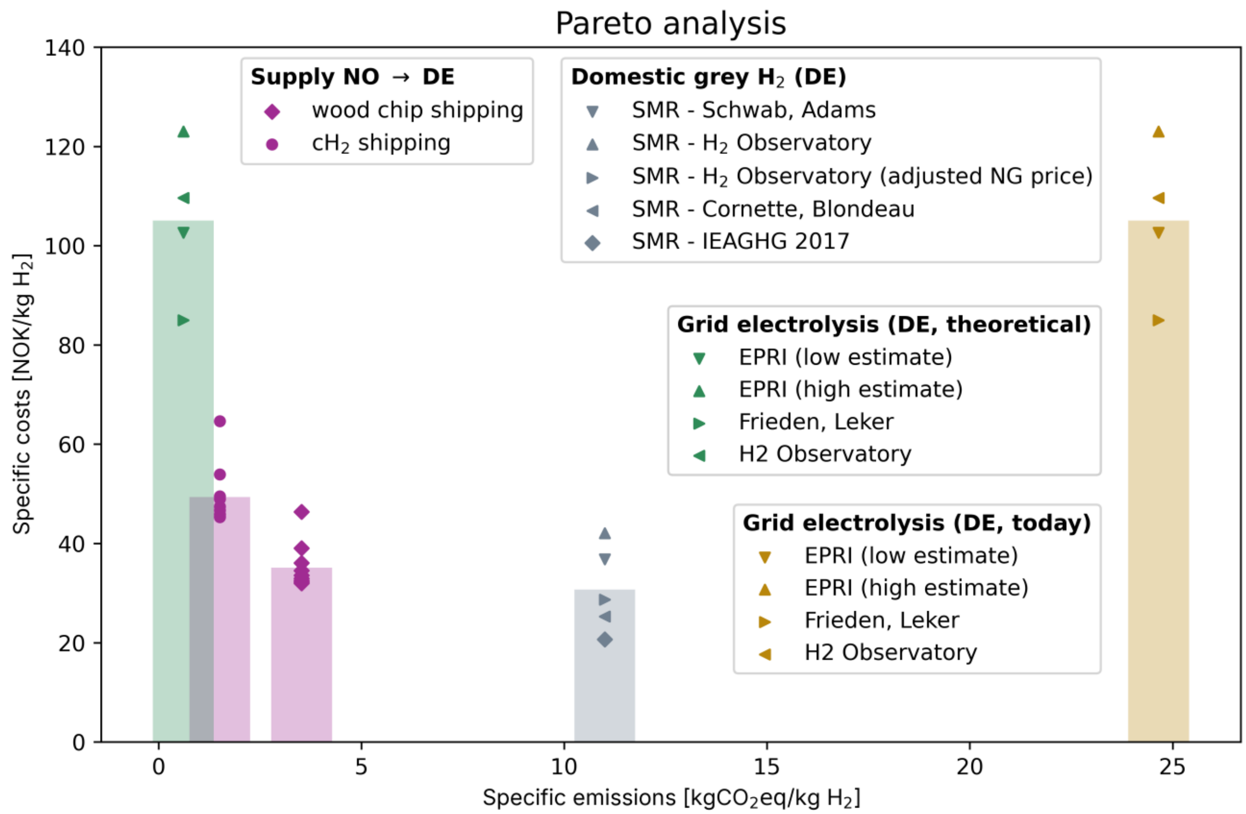

Fig 9: Pareto analysis for hydrogen supply

Germany through steam methane reforming (SMR) and electrolysis in terms of costs and emissions. Values for the latter pathways were taken from literature and adapted to year and currency. In terms of emissions, an average value was used for each technology. For supply from Norway, average emission values were calculated for supply chain sizes from 100 to 745 MW. For SMR, we used 11 $kgCO_{2eq}$/ kg_{H2} as reported in the reference case by Schwab and Adams [26]. For electrolysis, two scenarios were assumed. In the first scenario, electrolysis using electricity from the German grid was assumed with an electricity price of 99.2 EUR2024/MWh [27] and an emission intensity of 445 gCO_{2eq}/kWh_{el} [28]. Specific emissions were calculated assuming a power consumption of 55.4 kWh_{el}/kg_{H2} [29]. The second scenario is a theoretical scenario that should illustrate a fully decarbonized grid powered by wind energy. We assumed the same electricity prices but used an emission intensity of 11 gCO_{2eq}/kWh_{el}, which was calculated for the Kjøllefjord wind farm [30].

Costs and emissions for hydrogen supplied from Norwegian wood vary due to different supply chain dimensions. The points in Fig 9 reflect values for supply chain sizes from 100 to 745 MW. Costs for SMR vary significantly due to large variations in natural gas prices in the European Union in the last year and thus different natural gas prices considered in the cited studies. An extensive literature review was conducted by Schwab and Adams [26]. The study selected a reference case for SMR with 36.8 NOK2024/kg_{H2} for a considered natural gas price of 18.3 EUR2023/GJ_{HHV}, which translates to 67.3 EUR2024/MWh_{HHV}. In contrast, the EU Natural Gas TTF price was around 33 EUR/MWh_{HHV} in 2024 [31]. The European Hydrogen Observatory [32] reported LCOH for SMR of 42.1 NOK2024/kg_{H2} of which 30.8 NOK2024/kg_{H2} are due to natural gas purchase and 11.3 NOK2024/kg_{H2} are general production costs. Given these general production costs, a natural gas price of 33 EUR/MWh_{HHV} and a natural gas demand of 45.45 kWh_{HHV}/kg_{H2} [33], this translates to 28.7 NOK2024/kg_{H2}. Cornette and Blondeau [34] conducted a regression analysis on the correlation of hydrogen and conventional energy carriers. Using their equation for LCOH from SMR based on natural gas price, we calculated an LCOH of 25.3 NOK2024/kg_{H2}. Collodi et al. [35] reported a similar correlation, which yields a LCOH of 20.7 NOK2024/kg_{H2}.

For grid electrolysis, and a plant size of >100MW, we calculated a LCOH between 102.6 and 123 NOK2024/kg_{H2} using the LCRI tool provided by EPRI [29]. Frieden and Leker [36] reported an average LCOH of grid electrolysis in the EU of 85 NOK2024/kg_{H2}. The European Hydrogen Observatory [32] reported LCOH for grid electrolysis in Germany of 109.6 NOK2024/kg_{H2}.

4.2. Cost of CO_2 avoided

Table 2 shows the specific costs and emissions for the optimal supply chain (i.e., wood chip shipping) calculated in this study for equally spaced hydrogen demands from 100 MW to 745 MW. Based on these values and four different reference cases, four different costs of CO_2 avoided were calculated. For the calculation of the CCA, the following equation was used:

$$\mathrm{CCA} = \frac{c_{\mathrm{cH_2,wc}} - c_{\mathrm{ref}}}{e_{\mathrm{cH_2,wc}} - e_{\mathrm{ref}}},$$

where $c_{cH_2,wc}$ and $e_{cH_2,wc}$ describe the specific costs and emissions for the optimal supply chain investigated in this study, while c_{ref} and e_{ref} describe the specific costs and emissions for the reference system.

We have calculated CCA for four different scenarios: For CCA 1 and CCA 2, the reference system is defined as grey hydrogen production in Germany, where the specific costs are calculated based on the natural gas price using the regression from Cornette and Blondeau [34]. We assume a specific emission factor of 11 $kgCO_{2eq}/kg_{H2}$. We assume a natural gas price of 20 EUR2024/MWh (HHV) for CCA 1 and 60 EUR2024/MWh (HHV) for CCA 2. For CCA 3 and CCA 4, the reference system is defined as natural gas combustion for heat generation in Germany. This means that hydrogen imported using the supply chain described in this study is compared to natural gas combustion on a lower heating value basis. For natural gas combustion, we assume specific emissions of 201 $kgCO_2$/MWh (LHV) [37]. We approximated the natural gas price (LHV) from the natural gas price (HHV) using a factor of 0.9. We assume a natural gas price of 20 EUR2024/MWh (HHV) for CCA 3 and 60 EUR2024/MWh (HHV) for CCA 4.

A general trend that can be observed for all CCAs is that the CCA decreases with an increase in supply chain size. This mainly arises because of a cost reduction in biomass gasification, as the cost relation with plant size was modelled using generic scaling laws. Since the biomass gasification plants have the highest cost share (see Fig 5), cost reduction due to scaling has a high impact on supply chain costs (see Fig 4). Uncertainty in scaling laws thus impacts the CCA for large hydrogen demands and might underestimate gasification costs. If the scaling law turns out to be too optimistic, the CCAs for low hydrogen demands are a more accurate estimate.

On the other hand, all CCA calculations have a high dependency on the natural gas price. While natural gas prices have stabilized in 2024 with prices in the area of 30-40 EUR/MWh_{HHV} after reaching record highs the years before, they are still higher than before the Ukraine invasion [31]. In contrast, a timber price of 600 NOK/m^3 [38] translates into an energy price of 24 EUR/MWh_{LHV} using a timber density of 509 kg/m^3 (see supplementary material) and an LHV of 4.17 kWh/kg timber. If natural gas prices are much higher than that, this could incentivize building out a supply chain for timber and producing hydrogen from wood chips. This situation is illustrated by CCA 2. Given a natural gas price of 60 EUR2024/MWh (HHV), grey hydrogen production is neither economically nor environmentally attractive compared to green hydrogen from Norwegian wood.

On the other hand, CCA 3 and CCA 4 show that using green hydrogen from Norwegian wood as a fuel is unattractive compared to natural gas combustion, except perhaps at high gas prices and at the maximum possible supply chain size. In the best case, given a natural gas price of 60 EUR2024/MWh (HHV) and a hydrogen supply chain at its maximum size given current timber market conditions, a CO_2 price of 166 EUR/tCO_{2eq} would be required to justify displacing natural gas combustion with hydrogen from wood as a fuel specifically for the purpose of avoiding CO_2 emissions.

4.3. Supply chain design

The result for both the wood chip shipping case and the cH_2 shipping case are listed below for a hydrogen demand of 400MW. It is evident that the wood chip shipping is superior in terms of economics, while the hydrogen shipping case has slightly lower emissions. This is solely due to the high emission intensity of the German grid electricity, which results in high emissions for gasification (see Fig 7). The transport emissions for wood chip shipping are much lower than for cH_2 shipping due to higher transport efficiencies.

- Total costs (WC): 33.4 $NOK2024/kg_{H2}$
- Total costs (cH_2): 47.6 $NOK2024/kg_{H2}$
- Total emissions (WC): 3521 gCO_{2eq}/kg_{H2}
- Total emissions (cH_2): 1365 gCO_{2eq}/kg_{H2}

The following arguments suggest that the actual cost difference is even higher than stated:

- Shipping costs for wood chip shipping are pessimistic, since the ship is underutilized for all

Table 2: Cost of CO_2 avoided given H_2 demand

Demand	LCOH	Emissions	CCA 1 (NG = 20 €/MWh)	CCA 2 (NG = 60 €/MWh)	CCA 3 (NG = 20 €/MWh)	CCA 4 (NG = 60 €/MWh)
			compared to grey H_2		*compared to NG combustion*	
MW	*NOK/kg H_2*	*$kgCO_{2eq}/kg\ H_2$*	*EUR/tCO_{2eq}*	*EUR/tCO_{2eq}*	*EUR/tCO_{2eq}*	*EUR/tCO_{2eq}*
100	46.4	3.6	325	76	1033	561
172	39.0	3.5	240	-9	827	359
243	36.1	3.5	206	-43	742	277
315	34.5	3.5	188	-61	700	234
387	33.6	3.5	177	-71	675	209
458	33.0	3.5	170	-79	658	192
530	32.5	3.5	165	-83	647	181
602	32.3	3.5	162	-87	639	173
673	32.1	3.5	159	-89	634	168
745	32.0	3.5	159	-90	634	166

hydrogen demands and could be rented out.

- Shipping costs for cH_2 are rather optimistic, as only CAPEX for pressure vessels and the ship are considered. The cH_2 ship would most likely need additional safety equipment and other auxiliary devices.
- Moreover, the cost of the cH_2 ship is optimistic. We assumed that the entire cargo space can be used to stack modules and that the entire deadweight tonnage is available for cargo weight. In reality, cofferdams might have to be added, or other design constraints might impact the payload of the ship.
- Optimistic infrastructure cost of cH_2 shipping terminals (import). If the pipeline network cannot take up large hydrogen stream upon unloading of ships, intermediate storage would be needed, further increasing costs.
- Due to low utilization of the wood chip ship, the wood chip route is resilient to supply chain disruptions on the timber production side. Wood chips can easily be stored without high additional costs. On the other hand, the cH_2 export shipping terminals assume an intermediate terminal storage of 20 shipping modules [17], which translates to a buffer time of 127 minutes for a 100 MW supply chain or only 31 minutes for a 400 MW supply chain. This means that for cases where all ships in the fleet have high utilization, the supply chain has low resilience to disruptions in shipping.

While the techno-economic analysis of the cH_2 supply chain is subject to high uncertainty due to novelty and uncertain equipment costs, the cost difference between the two cases is 14.2 NOK/kg_{H2},which is an increase of 42%. The following points could improve the economic competitiveness of cH_2 shipping.

- Improved payload of the cH_2 ship. In the current design, the hydrogen payload is only 5.6% (weight based) of the ship's deadweight tonnage [17], while the entire deadweight tonnage of the wood chip ship is used for transporting cargo in our model.
- Significantly lower investment costs of the cH_2 ship (see Fig 6)
- Government subsidies or credits for CO_2 avoidance
- Possibly an integration into a much larger hydrogen supply chain could lead to lower costs due to economies of scale

While there is uncertainty in biomass gasification costs, it affects both supply chain cases in the same way and thus does not affect the economic superiority of wood chip shipping. This study assumes that the gasification plant can be scaled between 100 and 700 MW without any restrictions. In reality, the maximum size of the gasifier might be limited due to non-availability of very large biomass gasifiers in the market. Lundgren et al. [39] mentioned a maximum size for dual fluidized bed gasifiers in the area of 150 MW thermal. We investigated the effect on costs and supply chain design if a 150 MW size constraint is applied to biomass gasifiers. Herein, we assumed that larger plant sizes require two or more identical biomass gasifiers operating in parallel and that other equipment can be scaled to the total plant size. This resulted in an increase in supply chain costs from 33.4 to 35.5 NOK2024/kg_{H2} in the base case. While the total supply chain costs increased, the wood chip shipping case remained economically superior.

The shipping costs (assuming a fully utilized ship) are a linear function of shipping distance for both hydrogen and wood chip shipping. For cH_2 shipping, the specific cost increase with increasing shipping distance by 0.77 NOK/kg_{H2} per 100 km (one-way distance) [17]. This means that increasing shipping distance (one-way) from 600 km, which is representative for the Norway-Germany supply chain to 20.000 km, which would be a usual distance observed for the supply chain Norway-Japan, shipping costs would explode to 159 NOK/kg_{H2}. As for wood chip shipping, the specific cost increase with increasing shipping distance amounts to 42.81 NOK/t wood chips per 100 km (one-way distance). This means that a one-way shipping distance of 20.000 km leads to shipping costs of 781 NOK/t wood chips, which translates to 74 NOK/kg_{H2}. While it can be concluded that the economic advantage of wood chip shipping increases with shipping distance, both options are unrealistic for long distance shipping routes.

Data transparency

The supplementary material states general assumptions on project economics and financing, methodology on capital cost estimation and costs assumptions. The document draws on sources [4, 14, 15, 18, 20, 22, 27, 28, 37, 38, 40-65]. The python model developed for this work can be found in the Living Archive for Process Systems Engineering (LAPSE) at:

https://psecommunity.org/LAPSE:2025.0723

Abbreviations

CCA	Cost of CO_2 avoided
cH_2	Compressed hydrogen
EC	Equipment costs
EPC	Engineering Procurement and Construction cost
LH_2	Liquid hydrogen
LCOH	Levelized cost of hydrogen
LOHC	Liquid organic hydrogen carrier
MW	Megawatt (whenever used for fuels, the LHV is meant)
SMR	Steam methane reforming
TPC	Total direct plant cost
TOC	Total overnight costs
TASC	Total as spent capital
wc	Wood chips
p.a.	per annum

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