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Master Thesis

A model for the emerging hydrogen economy

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Statutory declaration

Hereby, I declare that I have developed and written this research completely by myself and that we have not used sources or means without declaration in the text. Any external thought, content, media, or literal quotation is explicitly marked and attributed to its respective owner or author.
As of the date of submission, this piece of document and its content have not been submitted anywhere else but to our supervisors.

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1. Introduction

The industrial sector significantly contributes to greenhouse gas emissions in Europe, accounting for approximately 20% of the European Union (EU) total CO2 emissions (Climate Change Mitigation 2024). Traditional manufacturing processes, particularly in energy-intensive industries like steel high-value chemicals (HVC) and fertilizer production, have historically relied heavily on fossil fuels, making deep decarbonization a complex challenge. Furthermore, the shipping industry contributed 13.5% of the EUs emission, while the aviation industry accounted for 3.5% of the EUs emission (Agency 2024).

A strong contender for decarbonizing these sectors is hydrogen, with the demand for hydrogen by these sectors exceeding 100 million tons per year in 2050 (Borup, Krause, and Brouwer 2021; Seck et al. 2022). However, the demand for hydrogen by these sectors is susceptible to the cost of supplying hydrogen and its derivatives and the prices of other fuels, such as natural gas and electricity, as well as potential subsidies and other policy instruments (Zhang, Davis, and Brear 2022). Furthermore, deep decarbonization in the industrial sector could also occur via electrification (Fleiter et al. 2020). Bio-based fuels are an alternative to synthetic fuels based on hydrogen for the shipping and aviation sector (Panoutsou et al. 2021). Thus, each industry's future demand for hydrogen and its derivatives remains uncertain at the current stage and requires a more detailed analysis.

Next to factors such as alternative fuels, the potential for electrification, and government policy, resulting market structures may also determine the extent to which hydrogen and its derivatives will be demanded as the market structure determines the cost at which they will be provided and whereas there exists abundant research on possible policies to support the ramp-up of hydrogen value chains are heavily discussed in the literature, and already many states in policy instruments such as the "Klimaschutzverträge", the aspects of designing a hydrogen market have been neglected (Niedrig et al. 2024).

Therefore, this work proposes a highly flexible model of a hydrogen economy that considers the demand for hydrogen not as given but accounts for its dependence on prices of alternative fuels, the costs of natural gas, and electricity for the consumers of hydrogen. It also considers the carbon price introduced by the European Emission Trading Scheme (EU ETS) and the Renewbale Fuel of Non-Biological Origin (EU RFNBO) policy. The model allows the consumers of hydrogen to choose between a range of alternative process routes to satisfy the demand for final goods and services and accounts for existing residual capacities over time, which are available to downstream industries. Then, the upcoming hydrogen market can be simulated under the assumption of perfect competition,

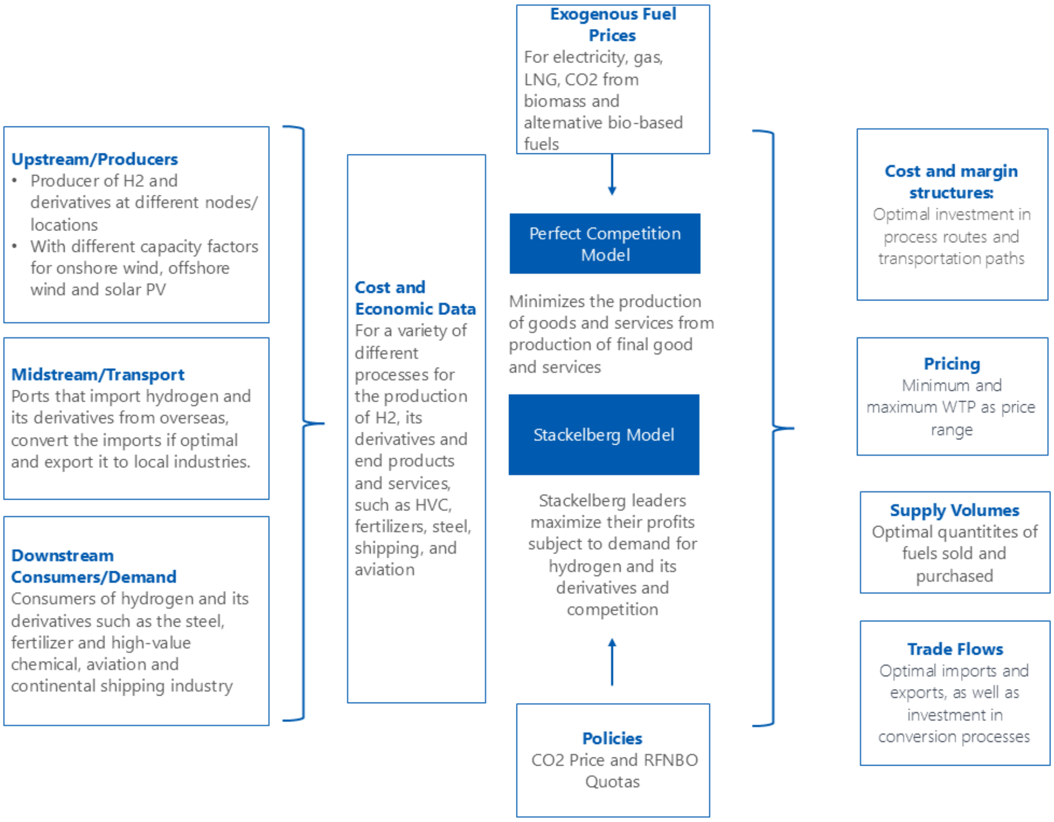


Figure 1: Model Overivew

which implies the minimization of costs over the entire supply chain, or under the assumption of some Stackelberg leaders, which decide to invest first and build up strategic production and export capacities and, thereby, shape the future hydrogen market. Thus, the model can resemble complex market structures.

An overview of the model, its structure, and the potential information it can provide is shown in figure (1). The questions the model can answer are wide-ranging. However, the focus of this thesis is the examination of the potential impact of the EU RFNBO policy and hydrogen market structure that could be created by a Stackelberg leader on the adoption of different processes among downstream consumers and the optimal hydrogen exports and imports from a set of exemplary locations and industries. The rest of this thesis is organized as follows (2) and provides a literature review of the existing work on modeling the hydrogen economy and essential factors driving its market structure.(3) introduces this model's sets, variables, parameters, and maps, (3.2) provides the mathematical description of the perfect competition. (3.3) describes the model of a Stackelberg hydrogen economy. (4) introduces the example case of a hydrogen economy with four suppliers of hydrogen and its derivatives, two ports, and four downstream industries and presents the data that drive the model's outcome. The results are presented in(5) and discussed in (6). Finally, the conclusion is given in (??). Last but not least, a detailed overview of all processes, costs, and policy data, and applied maps are reported in the appendix (A).

2. Literature Review

There exists an extensive literature on energy system modeling that includes the industrial and transport sector. The open-source Pypsa allows for analysis of the optimal technology transition path for the industrial sector under different carbon budgets (Victoria, Zeyen, and Brown 2022). Seck et al. (2022), for instance, predicts that hydrogen demand could exceed 100 million tons by 2050, where half of the hydrogen is solely used in the transport sector, and the industrial sector essentially consumes the other half. Furthermore, Neumann et al. (2023) show that developing a hydrogen network could reduce the overall system cost of the energy system by 3.4%. However, these models assume that all actors work together to reduce overall system costs.

Efforts to quantify the potential value of entering the hydrogen market and the profitability for producers have been limited. For instance, Wietschel et al. (2021) derives the value of hydrogen based on production cost. Moritz, Schönfisch, and Schulte (2023) evaluate the value of hydrogen based on total supply costs to German countries by optimizing the investment and operation of commodity production from 113 renewable resource-rich economies. Parra et al. (2019) derive value-based prices for hydrogen for several hydrogen in power-to-power, power-to-gas, and hydrogen refueling stations applications in the electricity, heat, and transport sectors.

However, given that uptakers of hydrogen need to undergo large investments to build production and transport capacities, pricing their hydrogen only on production cost, may not be sufficient to make build production and transport capacities, pricing their hydrogen only on production cost may not be enough to make the investments viable (Moreno-Benito, Agnolucci, and Papageorgiou 2017). Thus, exploring the opportunities for strategic investments to create market structures such as monopolies and Stackelberg games like hydrogen economy becomes vital for producers of hydrogen and its derivatives.

Guo et al. (2021) propose a game theoretic equilibrium model for heterogeneous consumers and retailers of hydrogen in a single country economy with a single monopolistic producer. Also, Dupke et al. (2024) focuses on the impact of market power in a single-period hydrogen market model. However, allowing only for one period enables the producers of hydrogen not to undertake strategic investments, deter market entry in the first periods against a loss, and recoup the benefits by charging higher prices later on as new entries in the hydrogen market become unprofitable. Furthermore, according to Barner (2024), hydrogen prices could rise up to 200€/MWh by 2030 compared to prices under perfect competition of about 150 €/MWh. Furthermore, Zhang et al. (2022) show that Vickrey auction-based pricing mechanism in a single hybrid-renewable-to-H2 provider with multiple followers

Stackelberg game achieves a win-win situation for leader and follower. Moreover, such a multi-nodal market reduces the risks for market power and anti-competitive behavior.

What differentiates this thesis from the existing literature is its consideration of downstream industries as part of the Stackelberg game, whereas usually, the demand for hydrogen has been assumed to be fix. Moreover, the model of this thesis also allows us to explore the impact of the EU RFNBO policy on the hydrogen producers to act strategically in different market environments in the future.

3. The Model

3.1. Sets, Variables, Parameters and Maps

First, table (1) introduces the sets, table (2) the variables, table (3) the parameters and table (4) the maps.

Table 1: Sets

Set	Name	Description
I	industries	Set of an industries. This includes hydrogen, ammonia, methanol consumers, producers, and ports.
C	consumers	The subset of industries at the downstream of the hydrogen supply chain and consume hydrogen and its derivatives.
S	sectors	Consumers are categorized into the different sectors for each particular target of the RFNBO policy exists. Therefore, the set of sectors compromises manufacturing industries and transport, shipping, and aviation.
$T \in I$	Traders	Traders that operate pipeline networks, ports and shipping infrastructure to transport hydrogen, ammonia, and methanol
$P \in I$	Producers	Producers that produce hydrogen, ammonia or methanol
$CT \in I$	Consumers & Traders	Consumers and traders taken together
$PT \in I$	Producers & Traders	Producers and traders taken together
N	Node	Set of nodes that where either a consumer, trader or producer operates.
G	goods	The goods that the downstream industries must produce to satisfy the final good demand.
$\mathcal{P}$	Processes	Set of anprocesses
0	Outputs	Set of anoutputs
$P_{\text{Fuel Swichting}}$	Processes with Fuel Switching	Set of processes that annow for fuel switching. This means that two or more fuels can be used as an almost perfect substitute in the same process without requiring additional capital expenditure.
F_{traded}	Traded fuels	The subset of fuels containing hydrogen and its derivatives ammonia and methanol, which are produced by producers and traded
F_{endo}	Endogenous fuels	The subset of fuels containing hydrogen and its derivatives ammonia and methanol and intermediate fuels, such as nitrogen and CO_2
F_{exog}	non-traded fuels	The subset of another fuels which are taken as exogenous and purchased at fixed prices from a market
M	Modes	Transport modes pipeline, submarine pipeline and shipping

Table 2: Variables

Variable	Description
$q^{\text{Process}}_{i,\rho,o,n,y}$	Production processes where $i \in$ Industries, $\rho \in$ processes,$o \in$ Outputs, $l \in$ locations, $y \in$ years. Defined for $(i,\rho) \in$ PIM, $(f,\rho) \in$ PFM, $(\rho, o \in POM$, and $(n,i) \in$ ILM
$q^{\text{ProcessFuelDemand}}_{i,\rho,f,n,y}$	Fuel consumption in process ρ by fuel f at industry i and location n in year y if $(i,\rho) \in$ PIM, $(f,\rho) \in$ PFM, and $(n,i) \in$ ILM
$q^{\text{FuelPurchased}}_{i,f,n,y}$	Non-negative quantity representing fuel f purchased by Industries i at location n in year y. Defined if there exists any process ρ for which $(i,\rho) \in$ PIM, $(f,\rho) \in$ PFM, and $(n,i) \in$ ILM
$q^{\text{ProcessCapacity}}_{i,\rho,n,y}$	Accumulated production capacity of process ρ, of industry i at location n and year y. Defined for $(i,\rho) \in$ PIM and $(n,i) \in$ ILM
$q^{\text{NewCapacity}}_{i,\rho,n,y}$	Capacity additions of industry i to the process ρ. Defined for $(i,\rho) \in$ PIM and $(n,i) \in$ ILM
$q^{\text{Exports}}_{i,ii,n,nn,m,y}$	Exports of industry i at location n to industry ii at location nn by mode m, where m can be either a pipeline or a ship based on geographic conditions. Defined for $i \in$ Producers $\vee$ Traders if $(i,n) \in$ ILM and $(ii,nn) \in$ ILM
$q^{\text{ExportCapacity}}_{i,ii,n,nn,m,y}$	Export capacity of industry i at location n to industry ii at location nn by mode m, where m can be either a pipeline or a ship based on geographic conditions. Defined for $i \in$ Producers $\vee$ Traders if $(i,n) \in$ ILM and $(ii,nn) \in$ ILM
$q^{\text{NewExportCapacity}}_{i,ii,n,nn,m,y}$	Export capacity addition between industry i at location n to industry ii at location nn by mode m, where m can be either a pipeline or a ship based on geographic conditions. Defined for $i \in$ Producers $\vee$ Traders if $(i,n) \in$ ILM and $(ii,nn) \in$ ILM
$q^{\text{Imports}}_{i,ii,n,nn,m,y}$	Imports of the industry i at location n from industry ii at location nn by mode m, where m can be either a pipeline or a ship based on geographic conditions. Defined for $i \in C \vee T$ if $(i,n) \in$ ILM and $(ii,nn) \in$ ILM
$q^{\text{FuelSold}}_{p,c,f,n,nn,y}$	Fuel f sold by producer p at location i to consumer c at location nn. Defined for $(p,l) \in$ ILM and $(c,nn) \in$ ILM
$q^{\text{RFNBO Fine}}_{c,\rho,f,n,y}$	The quantity of fuel f used in processes ρ for which a consumer pays the fine of the RFNBO if the consumption of fuel f in processes ρ violates the RFNBO quota of the consumer

Table 3: Parameters

Parameter	Description
$O_{\rho,y}$	OPEX for process ρ in year y
$O_{m,f,y}$	OPEX for transport mode m and fuel f in year y
$K_{\rho,y}$	CAPEX for process ρ in year y
$K_{m,f,y}$	CAPEX for transport mode m and fuel f in year y
$\text{FOM}_{\rho,y}$	FOM for accumulated export capacity
$\text{ExportFOM}_{m,f,y}$	FOM for accumulated export capacity
$s_{\rho,f,y}$	Input ratios for each input f in process ρ in year y
$cf_{\rho,l}$	Capacity factor for process ρ at location l
$p_y^{\text{CO}_2}$	CO_2 price of the EU ETS in year y
$D_{i,g,l,y}$	Demand for good g from industry i at location l in year y
$q_{i,\rho,l,y}^{\text{ResCapacity}}$	Residual capacity of process ρ, at location l in year y
ϵ_ρ	Emission factor for process ρ
$r_{s,y}^{\text{RFNBO}}$	EU RFNBO quota for sector s in year y
$\omega_{f,\rho}$	Weight in RFNBO quota for fuel f from process ρ
$\delta_{n,nn}$	Distance between location n and nn
$\delta_{m,f}^{\text{Losses}}$	Losses for using mode m for fuel f
r	Discount rate

Table 4: Maps

Map		Description
ILM	Industry location mapping	Maps industry i in I to their location l if and only if there exist industry i at the location l
PIM	Process industry mapping	Maps the processes ρ to the industry i that uses such processes.
PFM	Process fuel mapping	Maps the fuels f to the proceses ρ if f is used in ρ.
POM	Process output mapping	Maps the outputs, which can either be final goods g or fuels f to the corresponding processes
SIM	Sector industry mapping	Maps each industry i to its specific sector of the RFNBO policy s.
FSM	Fuel switching map	Maps several fuels to the same process if the process annows for fuel switching
FIM	Fuel industry mapping	Maps several fuels to the same process if the process annows for fuel switching
GIM	Goods industry mapping	Maps the goods and service to the industries that produce them
FTM	Fuel transport mode mapping	Maps each fuel to the mode it can be transported with
SFM	Supplier fuel mapping	Maps each fuel to its corresponding supplier, which are the union of all producers and ports.

3.2. The hydrogen market in perfect competition

We begin by examining the development of a hydrogen market under the assumption that all participants share the objective to minimize their cost. In this context, upstream producers of hydrogen, ammonia, and methanol are assumed to offer hydrogen and its derivatives at the lowest possible cost. Downstream industries operate within a perfectly competitive market, where the optimal strategy for maximizing revenue is to minimize input costs. Under perfect competition, the profit-maximizing behavior of all participants aligns with overall cost minimization (Samuelson 1972). Consequently, the hydrogen market can be represented as a single cost-minimization problem. The objective function (1) is therefore designed to minimize variable fuel costs, capital expenditure CAPEX, operational expenditure OPEX, and carbon emission costs across all industries and processes, ensuring that final goods demand is met subject to a set of defined constraints.

Equation (**??**) describes the demand constraint for goods and services produced by downstream industries.

The fuel balance implied by equation (2) and (3) ensures that all fuels an industry consumes are either imported or self-produced. Endogenous fuels are imported from ports or a hydrogen supplier and its derivatives directly. In the case of exogenous fuels, it is assumed that these are purchased from the wholesale market at each node. This implies that the prices for electricity, natural gas, and other exogenous fuels differ across nodes.

(4) describes the fuel demand for processes that take a single input to produce their respective output. The required input to produce one output unit is described by the parameter s_I. In contrast, for processes for which various fuels can be used, equation (5) ensures that the sum of all fuels produced is sufficient to produce the process‘s output.

Additionally, equation (6) demands the industries to provide sufficient production capacities, and equation (7) takes into account that once an industry invests in capacity, it has that capacity over its lifetime. Furthermore, the model also considers existing residual capacities for all processes.

The model includes two environmental policies that are put in place to induce the decarbonization of hydrogen. First, equation (8) ensures that all industries must cover their emission with CO2 certificates based on the EU ETF trading scheme and pay a given price for these certificates. Secondly, equation (9) restricts the use of bio-based fuels according to the EU RED III, FuelEU, and ReFuelEU Aviation regulations.

The equations (10) through (14) describe the import and export of hydrogen and its derivatives. (10) implies that the transport of hydrogen, ammonia, and methanol leads to losses, and thus, exporters of hydrogen have to export more than they seln, and imports have to be at least as large enough as the fuel purchased. Therefore, in this moden, the hydrogen producer is responsible for shipping enough hydrogen to compensate for losses.

Furthermore, producers of hydrogen and its derivatives purchased have to export at least the amount they are selling, as shown in equation (11) and, according to equation (12), importers can at maximum import the amount of hydrogen and its derivatives they have purchased from one of the producers. Additionally, exporters of hydrogen have to provide sufficient export capacities in terms of pipelines and shipping capacities implied by equation (13) and equation (14) keeps track of existing capacity. Residual shipping and pipeline capacities are sofar not considered.

Finally, equation (15) ensures that sold quantities of hydrogen and its derivatives meet quantities purchased based on bilateral contracts between producers and consumers of hydrogen and its derivatives.

$$
\begin{aligned}
\text{Minimize} \sum_{y \in Y} \frac{1}{(1+r)^y} \Bigg(& \sum_{\substack{i \in I, n \in N \\ (i,n) \in \text{INM}}} \sum_{\substack{f \in F_{\text{Exo}} \\ (f,i) \in \text{FIM}}} p_{f,n,y} \cdot q^{\text{Purchased}}_{i,f,n,y} \\
& + \sum_{\substack{i \in I, n \in N \\ (i,n) \in \text{INM}}} \sum_{\substack{\rho \in \mathcal{P} \\ (\rho,i) \in \text{PIM}}} K_{\rho,y} \cdot q^{\text{NewCapacity}}_{i,\rho,n,y} \\
& + \sum_{\substack{i \in P \cup T,\, ii \in T \cup C \\ n,\, ll \in N, m \in M \\ (i,n) \in \text{INM}, (ii,nn) \in \text{INM}}} \left(K_{m,f,y} \cdot q^{\text{NewExportCapacity}}_{i,ii,n,nn,m,y} + O_{m,f,y} \cdot q^{\text{Exports}}_{i,ii,n,nn,m,y} \right) \delta^{\text{Distance}}_{n,nn} \\
& + \sum_{\substack{i \in I, n \in N \\ (i,n) \in \text{INM}}} \sum_{\rho \in \mathcal{P}} \text{FOM}_{\rho,y} \cdot q^{\text{ProcessCapacity}}_{i,\rho,n,y} \\
& + \sum_{\substack{i \in P \cup T,\, ii \in T \cup C \\ n,\, ll \in N, m \in M \\ (i,n) \in \text{INM}, (ii,nn) \in \text{INM}}} \text{ExportFOM}_{m,f,y} \cdot \delta^{\text{Distance}}_{n,nn} \cdot q^{\text{ExportProcessCapacity}}_{i,ii,n,nn,m,y} \\
& + \sum_{\substack{i \in I, n \in N \\ (i,n) \in \text{INM}}} q^{\text{CO}_2}_{i,n,y} \cdot p^{\text{CO}_2}_{y} \\
& + \sum_{\substack{i \in I, n \in N \\ (i,n) \in \text{INM}}} \sum_{\rho \in \mathcal{P}, o \in O} \text{Opex}_{\rho,y} \cdot q^{\text{Process}}_{i,\rho,o,n,y} \Bigg)
\end{aligned}
$$

subject to:

$$\text{Final Goods Market Constraint}\, D_{i,g,n,y} \leq \sum_{\substack{\rho\in\mathcal{P} \\ \cap\{\rho|(i,\rho)\in\mathsf{PIM}\wedge \\ (\rho,g)\in\mathsf{POM}\}}} q_{\mathsf{Process}_{i,\rho_g,n,y}} + q^{\mathsf{Imports}_{i,\rho_g,n,y}} \tag{1}$$

$$\forall i \in I, g \in G, n \in N, y \in Y \cup (i,n) \in \mathsf{INM} \cup (i,g) \in \mathsf{IGM}$$

$$\begin{aligned}\text{Endogenous Fuel Balance} \quad & \sum_{\substack{c\in CT,n\in N,nn\in N,m\in M \\ \cup(nn,c)\in\mathsf{INM} \\ \cup(p,f)\in\mathsf{SFM}\cup(m,f)\in\mathsf{FTM}}} q^{\mathsf{Exports}}_{i,c,f,n,nn,m,y} \\ & + \sum_{\substack{\rho\in\mathcal{P},o\in O \\ \cup(\rho,i)\in\mathsf{PIM} \\ \cup(\rho,f,o,y)\in\mathsf{SI}}} q^{\mathsf{ProcessFuelDemand}}_{i,\rho,f,o,n,y} \\ & \leq \sum_{\substack{p\in PT,n\in N,nn\in N,m\in M \\ \cup(nn,p)\in\mathsf{INM} \\ \cup(p,f)\in\mathsf{SFM}\cup(m,f)\in\mathsf{FTM}}} q^{\mathsf{Imports}}_{i,p,f,n,nn,m,y} \\ & + \sum_{\rho\in\mathcal{P}\cup(\rho\rho,o)\in POM\}} q^{\mathsf{Process}}_{i,\rho\rho,n,y} \\ & \forall i \in I, f \in F, n \in N, y \in Y \cup (\rho,i) \in \mathsf{PIM} \cup (f,\rho) \in \mathsf{PFM} \end{aligned} \tag{2}$$

$$\begin{aligned}\text{Exogenous Fuel Balance} \quad & \sum_{\substack{\rho \\ \cup|(\rho,p)\in PIM}} q^{\mathsf{ProcessFuelDemand}}_{i,\rho,f,n,y} \leq \sum_{\rho\in\mathcal{P}\cup(\rho\rho,o)\in POM} q^{\mathsf{Process}}_{i,\rho\rho,n,y} \\ & + q^{\mathsf{qFuelPurchased}}_{i,f,n,y} \\ & \forall i \in I, f \in F, n \in N, y \in Y \cup (\rho,i) \in \mathsf{PIM} \cup (f,\rho) \in \mathsf{PFM} \end{aligned} \tag{3}$$

Fuel Demand Constraint

$$q^{\mathsf{Process}}_{i,\rho,o,n,y} \leq \frac{1}{s_{I\rho,f,y}} q^{\mathsf{ProcessFuelDemand}}_{i,\rho,f,n,y} \tag{4}$$

$$\forall i \in I,\ \rho \in \mathcal{P}, f \in F, y \in Y \cup (\rho,i) \in \mathsf{PIM} \cup (\rho,f) \in \mathsf{PFM}$$

$$\cup (i,n) \in \mathsf{INM}$$

Fuel Switching Constraint

$$q^{\mathsf{Process}}_{i,\rho,o,n,y} \leq \sum_{f\in F\cup(\rho,f)PFM} \frac{1}{s_{I_{\rho,\mathsf{Fuel\ Switching},f,y}}} q^{\mathsf{ProcessFuelDemand}}_{i,\rho,f,n,y} \tag{5}$$

$$\forall i \in I, \rho \in \mathcal{P}, f \in F, n \in N, y \in Y$$

$$\cup (i,n) \in \mathsf{INM} \cup (f,\rho) \in \mathsf{FSM} \cup (i,n) \in \mathsf{INM}$$

Capacity Constraint
$$\frac{1}{\mathsf{cf}_{\rho,l}} q^{\mathsf{Process}}_{i,\rho,o,n,y} \leq \sum_{o \in O \cup \{o|(\rho,o) \in \mathsf{POM}\}} q^{\mathsf{ProcessCapacity}}_{i,\rho,n,y} \tag{6}$$
$$\forall i \in I, \rho \in \mathcal{P}, n \in N, y \in Y \cup (\rho, i) \in \mathsf{PIM} \cup (i,n) \in \mathsf{INM}$$

Capacity Accumulation
$$q^{\mathsf{ProcessCapacity}}_{i,\rho,n,y} \leq \sum_{\substack{\forall yy \\ \in yy-y \leq L^{\mathsf{Lifetime}}_{\rho}}} q^{\mathsf{NewCapacity}}_{i,\rho,n,yy} + q^{\mathsf{ResCapacity}}_{i,\rho,n,yy}$$
$$\forall i \in I, \rho \in R, n \in N, y \in Y \cup (\rho, i) \in \mathsf{PIM} \cup (i,n) \in \mathsf{INM} \tag{7}$$

CO_2 Constraint
$$\sum_{\rho \in \mathcal{P}} q^{\mathsf{ProcessFuelDemand}}_{c,\rho,n,y} \epsilon_{\rho} \leq q^{\mathsf{CO2}}_{c,n,y}$$
$$\forall c \in C, n \in N, y \in Y \cup (c,l) \in \mathsf{INM} \tag{8}$$

RNFBO Constraint
$$r^{\mathsf{RFNBO}}_{s,y} \sum_{\substack{f \in F, \rho \in \mathcal{P} \\ \cup (\rho,f) \in \mathsf{PFM} \\ c \in C \cup (c,s) \in \mathsf{SIM}}} q^{\mathsf{ProcessesFuelDemand}}_{c,\rho,f,l} \leq$$
$$\sum_{\substack{f \in F, \rho \in \mathcal{P} \\ (\rho,f) \in \mathsf{PFM} \\ c \in C \cup (c,s) \in \mathsf{SIM}}} \omega_f \, q^{\mathsf{ProcessesFuelDemand}}_{c,\rho,f,l} + q^{\mathsf{RFNBO\ Fine}}_{c,\rho,f,n,y}$$
$$\forall s \in S, \; y \in Y \tag{9}$$

Export Import Balance
$$q^{\mathsf{Imports}}_{c,t,f,n,nn,m,y} <= \delta^{\mathsf{losses}}_{m,f} \delta^{\mathsf{Distance}}_{n,nn} \, q^{\mathsf{Exports}}_{p,t,f,nn,n,y}$$
$$\forall c \in C \cup T, \forall p \in P \cup T, n, nn \; \in N, y \in Y \tag{10}$$

Export Constraint
$$\sum_{c,ll \in \mathsf{INM} \subseteq CxL} q^{\mathsf{FuelSold}}_{p,c,f,ln,n,y} \leq \sum_{\substack{t,nn \in \mathsf{INM} \subseteq T \times N \\ m \in M}} q^{\mathsf{Exports}}_{p,t,nn,n,m,y} \tag{11}$$
$$\forall p \in P, n \in N$$

Import Constraint
$$\sum_{\substack{t,nn \in \mathsf{INM} \subseteq T \times N \\ m \in M}} q^{\mathsf{Imports}}_{c,t,n,nn,m,y} \leq \sum_{p,ll \in \mathsf{INM} \subseteq PxL} q^{\mathsf{FuelPurchased}}_{c,p,f,n,ln,y} \tag{12}$$
$$\forall c \in C, n \in N$$

Export Capacity Constraint
$$q^{\mathsf{Exports}}_{p,t,f,n,ln,y} \leq q^{\mathsf{Export\ Capacity}}_{p,t,f,n,ln,y} \tag{13}$$
$$\forall p \in P, t \in T, f \in F, n \in N, y \in Y$$

$$\text{Export Capacity Accumulation} \quad q^{\text{Export Capacity}}_{p,t,f,n,ln,y} \leq \sum_{\substack{\forall yy \\ \in yy-y \leq L^{\text{Lifetime}}_{\rho}}} q^{\text{NewExportCapacity}}_{p,t,f,n,ln,y} \tag{14}$$

$$\forall p \in P, t \in T, f \in F, n \in N, y \in Y$$

$$\text{Monetary Clearing} \quad q^{\text{Fuel Sold}}_{p,c,f,nn,n,y} == \sum_{c \in C} q^{\text{Fuel Purchased}}_{c,p,f,n,nn,y}$$

$$\forall p \in P, c \in C, f \in F_{\mathsf{t}}, n, nn \in N, y \in Y$$

$$\cup (c,l) \in \text{INM}\} \cup (p,nn) \in \text{INM}$$

$$\cup (f,c) \in \text{FIM}\} \cup (f,p) \in \text{FIM} \tag{15}$$

Furthermore, to diversify the hydrogen supply, the following capacity expansion constraints are imposed on the production site. Equation (16) allows a single producer only to produce 30% of all hydrogen imported by downstream industries. Equation (17) limits the capacity addition in any year beyond 2030 to 50% of existing capacities.

Capacity Expansion Constraint in 2030

$$\sum_{\substack{\rho \in \mathcal{P} \cup (\rho,i) \in \text{PIM} \\ \cup (\rho,f) \in \text{PFM}}} q^{\text{NewCapacity}}_{p,\rho,n,y} \leq 0.3 \sum_{\substack{c \in C, t \in \text{PT}, n \in n, nn \in N, m \in M \\ \cup (f,c) \in \text{FIM} \cup (t,f) \in \text{SFM} \\ \cup (c,n) \in \text{INM} \cup (p,nn) \in \text{INM}}} q^{\text{Imports}}_{c,t,n,nn,m,y} \tag{16}$$

$$\forall p \in P, f \in \text{H}_2, \text{NH}_3, \text{MeOH}, n \in N, y \in Y \cup (\rho, f) \in PFM \cup (p,f) \in \text{SFM} \cup (p,n) \in \text{INM}$$

Capacity Expansion Constraint for 2035 - 2050

$$q^{\text{NewCapacity}}_{p,\rho,n,y} \leq 0.5 q^{\text{ProcessCapacity}}_{p,\rho,n,y-1} \tag{17}$$

$$\forall p \in P, f \in \{\text{H}_2, \text{NH}_3, \text{MeOH}\}, n \in N, y \in Y \cup (\rho, f) \in \text{PFM} \cup (p,f) \in \text{SFM} \cup (p,n) \in \text{INM}$$

3.3. The hydrogen market with monopolistic supply

Alternatively, to the perfect competition mode, the producers may engage in strategic behavior and rationing the hydrogen supply and its derivatives. Given that producing hydrogen and its derivatives requires large investments, it could be imagined that early investors behave like Stackelberg leaders and undertake larger investments than optimal under perfect competition to deter entry.

This allows the producer of these commodities to raise the price of hydrogen to the maximum willingness to pay for their products instead of offering hydrogen at the lowest cost. Suppose producers have some market power from being a Stackelberg leader. Producers benefit from consuming hydrogen and its derivatives, driven by a higher carbon price and the EU RFNBO quota system. To analyze the potential impact of such behavior, the following Stackelberg game is designed. The model's objective represents the producer's profit as shown in (18). Producers maximize the difference between the revenue they make by selling hydrogen and its derivatives and the CAPEX and OPEX cost they incur in producing these and delivering them to their customers in Germany.

$$
\begin{aligned}
\max_{\lambda_{c,p,f,n,nn,y}} \sum_{p\in P, n\in N y\in Y} \Pi_{p,n,y} = & \sum_{p\in P,c\in C,n\in N,nn\in N,y\in Y} (\lambda_f) q^{\text{Fuel Sold}}_{p,c,f,nn,n,y} \\
& - \left(\sum_{\substack{f\in F_{\text{Endo}} \\ \cap\{f|(f,i)\in \text{FIM}\}}} p_{f,y} \cdot q^{\text{Purchased}}_{i,f,n,y} + \sum_{\substack{\rho\in\mathcal{P} \\ \cap\{\rho|(\rho,i)\in \text{PIM}\}}} \left(K_{\rho,y} \cdot q^{\text{NewCapacity}}_{i,\rho,n,y} + O_{\rho,y} \cdot q^{\text{Process}}_{i,\rho,o,n,y} \right) \right) \\
& - \sum_{\substack{i\in P\cup T,\, ii\in T\cup C,n,\, ll\in N,\, m\in M,\, y\in Y \\ \cup\{f|(f,i)\in \text{FIM}\},\cup\{i|(i,n)\in ILM\},\cup\{ii,|(ii,nn)\in ILM\}}} \left(K_{m,y} \cdot q^{\text{NewExportCapacity}}_{i,ii,n,nn,m,y} + O_{m,f,y} \cdot q^{\text{Exports}}_{i,ii,n,nn,m,y} \right) \delta_{n,nn}
\end{aligned}
\tag{18}
$$

They face the same constraints presented in the model under perfect competition

$$\text{Exogenous Fuel Balance} \quad \sum_{\substack{\rho \\ \cup\{\rho|(\rho,p)\in PIM\}}} q^{\text{ProcessFuelDemand}}_{p,\rho,f,n,y} \leq \sum_{\rho\in\mathcal{P}\cup\{\rho\rho|(\rho\rho,o)\in POM\}} q^{\text{Process}}_{i,\rho\rho,n,y}$$

$$+ q^{\text{qFuelPurchased}}_{p,f,n,y} \tag{19}$$

$$\forall p \in P, f \in F, n \in N, y \in Y \cup (\rho, p) \in \text{PIM} \cup (f, \rho) \in \text{PFM} \tag{20}$$

$$\text{Fuel Demand Constraint} \quad q^{\text{Process}}_{p,\rho,o,n,y} \leq \frac{1}{s_{I\,\rho,f,y}} q^{\text{ProcessFuelDemand}}_{p,\rho,f,n,y}$$

$$\forall p \in P, \rho \in \mathcal{P}, f \in F, y \in Y \cup (\rho, p) \in \text{PIM} \cup (\rho, f) \in \text{PFM}$$

$$\cup\,(p, l) \in \text{INM}$$

$$\text{Capacity Constraint} \frac{1}{\text{cf}_{\rho,l}} \sum_{o\in O\cup(\rho,o)\in POM} q^{\text{Process}}_{i,\rho,o,n,y} \leq q^{\text{ProcessCapacity}}_{i,\rho,n,y} \tag{21}$$

$$\forall p \in P, \rho \in \mathcal{P}, n \in N, y \in Y \cup (\rho, p) \in \text{PIM} \cup (p, l) \in \text{INM}$$

$$\text{Capacity Accumulation} \quad q^{\text{ProcessCapacity}}_{p,\rho,n,y} \leq \sum_{\substack{\forall yy \\ \in yy-y\leq L^{\text{Lifetime}}_{\rho}}} q^{\text{NewCapacity}}_{p,\rho,n,yy} + q^{\text{ResCapacity}}_{p,\rho,n,yy}$$

$$\forall p \in P, \rho \in R, n \in N, y \in Y \cup (\rho, p) \in \text{PIM} \cup (p, l) \in \text{INM} \tag{22}$$

$$\text{Monetary Clearing} \quad q^{\text{Fuel Sold}}_{p,c,f,nn,n,y} == \sum_{c\in C} q^{\text{Fuel Purchased}}_{c,p,f,n,nn,y}$$

$$\forall p \in P, c \in C, f \in F_{\text{t}}, n, nn \in N, y \in Y$$

$$\cup\,\{c \mid (c, l) \in \text{INM}\} \cup p \mid (p, nn) \in \text{INM}$$

$$\cup\,\{f \mid (f, c) \in \text{FIM}\} \cup \{f \mid (f, p) \in \text{FIM}\}$$

$$\text{Export Import Balance} \quad q^{\text{Imports}}_{c,t,n,nn,m,y} <= \delta^{\text{losess}}_{mm,y}\, q^{\text{Exports}}_{p,t,f,n,ln,y}$$

$$\forall c \in C \cup T, \forall p \in P \cup T, n, nn \ \in N, y \in Y \tag{23}$$

In addition to the usual constraint, the producers of hydrogen, ammonia and methanol in this model are constraint by the optimal choices made by the downstream industries and the optimal export and production decisions by potential competitors. These are represented as the First-Order conditions (FOC) of the industries in minimizing their cost while satisfying the demand for their final good or service and their emission constraint and EU RFNBO quota.

$$\text{Exo Fuel Purchase FOC} \quad 0 \leq \lambda_{f\,c,p,f,n,ln,y} - \mu^{\text{FuelBalance}}_{c,f,n,y} \quad \perp \quad q^{\text{qFuelImports}}_{c,p,f,n,ln,y} \geq 0$$
$$\forall c \in C, p \in P, f \in F_{\text{Endo}}, n, nn \in N, y \in Y \cup (c,l) \in \text{INM} \cup (f,c) \in \text{FIM}$$
$$\cup\, (p,nn) \in \text{INM} \cup (f,p) \in \text{FIM} \tag{24}$$

$$\text{Endo Fuel Purcahse FOC} \quad 0 \leq c_f - \mu^{\text{FuelBalance}}_{c,f,n,y} \quad \perp \quad q^{\text{qFuelPurchased}}_{c,p,f,n,ln,y} \geq 0$$
$$\forall c \in C, p \in P, f \in F_{\text{Exo}}, n, nn \in N, y \in Y \in \text{INM} \cup (f,c) \in \text{FIM}$$
$$\cup\, (p,nn) \in \text{INM} \cup (f,p) \in \text{FIM} \tag{25}$$

$$\text{Fuel Demand FOC} \quad 0 \leq \mu^{\text{FuelBalance}}_{c,f,n,y} - \mu^{\text{RFNBO}}_{c,f,\rho,n,y} - (r_{s,y} - \omega_f)\mu^{\text{RFNBO}}_{s,y} - (1 - \text{I}_{\text{FuelSwitching}})\mu^{\text{ProcessFuelDemand}}_{c,f,\rho,n,y}$$
$$- \text{I}_{\text{FuelSwitching}}\mu^{\text{FuelSwichting}}_{c,f,\rho,n,y} \quad \perp \quad q^{\text{ProcessFuelDemand}}_{c,f,\rho,n,y} \geq 0$$
$$\forall c \in C, p \in P, f \in F_{\text{Exo}}, n, nn \in N, y \in Y \cup (c,l) \in \text{INM} \cup (f,c) \in \text{FIM} \tag{26}$$

$$\text{Process FOC} \quad 0 \leq O_{\rho,y} + \sum_{f \cup \{f|(f,\rho)\} \in \text{POM}} \mu^{\text{ProcessFuelDemand}}_{c,f,\rho,n,y} + \mu^{CO_2}_{c,y} - \mu^{\text{FuelBalance}}_{c,f,n,y} - \lambda^{\text{FGMC}}_{g,n,y}$$
$$\perp \quad q^{\text{Process}}_{c,\rho,n,y} \geq 0 \quad \forall c \in C, \rho \in \mathcal{P}, g \in G, n \in N, y \in Y$$
$$\cup\, (c,l) \in \text{INM} \cup (\rho,c) \in \text{PIM} \tag{27}$$

$$\text{Process Capacity FOC} \quad 0 \leq \sum_{\substack{\forall yy \\ \in yy - y \leq L^{\text{Lifetime}}_{\rho}}} \mu^{\text{NewCapacity}}_{c,\rho,n,y} - \mu^{\text{ProcessCapacity}}_{c,\rho,n,y} \quad \perp \quad q^{\text{Capacity}}_{c,\rho,n,y} \geq 0$$
$$\forall c \in C, p \in P, l \in N, y \in Y \cup (c,l) \in \text{INM} \cup (\rho,c) \in \text{PIM} \tag{28}$$

$$\text{Capacity Investment FOC} \quad 0 \leq K_{\rho,y} - \mu^{\text{NewCapacity}}_{c,\rho,n,y} \quad \perp \quad q^{\text{NewCapacity}}_{c,\rho,n,y} \geq 0$$
$$\forall c \in C, p \in P, l \in N, y \in Y \cup (c,l) \in \text{INM} \cup (\rho,c) \in \text{PIM} \tag{29}$$

$$\text{Emission FOC} \quad 0 \leq p^{CO_2}_{y} - \mu^{CO_2}_{c,n,y} \quad \perp \quad q^{CO_2\text{Purchased}} \geq 0 \tag{30}$$
$$\forall c \in C, n \in N, y \in Y \cup (c,l) \in \text{INM} \tag{31}$$

$$\text{Import FOC} \quad 0 \leq p^{\text{Imports}}_{c,g,n,y} - \lambda^{FGMC}_{c,g,n,y} \quad \perp \quad q^{\text{Imports}}_{c,\rho,n,y} \geq 0$$
$$\forall c \in C, g \in G, l \in N, y \in Y \cup (n,c) \in \text{INM} \cup (c,g) \in \text{GIM} \tag{32}$$

Demand Constraint

$$0 \leq \sum_{\substack{\rho \in mathcalP \\ \cap\{\rho|(c,\rho)\in \mathsf{pIm} \wedge \\ (\rho,g)\in \mathsf{pGm}\}}} q_{\mathsf{Process}_{c,\rho g,n,y}} - \sum_{\rho} q^{\mathsf{Imports}}_{c,\rho,n,y} - D_{c,g,n,y} \perp \lambda^{FGMC}_{c,\rho,n,y} \geq 0$$

$$\forall c \in C, g \in G, n \in N, y \in Y \cup (n,c) \in \mathsf{INM} \cup (c,g) \in \mathsf{GIM} \tag{33}$$

$$\text{Fuel Balance} \quad 0 \leq q^{\mathsf{FuelPurchased}}_{c,p,i,f,n,nn,y} + \sum_{\substack{\rho\rho \in \mathcal{P} \\ ff \in F}} q^{\mathsf{Process}}_{c,\rho\rho,ff,f,n,y} - \sum_{\rho in \mathcal{P}} q^{\mathsf{ProcessFuelDemand}}_{c,\rho,f,n,y}$$

$$\perp \quad \mu^{\mathsf{FuelBalance}}_{c,f,\rho,n,y} \geq 0$$

$$\forall c \in C, f \in F, n \in N, y \in Y \cup (n,c) \in \mathsf{INM} \cup (f,c) \in \mathsf{FIM} \tag{34}$$

$$\text{Fuel Demand Constraint} \quad 0 \leq q^{\mathsf{Process}}_{c,\rho,f,o,n,y} - \frac{1}{s_{\mathsf{I}\rho,f}, y} q^{\mathsf{ProcessFuelDemand}}_{c,\rho,f,n,y}$$

$$\perp \quad \mu^{\mathsf{ProcessFuelDemand}}_{c,f,\rho,n,y} \geq 0$$

$$\forall c \in C, \rho \in \mathcal{P}, f \in F, o \in O, l \in N, y \in Y$$

$$\cup (n,c) \in \mathsf{INM} \cup \in (\rho,c)\mathsf{PIM} \cup (f,c) \in \mathsf{FIM} \tag{35}$$

Fuel Demand Constraint for processes with fuel switching

$$0 \leq q^{\mathsf{Process}}_{i,\rho,o,n,y} - \sum_{f \in F \cup (\rho,f) PFM} \frac{1}{s_{I_{\rho,\mathsf{Fuel\ Switching},f,y}}} q^{\mathsf{ProcessFuelDemand}}_{i,\rho,f,n,y}$$

$$\perp \mu^{\mathsf{FuelSwitching}}_{c,\rho,f,o,n,y} \geq 0 \quad \forall i \in I, \rho \in \mathcal{P}, f \in F, n \in N, y \in Y$$

$$\cup (i,n) \in \mathsf{INM} \cup (f,\rho) \in \mathsf{FSM} \cup (i,n) \in \mathsf{INM} \tag{36}$$

$$\text{RNFBO Constraint} \quad 0 \leq r^{\mathsf{RFNBO}}_{s,y} \sum_{\substack{f \in F,\, \rho \in \mathcal{P} \\ \cup(\rho,f)\in \mathsf{PFM} \\ c \in C \cup \{c|(c,s)\in \mathsf{SIM}\}}} q^{\mathsf{ProcessesFuelDemand}}_{c,\rho,f,l}$$

$$- \sum_{\substack{f \in F,\, \rho \in \mathcal{P} \\ (\rho,f)\in \mathsf{PFM} \\ c \in C \cup \{c|(c,s)\in \mathsf{SIM}\}}} \omega_f \, q^{\mathsf{ProcessesFuelDemand}}_{c,\rho,f,l} \quad \perp \quad \mu^{\mathsf{RFNBO}}_{s,y} \geq 0$$

$$\forall s \in S,\ y \in Y \tag{37}$$

$$\text{Process Constraint} \quad 0 \leq \sum_{f \in F \cup \{f|(\rho,f)\in PFM\}} q^{\mathsf{Process}}_{c,\rho,f,o,n,y} - q^{\mathsf{ProcessCapacity}}_{c,\rho,n,y}$$

$$\perp \quad \mu^{\mathsf{Capacity}}_{c,f,\rho,n,y} \geq 0$$

$$\forall c \in C, f \in F, \rho \in \mathcal{P}, o \in O, n \in N, y \in Y$$

$$\cup (n,c) \in \mathsf{INM} \cup (\rho,c) \in \mathsf{PIM} \cup (f,\rho) \in \mathsf{PFM} \tag{38}$$

$$\text{Capacity Accumulation} \quad 0 \leq \quad q^{\text{ProcessCapacity}}_{c,\rho,n,y} - \sum_{\substack{\forall yy \\ \in yy-y \leq L^{\text{Lifetime}}_{\rho}}} q^{\text{NewCapacity}}_{c,\rho,n,yy} - q^{\text{ResCapacity}}_{c,\rho,n,yy}$$

$$\perp \quad \mu^{\text{NewCapacity}}_{c,\rho,n,y} \geq 0$$

$$\forall c \in C, \rho \in R, n \in N, y \in Y$$

$$\cup (n,c) \in \text{INM} \cup (\rho, c) \in \text{PIM} \cup (f, \rho) \in \text{PFM} \tag{39}$$

$$\text{CO}_2 \text{ Constraint} \quad 0 \leq \sum_{\rho \in \mathcal{P}} q^{\text{ProcessFuelDemand}}_{c,\rho,n,y} \epsilon_{\rho} - q^{\text{CO2}}_{c,n,y} \quad \perp \quad \mu^{\text{CO}_2}_{c,y} \geq 0$$

$$\forall c \in C, n \in N, y \in Y \cup (c,l) \in \text{INM} \tag{40}$$

Equations (24) and (24) ensure that downstream industries purchase fuel as long as its shadow price of the fuel balance constraint exceeds its cost. (26) provides that fuel is demanded as long as the value of reducing the constraint imposed by the fuel balance exceeds the costs imposed on using the fuel by the EU RFNBO quota. Equation (27) ensures that the cost of operating a process, including CAPEX and OPEX, is compensated by its marginal benefits by its effect on the emission constraint, fuel balance, and satisfying demand. Equation (27) and (27) imply that an investment decision considers the future value the investment brings about. Equation (28) ensures the optimal investment equation equates marginal benefits and costs of these.

Equations (24) and (24) ensure that downstream industries purchase fuel as long as the shadow price of the fuel balance constraint exceeds the fuel's cost, effectively guiding optimal procurement decisions under the balance constraints. Similarly, Equation (26) establishes that fuel is demanded when the value of easing the constraint imposed by the fuel balance surpasses the costs of using the fuen, factoring in any penalties or obligations introduced by the EU RFNBO quota.

Equation (27) ensures that a process operates only when the associated costs, including CAPEX and OPEX, are offset by its marginal benefits. These benefits arise from the process's contribution to alleviating emission constraints, balancing fuel requirements, and meeting demand. Together, Equations (27) and (28) imply that investment decisions in processes consider their long-term value, encompassing benefits from improved compliance, increased capacity, or efficiency gains. Equation (29) ensures that the optimal investment decision aligns the marginal benefits of additional capacity with the marginal costs incurred, driving efficient capital allocation.

The equation (31) stipulates that emissions are priced at the equilibrium between the market cost of emitting $p_y^{CO_2}$ and the marginal value of reducing the emission constraint $\mu_{c,n,y}^{CO_2}$. This balance ensures that purchasing or reducing emission allowances occurs only when economically justified.

4. Model Assumptions and Data

4.1. Nodes and Transport

Figure (2) provides a simplified visualization of the emerging hydrogen economy as represented in this model. Production sites in Chañaral, Guelmim, and Teruel are chosen as examples, reflecting distinct combinations of production and transport costs. Nearby larger ports, such as Antofagasta and Agadir, serve as regional hubs for Chañaral and Guelmim, respectively. These are locations that are likely to emerge as the first producing regions of hydrogen according to Riemer et al. (2022). Furthermore, there is a supplier of low-carbon hydrogen supplied from Fiska in Norway. Downstream industries are located at well-known industrial sites in Germany, ensuring realistic examples of demand locations.

The model does not make specific assumptions about these sites' hydrogen, ammonia, and methanol production processes. Instead, each production location hosts hydrogen, ammonia, and methanol producers, as depicted in Figure (2). For Chañaral and Guelmim, hydrogen, ammonia, and methanol are transported to Antofagasta and Agadir, respectively, and then shipped to Rotterdam and Hamburg. From these ports, the products are moved via pipeline to end consumers. The producer in Norway transports its hydrogen via a submarine pipeline from Fiska to Hamburg, from it is distributed further. In contrast, producers in Spain have the advantage of delivering their products directly to European consumers through the European hydrogen backbone, bypassing the need for port handling.

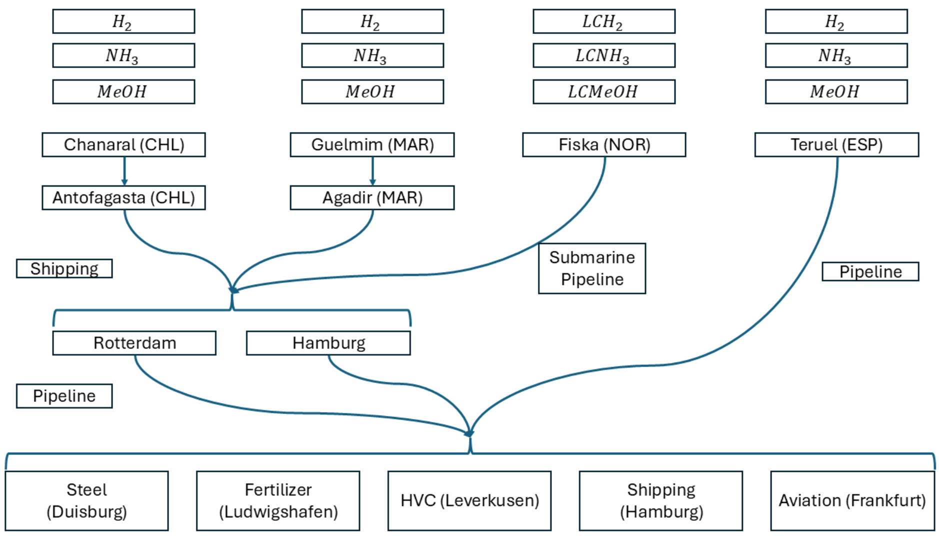


Figure 2: Simplified map of the emerging hydrogen economy

subsectionActors and Processes The midstream consists of traders at ports in the three exporting countries, Rotterdam and Hamburg, from which the commodities are imported to Germany. Further, downstream of the hydrogen supply chain exists the steel-making, fertilizer production, shipping, and aviation industries in Germany, which produce their goods in a market with perfect competition.

Hence, the best they can do to maximize their revenues is to reduce their input cost.

Upstream, producers generate hydrogen, ammonia, and methanol with zero emissions via electrolysis, using electricity supplied by onshore wind and solar photovoltaic power generation (solar PV) power. Their investments in electricity generation capacity are based on average annual capacity factors. In addition, ammonia producers operate air separation units to supply the nitrogen needed for the Haber-Bosch process in ammonia synthesis. Similarly, methanol producers use direct air capture (DAC) units to obtain the CO_2 required for methanol synthesis. For simplicity, the model assumes that only CO_2 sourced from direct carbon air capture (DAC) is used at the production site, as incorporating other CO_2 sources would complicate tracking the carbon emissions of the following production processes.

In the model's midstream segment, traders at port locations handle commodities by either importing from local producers via pipeline, converting them, and exporting by ship or by importing via ship, converting, and exporting through pipelines to local consumers. Traders must invest in pipeline infrastructure and conversion capacity to support these activities. Furthermore, anticipating that hydrogen, ammonia, and methanol will be prohibitively expensive for electricity generation within an emerging hydrogen market, traders must also secure sufficient electricity to meet the energy demands of the conversion processes.

Downstream, industries such as steelmaking, fertilizer production, high-value chemical manufacturing, and the shipping and aviation sectors produce final goods and services to meet demand. Although demand is fixed, these industries can select from various available production processes or import final goods from the global market. For steelmakers, the main production methods include the traditional blast Furnace - basic oxygen furnace (BF-BOF) route and the leading route to decarbonize the production of steel making through the direct reduced of iron ore - electric arc furnace (DRI-EAF) processes (Kim et al. 2022). Unlike some studies in the literature, this model does not yet incorporate steel scrap as a substitute for reduced iron in the DRI route.

The fertilizer producer is assumed to produce ammonia-based compounds, such as urea. It can choose between using natural gas-based steam methane reformation (SMR) to produce hydrogen or purchasing hydrogen to fuel the Haber-Bosch synthesis (HB) process for ammonia synthesis, which is considered the primary pathway to decarbonize the production of fertilizers (Walden et al. 2023). Additionally, the fertilizer producer can directly purchase ammonia to make its fertilizer. However, the procurement of CO_2 for synthesizing urea and the potential reuse of CO_2 from the SMR process are not considered.

The HVC producer initianny relies on naphtha steam cracking to produce aromatics and olefins, such as benzene and ethylene. A critical decarbonization pathway involves substituting naphtha steam cracking (NTO/NTA) with methanol-to-olfins/aromatics (MTO/MTA) (Nesterenko et al. 2023). The producer can achieve zero emissions for methanol production by synthesizing methanol using purchased hydrogen and CO_2 from DAC or by opting for biomass-based methanol production via the biomass-to-methanol (BTM) process. Additionally, the producer has the option to purchase methanol directly. Alternatively, the HVC industry could also adopt a process and, thus, decarbonize its production without requiring hydrogen or its derivatives.

The shipping and aviation industry must satisfy the demand for goods and transporting consumers. In the case of this model, shipping refers primarily to inter-continental container shipping and the aviation industry because previous research has shown that hydrogen-based fuels become only competitive at longer ranges (Kranenburg-Bruinsma et al. 2020). Assuming that the demand for these goods is fixed and there is no international competition for domestic demand of shipping and flying, these translate into a fixed demand for fuels that must be procured. The shipping industry can fuel a internal combustion engine (ICE) with either maritime gas oil (MGO) or bio-diesel without additional investments or invest in a new set of engines, such as an maritime liquified natural gas internal combustion engine (LNG ICE), maritime hydrogen internal combustion engine (H_2 ICE), maritime ammonia internal combustion engine (NH_3 ICE) and a maritime liquified natural gas internal combustion engine (MeOH ICE) representing the standard set of technologies discussed around the decarbonization of maritime shipping Horvath, Fasihi, and Breyer (2018) and Karvounis et al. (2022). Though, while (Horvath, Fasihi, and Breyer 2018) considers the introduction of an engine for liquefied hydrogen, this model only a simple hydrogen engine and ignores the environmental risks associated with the combustion of ammonia (Karvounis et al. 2022).

In the aviation industry, the existing use of JetA fuel in jet turbines on long haul flights is expected to be substituted with synthetic kerosene of electric origin (E-kerosene) or bio-based fuels such as hydrotreated feedstocks (HEFA) fuels, which compromise treated cooking oil, animal fats or plant oils (Vardon et al. 2022; Watson et al. 2024). The E-kerosene is either derived from a Fischer-Tropsch process (FT) or derived from methanol via a methanol-to-kerosene (MTK) process. Hydrogen and methanol can be purchased. The industry can also produce methanol using the BTM process.

4.2. Residual Capacities

The model considers existing residual capacities for downstream industries, as shown in figure (3). The residual capacities are based on production data for each local site previously shown and extrapolated

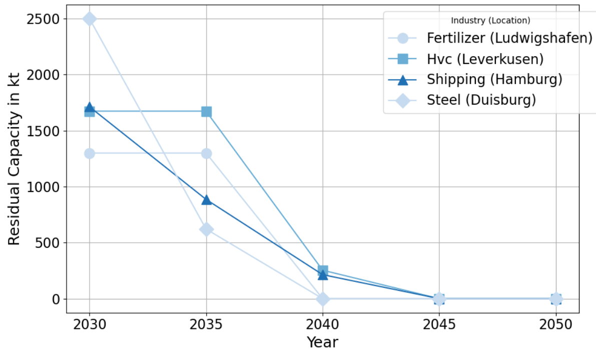


Figure 3: Residual capacities in kt

with the age structure of existing residual capacity, which is only. The age structure of the residual capacity for the BF-BOF route is taken from Vogl, Olsson, and Nykvist (2021). The data on existing SMR and NTO/NTA is derived from the International Energy Agency (2020). For the fertilizer industry, the structure of the processes adjacent to the SMR, like the air-seperation unit (ASU) and fertilizer synthesis, are assumed to have the same age structure as the SMR processes. The age structure of the existing fuel demand by conventional ICE is inferred from Statista (2023). For the aviation industry, residual capacities are ignored as it is assumed that any jet engine can be fueled by FT, low carbon fuel derived from a Fischer-Tropsch process (LCFT), HEFA or JetA and, thus, the capacity costs for jet engines do not contribute to the costs of decarbonization.

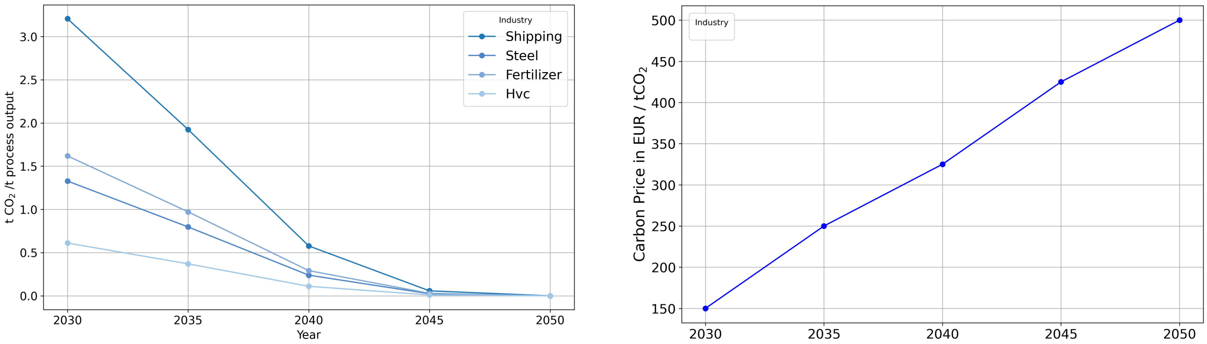
4.3. Policies

In this model, hydrogen demand is influenced by two key policies. First, the EU ETS sets a cap on the total emissions that downstream industries are permitted to emit. The emissions limit under the EU ETS is defined until 2030. Since this model starts in 2030, it is assumed that the total emissions for each industry will decrease according to an exponential interpolation, as shown in equation (41). The reference values for this calculation are the emissions limits for the latest trading period (2021–2030), with the target of zero emissions by 2050, according to (European Commission 2024). Figure (**??**) illustrates the resulting emission benchmarks for each industry, while the emission of each technology in use is shown in the appendix.

$$y_t = y_{2030} \frac{y_{2050}}{y_{2030}}^{t-2030} \tag{41}$$

The model does not cover ansectors included in the EU ETS, as it ignores, for instance, the power sector, which is one of the industries with the least cost abatement (Brink, Vollebergh, and Werf

2016), the industries within the model can purchase additional CO_2 certificates from the market at exogenous prices. These certificates are priced according to CO_2 price projections from (Enerdata Intelligence 2023) and are extrapolated using equation (41). The resulting CO_2 price applied in the model is depicted in figure (4b).



(a) Allowed CO_2 emissions **(b) Price of carbon**

Figure 4: A comparison of CO_2 emissions and carbon prices.

The second policy determining the demand for hydrogen is the European policy on EU RFNBO. These fuels, primarily produced through renewable electricity electrolysis, encompass hydrogen, ammonia, and methanol. The EU's Renewable Energy Directive (RED III) establishes ambitious targets for RFNBO integration, mandating 42% of industrial hydrogen to be RFNBO-sourced by 2030, increasing to 60% by 2035, and requiring a minimum 1% RFNBO contribution to the transport sector's energy mix by 2030. There are also specific targets for the aviation sector at 5% in 2035. The quota for the shipping sector is set at 1% for 2030 and 2% in 2035. Beyond this published target, it is assumed that the RFNBO targets are increased until they reach 70% for steel, fertilizer, and HVC producers and 35 for the transport sector. The, thus, assumed RFNBO targets are shown in figure.

To qualify as RFNBOs, fuels must meet stringent criteria regarding renewable electricity sources, additionality, and temporal and geographical correlation between electricity and fuel production. To

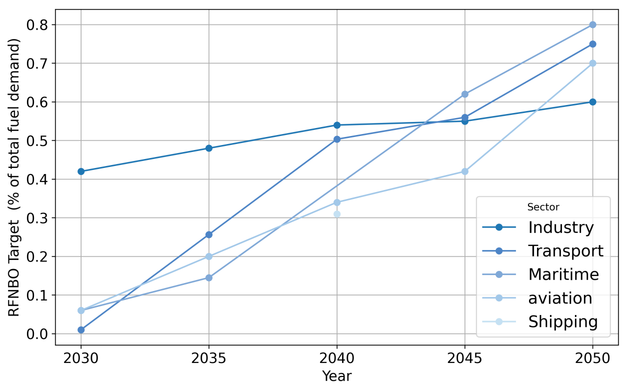


Figure 5: Actual and assumed RFNBO Targets by Sector

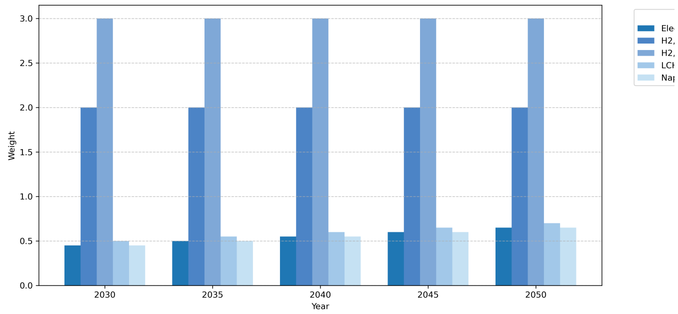


Figure 6: Comparison of RFNBO targets and weights by sector.

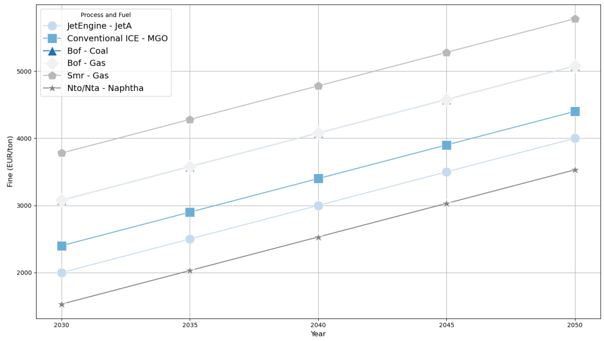


Figure 7: RFNBO Fines

facilitate its representation in the model, it is assumed that anfuels endogenous to the model are produced with renewable electricity and carbon and nitrogen produced by DAC and ASU. An additional simplification is made by ignoring other subsectors in the industrial and transport sectors, which are also subject to the EU RFNBO policy.

The weight of hydrogen, ammonia, and methanol purchased from the producers weighs one in the EU RFNBO quota. The carbon capture rate and the, thus assigned a weight for low carbon hydrogen (LCH_2) and its derivatives is based on conservative estimates from Romano et al. (2022) and Nessi, Papadopoulos, and Seferlis (2021) and is assumed to increase as shown in the figure (6). Likewise, the grid's electricity weight is considered to increase as the power sector decarbonizes its processes. another fuels are assumed to be purely fossil-based and, thus, weight 0 zero in the RFNBO quota.

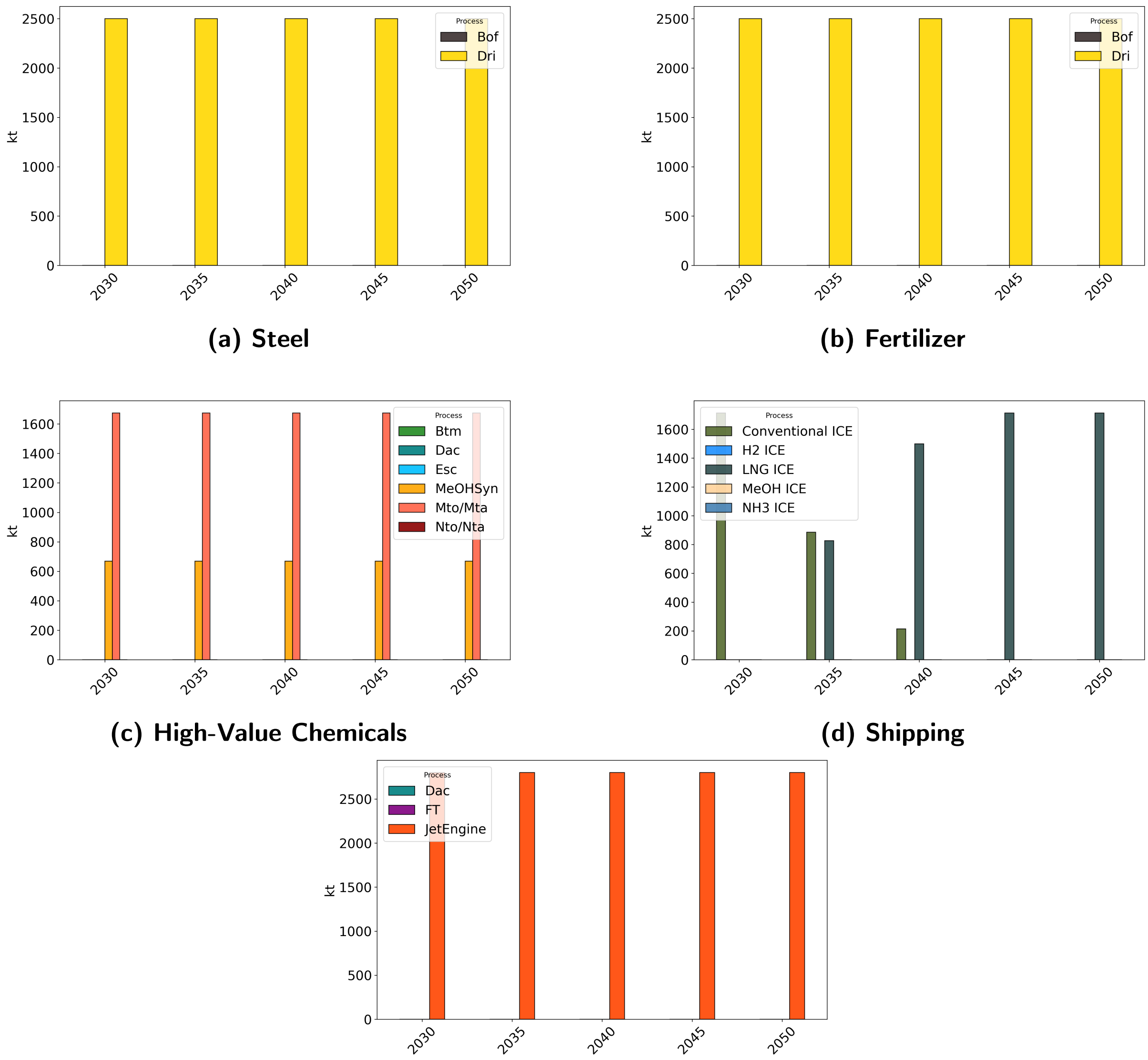
If the industries do not meet their RFNBO quota, they are subject to the fines shown in figure (7). The fine for using JetA fuel in aviation is based on. The fine for the use of MGO is based on DNV (2023) and the fine for using any fossil fuel is based on a penalty of 600 EUR per ton of emitted CO_2 according to Laer, Honselaar, and François (2023).

5. Results

5.1. Model results under the assumption of perfect competition

First, we examine the results of the hydrogen model under the assumption of perfect competition.

5.1.1. Process usage without RFNBO



(a) Steel **(b) Fertilizer** **(c) High-Value Chemicals** **(d) Shipping** **(e) Aviation**

Figure 8: Process Usage by Year for Different Industries without the RFNBO policy in kt

We examine the optimal process usage if no EU RFNBO policy and only the CO_2 price is in place. Without the policy figure, the steel and HVC industry decarbonizes its production totally, as it replaces its BF-BOF and routes by 2030. This scenario assumes no production limits exist for any producer; thus, a single producer can supply the entire demand for hydrogen and its derivatives. In contrast, the HVC industry first invests into the BTM in 2030 and 2035 and only adopts the MTO/MTA route in 2040. As the HB route in the fertilizer industry can be fueled with hydrogen from the SMR route and hydrogen, no process change occurs In the transport sector. The use of JetA fuel prevails as no investment in FT production is undertaken, and in the shipping industry, the conventional ICE is used until 2040, and the LNG ICE is adopted from 2035 onward. Conclusively, a CO_2 of up too 500 EUR/ton is insufficient to decarbonize these sectors.

5.1.2. Process usage with RFNBO

Next, we examine the effect of EU RFNBO, as illustrated in Figure (9). The introduction of EU RFNBO facilitates the decarbonization of processes in the shipping and aviation industries. In shipping, alongside the continued use of LNG ICE processes, NH_3 ICE is also adopted as a viable solution. Meanwhile, the aviation industry transitions to utilizing the FT pathway to produce sustainable fuels for jet engines. The usage of the DAC process in the aviation process, which appears to be unusual, can be explained by the usage of the DAC process is based on the EU RFNBO quota, the price for electricity and the price for CO_2 purchased from the wholesale market.

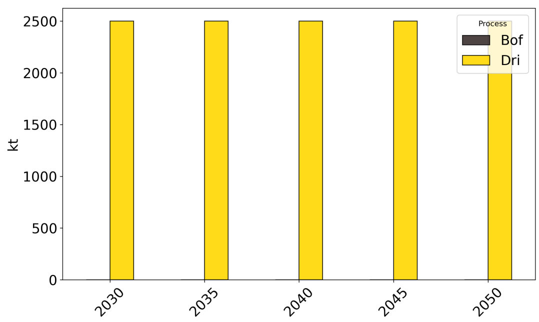
5.1.3. Process usage with RFNBO and capacity expansion constraints

5.1.4. Commodity flow without RFNBO

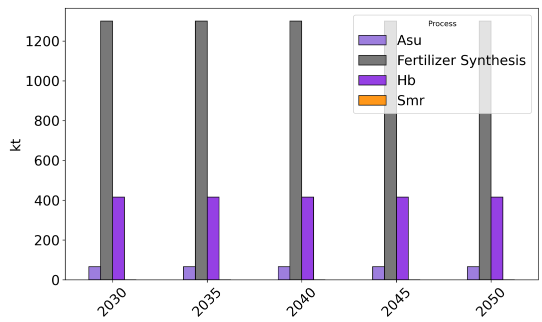
Next, we examine the distribution of hydrogen production and its derivatives. Figure (10) shows that without the RFNBO and constraints on capacity expansion in place, all hydrogen would be produced in Teruel in Spain. The consumers of hydrogen are the HVC industry in Leverkusen, the steel industry in Duisburg, and the fertilizer industry in Ludwigshafen. Furthermore, the amount of hydrogen consumed does not rise significantly over time. Additionally, without the RFNBO, there is no demand for ammonia or methanol.

5.1.5. Commodity flow with RFNBO

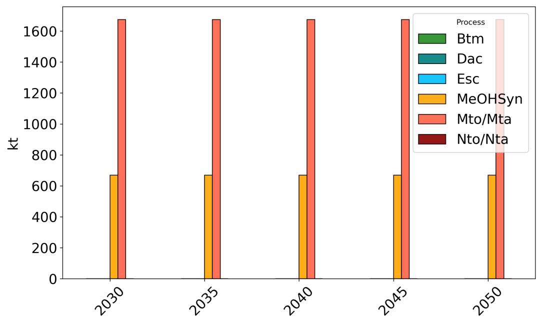
Under the EU RFNBO constraint, the transport sector becomes the greatest demand sector for hydrogen as shown in figure (11). In 2030, the aviation industry will already demand about 1.4 million tons of hydrogen for its Fischer-Tropsch processes, and by 2050, the aviation and shipping industry make up about two-thirds of the total demand for hydrogen and its derivatives.



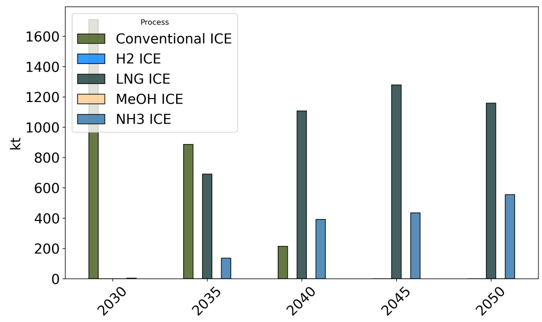
(a) Steel



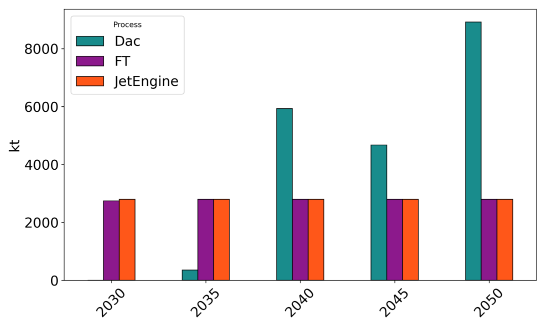
(b) Fertilizer



(c) High-value chemicals

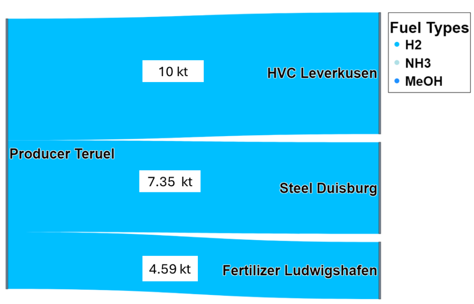


(d) Shipping

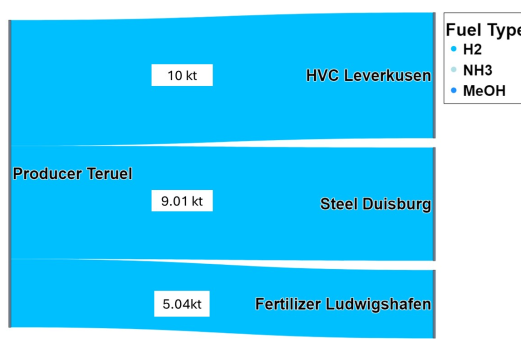


(e) Aviation

Figure 9: Process Usage by Year for Different Industries with the RFNBO policy in kt



(a) 2030

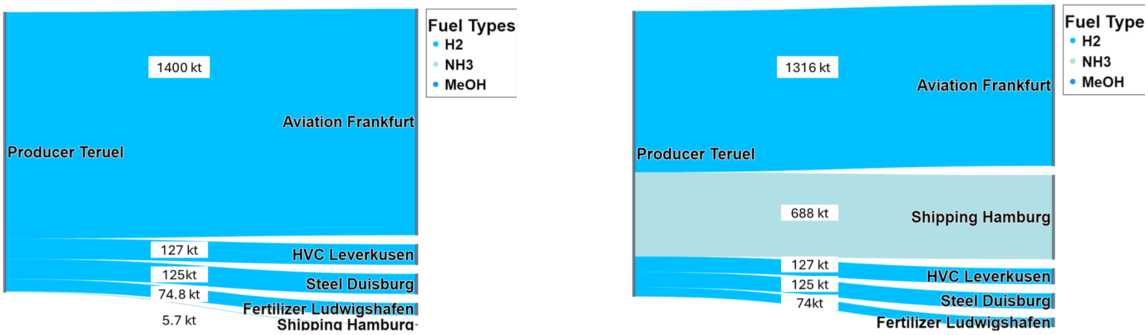


(b) 2050

Figure 10: Commodity flow without RFNBO in kt

5.1.6. Commodity flow with RFNBO and capacity expansion constraint

As the previous results have shown, if all hydrogen could be produced in Spain, no imports from Morocco, Norway, or Chile would be necessary. Since this assumption is unrealistic, two constraints



(a) 2030

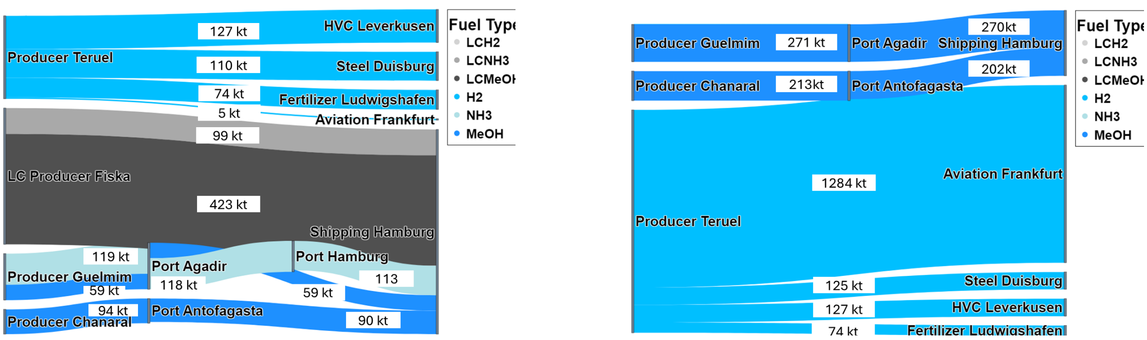
(b) 2050

Figure 11: Commodity flow with RFNBO in kt

are introduced to limit the capacity constraint. First, in the first year, any producer is allowed only to supply 30% of the total demand for hydrogen, ammonia, and methanol. Second, capacity restraints the following capacity expansions to 50% of the previous capacity.

Limiting the maximum capacity each producer can install substantially shapes the model results, as figure (14) shows. With the capacity expansion constraints introduced by equation (16) and (17), low-carbon ammonia and methanol imports from Norway become viable and supply the shipping industry. Additionally, MeOH imports from Morocco and Chile supply the shipping industry too. Furthermore, compared to the previous results in figure (11), the aviation industry is no longer the primary industry that demands hydrogen by 2030. The demands for hydrogen from Spain by the HVC, steel, and fertilizer industry remain unchanged.

As the fine for violating the RFNBO constraint increases, low-carbon fuels will become less attractive and does no longer supply the downstream industries in 2050. Moreover, Chile and Morrocco supply the shipping industry with methanol, while the producer in Spain supplies the aviation industry, steel, HVC, and fertilizer industry.



(a) 2030

(b) 2050

Figure 12: Commodity flow with RFNBO and capacity expansion constraints in kt

5.2. Model results under the assumption of a Stackelberg hydrogen economy

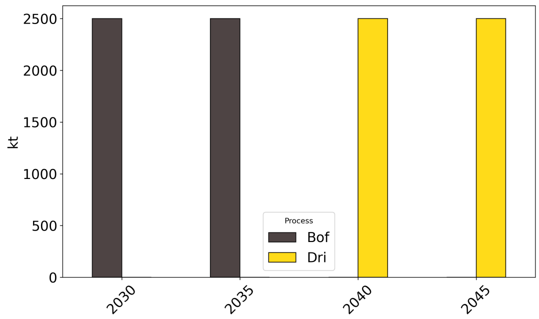
Next, we present the results of the Stackelberg model. The producers in Guelmim, Morocco, the producer in Chanaral, Chile, and their corresponding import and export infrastructure in Antofagasta, Agadir, Hamburg, and Rotterdam represent the Stackelberg leader and the producer in Spain and the low carbon producer in Norway, as well as all downstream industries, represent the Stackelberg follower. Furthermore, the same constraints on capacity expansion by equation (16) and (16) are applied.

5.2.1. Process usage under the assumption of a Stackelberg hydrogen economy

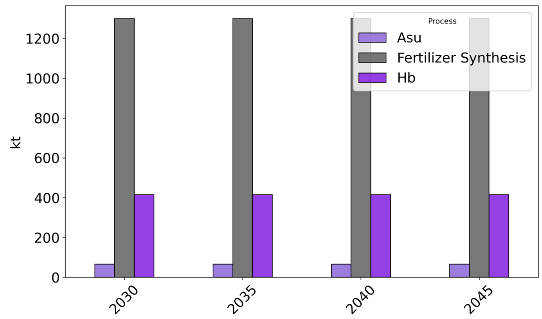
Figure (13) shows the processes used over time by downstream industries under the Stackelberg game assumption and capacity expansion constraint. Under these assumptions, the steel industry does not fully decarbonize by building up DRI-EAF capacities by 2040 but only two-thirds, as shown in (13). However, using different processes does not change for the fertilizer and HVC industry. No results could be derived for the aviation and shipping industry. This results, can be explained by rationing the supply of hydrogen to drive up its price, forbidding the steel industry to decarbonize early while the fact that the HVC and fertilizer industry decarbonize and alleviate the pressure from the EU RFNBO policy on the steel industry. Furthermore, supplying hydrogen to the HVC and fertilizer industry appears to be much more profitable for a Stackelberg leader than supplying hte steel industry.

5.2.2. Commodity under the assumption of a Stackelberg hydrogen economy

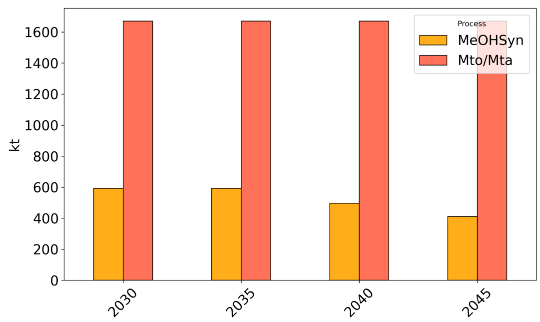
Figure (14) shows the commodity flow under the Stackelberg assumption in the years 2030 and 2050. Comparing the results of figure (14) witht the results in figure (14) shows that indeed flow of commodities can be influenced by a potential Stackelberg leader. Now, the producer in Guelmim drives the low-carbon producer in Fiska out of the market and supplies larger quantities of hydrogen than under perfect competition.



(a) Steel

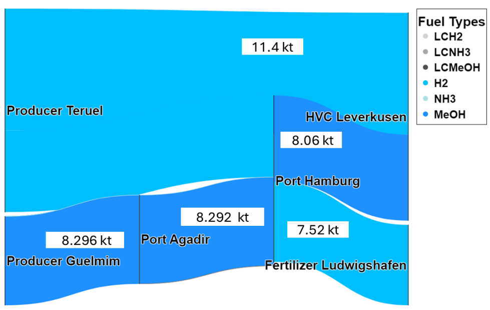


(b) Fertilizer

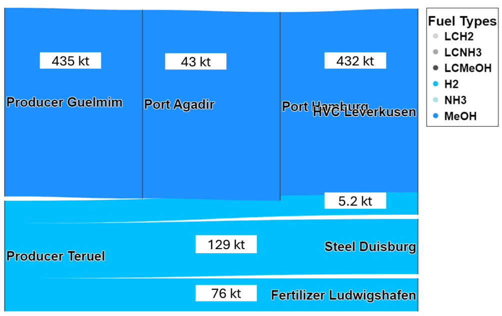


(c) High-value chemicals

Figure 13: Process usage under the assumption of a Stackelberg hydrogen economy



(a) 2030



(b) 2050

Figure 14: Commodity flow under Stackelberg hydrogen economy

6. Discussion

This thesis presents a highly flexible mode of the hydrogen economy, which allows for detailed modeling of different environmental policies as well as different market structures, such as the Stackelberg game. The results of the hydrogen market model demonstrate how policies and market structures influence industrial decarbonization and hydrogen demand. Without an RFNBO mandate, a CO price alone encourages significant decarbonization in the steel and high-value chemical (HVC) industries through the adoption of more efficient processes like direct reduced iron (DRI) and methanol-to-olefins (MTO). However, other sectors, particularly transport and shipping, continue to rely on conventional fuels, as the economic incentives for adopting alternative fuels remain insufficient. Introducing the RFNBO policy changes this by promoting low-carbon technologies, such as Fischer-Tropsch synthesis for aviation fuels and ammonia engines for shipping. Capacity constraints and Stackelberg market dynamics further highlight the impact of limited production capacity and strategic behaviors. These factors delay decarbonization in some industries while prioritizing others, depending on profitability and policy compliance. These results emphasize the importance of coordinated policies that address both production and distribution challenges to support widespread decarbonization.

These results resemble previous findings that show that there is the potential for market power in the hydrogen economy, as indicated by Dupke et al. (2024) and Barner (2024). Furthermore, this potential for market power can be exploited by investing strategically as shown by Zhang et al. (2022). However, contrary to the findings by Zhang et al. (2022) exploiting this market does not lead to an overall improvement in welfare, as the results deviates from the results of the market under perfect competition.

Overall, the results have to be considered carefully, because model lacks sufficiently detailed technological representation of the technologies to the downstream industries available to decarbonize their production processes. For instance, integrating renewable energy into fertilizer production, such as through biomass-based ammonia supply chains, may offer environmental and economic benefits by reducing the carbon footprint and dependency on natural gas, major challenges for the nitrogen fertilizers sector (Ribeiro Domingos et al. 2024). Furthermore, it also ignores the fact that CO_2 is likely to be used in a steam methane reforming with carbon capture (SMR-CC) process (Zhao et al. 2023). Furthermore, in the HVC industry, the electrification of naphtha steam cracking gains attention and is a possible contender for hydrogen imports (Schiffer and Manthiram 2017). Moreover, the model does not yet consider the possibility of full container shipping and aviation electrification in the transport sector, which could, however, emerge in the future (El-Sherif 2023).

Significant uncertainty surrounds carbon price trajectories beyond 2030, making forecasting and planning for long-term industrial decarbonization challenging. Pietzcker, Osorio, and Rodrigues (2021) suggest that carbon prices could reach around 129 EUR/t CO_2 by 2030, a level likely to drive substantial emissions reductions in industrial processes. Similarly, Glenk, Meier, and Reichelstein (2024) project a price of 141 EUR/t CO_2, further indicating high compliance costs and the need for low-carbon innovations across industries. Meanwhile, the grey literature presents an even wider range, estimating carbon prices between 200 and 250 EUR/t CO_2 by 2030, with some projections suggesting prices could exceed 500 EUR/t CO_2 after that (Enerdata Intelligence 2023; Homaio 2024).

Furthermore, when this thesis was written, it is unclear how explicitly the policy will be rolled out. The height of the fines has only been defined more clearly for the year 2030, and assumptions regarding the future increase of the EU RFNBO fines had to be made. Moreover, the accreditation of different fuels in accounting for the EU RFNBO quota has been heavily simplified. These assumptions, however, are the main driver of the model results. Therefore, the results of this model have to be treated carefully and must always be interpreted with respect to the assumed development of the policies.

7. Conclusion

This thesis highlights the development of a flexible hydrogen economy model designed to analyze the effects of environmental policies and market structures on industrial decarbonization and hydrogen demand. The results show that CO pricing alone drives significant emissions reductions in the steel and high-value chemical industries through technologies like DRI and MTO. However, sectors such as transport and shipping largely remain dependent on conventional fuels due to insufficient economic incentives. The introduction of RFNBO mandates alters this dynamic, supporting the adoption of low-carbon technologies like Fischer-Tropsch aviation fuels and ammonia engines for shipping. The inclusion of Stackelberg market structures further illustrates how capacity constraints and strategic behavior can delay decarbonization in some industries while advancing it in others, depending on profitability and policy requirements. These findings underline the importance of coordinated policies that balance production capabilities with broader decarbonization goals.

The model's results must be interpreted with caution due to several limitations. The simplified representation of downstream decarbonization technologies excludes pathways such as biomass-based ammonia, electrification of naphtha steam cracking, and the potential for fully electrified shipping and aviation. Assumptions regarding RFNBO policy implementation, including the trajectory of fines and accreditation criteria, add further uncertainty. Additionally, varying projections for carbon prices beyond 2030 introduce challenges for long-term planning, with estimates ranging widely from moderate to very high levels. These factors underscore the need for future work to include a more detailed technological representation, consider evolving policies, and address uncertainties in economic and regulatory frameworks. This approach would provide a stronger basis for understanding the hydrogen economy's role in supporting industrial decarbonization.

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A. Appendix

A.1. Data

A.1.1. Demand

The demand data shown in (5) is derived based on annual production figures for the steEL, fertilizer, and high-value chemical industry from Concawe (2022). The demand for the demand of MGO and jet Fuel are based on Eurostat (2024b) and Eurostat (2024a). For the fertilizer industry, the production of nitrogen, phosphor, potassium fertilizer (NPK), Nitrogen and potassium fertilizer (NK), Nitrogen and phosphor fertilizer (NP) and Ammonium sulfate nitrate (ASS) are summed up. Since jet and maritime Fuel can be replaced by their low carbon, carbon-free hydrogen and derivatives, the current consumption of jet and maritime Fuel translates directly into demand for hydrogen and its derivatives. However, these are considered final good equivalence, where the final goods are aviation and shipping services, as shown in the mapping of processes to outputs (23).

Table 5: Demand

Industry	Location	Year	Unit	Demand
Shipping	Germany	2030	kt MGO/a	1713
Shipping	Germany	2035	kt MGO/a	1713
Shipping	Germany	2040	kt MGO/a	1713
Shipping	Germany	2045	kt MGO/a	1713
Shipping	Germany	2050	kt MGO/a	1713
Hvc	Leverkusen	2030	kt OlefinsAromatics/a	1674
Hvc	Leverkusen	2035	kt OlefinsAromatics/a	1674
Hvc	Leverkusen	2040	kt OlefinsAromatics/a	1674
Hvc	Leverkusen	2045	kt OlefinsAromatics/a	1674
Hvc	Leverkusen	2050	kt OlefinsAromatics/a	1674
Fertilizer	Ludwigshafen	2030	kt NPK, NP, NK,ASS /a	1300
Fertilizer	Ludwigshafen	2035	kt NPK, NP, NK,ASS /a	1300
Fertilizer	Ludwigshafen	2040	kt kt NPK, NP, NK,ASS /a	1300
Fertilizer	Ludwigshafen	2045	kt kt NPK, NP, NK,ASS /a	1300
Fertilizer	Ludwigshafen	2050	kt Nkt NPK, NP, NK,ASS /a	1300
Aviation	Frankfurt	2030	kt JetFuel/a	2800
Aviation	Frankfurt	2035	kt JetFuel/a	2800

(Continued)

Industry	Location	Year	Unit	Demand
Aviation	Frankfurt	2040	kt JetFuel/a	2800
Aviation	Frankfurt	2045	kt JetFuel/a	2800
Aviation	Frankfurt	2050	kt JetFuel/a	2800
SteEL	Duisburg	2030	kt SteEL/a	2500
SteEL	Duisburg	2035	kt SteEL/a	2500
SteEL	Duisburg	2040	kt SteEL/a	2500
SteEL	Duisburg	2045	kt SteEL/a	2500
SteEL	Duisburg	2050	kt SteEL/a	2500

A.1.2. Input Ratios

The following input ratios in the table (**??**) define the physical relationships between inputs and outputs in the model. Efficiency increases in the future are resembled by decreasing input ratios over time. , low carbon ammonia ($LCNH_3$) and low carbon methanol (MeOH) and high-carbon hydrogen (HCH2), high-carbon ammonia (HCNH3) and high-carbon methanol (HCMeOH) are the Fuels generated from SMR-CC and SMR. The data for the inputs on the BF-BOF steelmaking route are taken from Hauser et al. (2021). The data on the fertilizer syntheses are taken from Mayer et al. (2023). All other input data is taken from Victoria et al. (2024).

Table 6: Process Inputs and Values Across Years

Process	Input	Unit	Year	Value
BOF	Coal	tCoal/tSteEL	2030	0.5
BOF	Coal	tCoal/tSteEL	2035	0.5
BOF	Coal	tCoal/tSteEL	2040	0.5
BOF	Coal	tCoal/tSteEL	2045	0.5
BOF	Coal	tCoal/tSteEL	2050	0.5
BOF	Gas	MWh ELec/tSteEL	2030	0.2
BOF	Gas	MWh ELec/tSteEL	2035	0.2
BOF	Gas	MWh ELec/tSteEL	2040	0.2
BOF	Gas	MWh ELec/tSteEL	2045	0.2
BOF	Gas	MWh ELec/tSteEL	2050	0.2

(Continued)

Process Source	Input	Unit	Year	Value
DRI	ELectricity	MWh ELec/tSteEL	2030	1
DRI	ELectricity	MWh ELec/tSteEL	2035	1
DRI	ELectricity	MWh ELec/tSteEL	2040	1
DRI	ELectricity	MWh ELec/tSteEL	2045	1
DRI	ELectricity	MWh ELec/tSteEL	2050	1
DRI	H_2	tH_2/tSteEL	2030	60
DRI	H_2	tH_2/tSteEL	2035	60
DRI	H_2	tH_2/tSteEL	2040	60
DRI	H_2	tH_2/tSteEL	2045	60
DRI	H_2	tH_2/tSteEL	2050	60
DRI	Gas	MWh Gas/tH_2	2030	49
DRI	Gas	MWh Gas/tH_2	2035	49
DRI	Gas	MWh Gas/tH_2	2040	49
DRI	Gas	MWh Gas/tH_2	2045	49
DRI	Gas	MWh Gas/tH_2	2050	49
Fertilizer Synthesis	NH_3	tNH_3/tFertilizer	2030	0.32
Fertilizer Synthesis	NH_3	tNH_3/tFertilizer	2035	0.32
Fertilizer Synthesis	NH_3	tNH_3/tFertilizer	2040	0.32
Fertilizer Synthesis	NH_3	tNH_3/tFertilizer	2045	0.32
Fertilizer Synthesis	NH_3	tNH_3/tFertilizer	2050	0.32
HB	ELectricity	MWh ELec/tNH_3	2030	1.31
HB	ELectricity	MWh ELec/tNH_3	2035	1.31
HB	ELectricity	MWh ELec/tNH_3	2040	1.31
HB	ELectricity	MWh ELec/tNH_3	2045	1.31
HB	ELectricity	MWh ELec/tNH_3	2050	1.31
HB	H_2	tH_2/tNH_3	2030	0.18
HB	H_2	tH_2/tNH_3	2035	0.18
HB	H_2	tH_2/tNH_3	2040	0.18
HB	H_2	tH_2/tNH_3	2045	0.18
HB	H_2	tH_2/tNH_3	2050	0.18
HB	LCH_2	tH_2/tNH_3	2030	0.18

(Continued)

Process Source	Input	Unit	Year	Value
HB	LCH_2	tH_2/tNH_3	2035	0.18
HB	LCH_2	tH_2/tNH_3	2040	0.18
HB	LCH_2	tH_2/tNH_3	2045	0.18
HB	LCH_2	tH_2/tNH_3	2050	0.18
HB	HCH_2	tH_2/tNH_3	2030	0.18
HB	HCH_2	tH_2/tNH_3	2035	0.18
HB	HCH_2	tH_2/tNH_3	2040	0.18
HB	HCH_2	tH_2/tNH_3	2045	0.18
HB	HCH_2	tH_2/tNH_3	2050	0.18
Conventional ICE	BiodiesEL	tBiodiesEL/tMGO	2030	1
Conventional ICE	BiodiesEL	tBiodiesEL/tMGO	2035	1
Conventional ICE	BiodiesEL	tBiodiesEL/tMGO	2040	1
Conventional ICE	BiodiesEL	tBiodiesEL/tMGO	2045	0.95
Conventional ICE	BiodiesEL	tBiodiesEL/tMGO	2050	0.9
H_2 ICE	H_2	tH_2/tMGO	2030	1.63
H_2 ICE	H_2	tH_2/tMGO	2035	1.64
H_2 ICE	H_2	tH_2/tMGO	2040	1.64
H_2 ICE	H_2	tH_2/tMGO	2045	1.56
H_2 ICE	H_2	tH_2/tMGO	2050	1.47
H_2 ICE	LCH_2	tH_2/tMGO	2030	1.63
H_2 ICE	LCH_2	tH_2/tMGO	2035	1.64
H_2 ICE	LCH_2	tH_2/tMGO	2040	1.64
H_2 ICE	LCH_2	tH_2/tMGO	2045	1.56
H_2 ICE	LCH_2	tH_2/tMGO	2050	1.47
MeOH ICE	MeOH	tH_2/tMGO	2030	1.01
MeOH ICE	MeOH	tH_2/tMGO	2035	0.99
MeOH ICE	MeOH	tH_2/tMGO	2040	0.97
MeOH ICE	MeOH	tH_2/tMGO	2045	0.92
MeOH ICE	MeOH	tH_2/tMGO	2050	0.88
MeOH ICE	LCMeOH	tH_2/tMGO	2030	1.01
MeOH ICE	LCMeOH	tH_2/tMGO	2035	0.99

(Continued)

Process Source	Input	Unit	Year	Value
MeOH ICE	LCMeOH	$tH_2/tMGO$	2040	0.97
MeOH ICE	LCMeOH	$tH_2/tMGO$	2045	0.92
MeOH ICE	LCMeOH	$tH_2/tMGO$	2050	0.88
NH_3 ICE	NH_3	$tH_2/tMGO$	2030	1.68
NH_3 ICE	NH_3	$tH_2/tMGO$	2035	1.53
NH_3 ICE	NH_3	$tH_2/tMGO$	2040	1.37
NH_3 ICE	NH_3	$tH_2/tMGO$	2045	1.3
NH_3 ICE	NH_3	$tH_2/tMGO$	2050	1.24
NH_3 ICE	$LCNH_3$	$tH_2/tMGO$	2030	1.68
NH_3 ICE	$LCNH_3$	$tH_2/tMGO$	2035	1.53
NH_3 ICE	$LCNH_3$	$tH_2/tMGO$	2040	1.37
NH_3 ICE	$LCNH_3$	$tH_2/tMGO$	2045	1.3
NH_3 ICE	$LCNH_3$	$tH_2/tMGO$	2050	1.24
Conventional ICE	MGO	tMGO/tMGO	2030	1
Conventional ICE	MGO	tMGO/tMGO	2035	1
Conventional ICE	MGO	tMGO/tMGO	2040	1
Conventional ICE	MGO	tMGO/tMGO	2045	1
Conventional ICE	MGO	tMGO/tMGO	2050	1
LNG ICE	LNG	tLNG/tMGO	2030	2.22
LNG ICE	LNG	tLNG/tMGO	2035	2.19
LNG ICE	LNG	tLNG/tMGO	2040	2.17
LNG ICE	LNG	tLNG/tMGO	2045	2.06
LNG ICE	LNG	tLNG/tMGO	2050	1.95
MeOH Syn	CO_2	$tCO_2/tMeOH$	2030	1.373
MeOH Syn	CO_2	$tCO_2/tMeOH$	2035	1.373
MeOH Syn	CO_2	$tCO_2/tMeOH$	2040	1.373
MeOH Syn	CO_2	$tCO_2/tMeOH$	2045	1.373
MeOH Syn	CO_2	$tCO_2/tMeOH$	2050	1.373
MeOH Syn	H_2	$tH_2/tMeOH$	2030	0.12
MeOH Syn	H_2	$tH_2/tMeOH$	2035	0.12
MeOH Syn	H_2	$tH_2/tMeOH$	2040	0.12

(Continued)

Process Source	Input	Unit	Year	Value
MeOH Syn	H_2	$tH_2/tMeOH$	2045	0.12
MeOH Syn	H_2	$tH_2/tMeOH$	2050	0.12
MeOH Syn	LCH_2	$tH_2/tMeOH$	2030	0.12
MeOH Syn	LCH_2	$tH_2/tMeOH$	2035	0.12
MeOH Syn	LCH_2	$tH_2/tMeOH$	2040	0.12
MeOH Syn	LCH_2	$tH_2/tMeOH$	2045	0.12
MeOH Syn	LCH_2	$tH_2/tMeOH$	2050	0.12
AmCr	NH_3	tNH_3/tH_2	2030	1.46
AmCr	NH_3	tNH_3/tH_2	2035	1.46
AmCr	NH_3	tNH_3/tH_2	2040	1.46
AmCr	NH_3	tNH_3/tH_2	2045	1.46
AmCr	NH_3	tNH_3/tH_2	2050	1.46
H_2Liq	H_2	tH_2/tLH_2	2030	1.017
H_2Liq	H_2	tH_2/tLH_2	2035	1.017
H_2Liq	H_2	tH_2/tLH_2	2040	1.017
H_2Liq	H_2	tH_2/tLH_2	2045	1.017
H_2Liq	H_2	tH_2/tLH_2	2050	1.017
H_2Eva	LH_2	tLH_2/tH_2	2030	1
H_2Eva	LH_2	tLH_2/tH_2	2035	1
H_2Eva	LH_2	tLH_2/tH_2	2040	1
H_2Eva	LH_2	tLH_2/tH_2	2045	1
H_2Eva	LH_2	tLH_2/tH_2	2050	1
EL	ELectricity	MWh ELec/ tH_2	2030	0.06994
EL	ELectricity	MWh ELec/ tH_2	2035	0.6532
EL	ELectricity	MWh ELec/ tH_2	2040	0.6217
EL	ELectricity	MWh ELec/ tH_2	2045	0.6217
EL	ELectricity	MWh ELec/ tH_2	2050	0.5773
ASU	ELectricity	MWh ELec/ tN	2030	0.25
ASU	ELectricity	MWh ELec/ tN	2035	0.25
ASU	ELectricity	MWh ELec/ tN	2040	0.25
ASU	ELectricity	MWh ELec/ tN	2045	0.25

(Continued)

Process Source	Input	Unit	Year	Value
ASU	ELectricity	MWh ELec/ tN	2050	0.25
HB	ELectricity	MWh ELec/ tNH_3	2030	0.2473
HB	ELectricity	MWh ELec/ tNH_3	2035	0.2473
HB	ELectricity	MWh ELec/ tNH_3	2040	0.2473
HB	ELectricity	MWh ELec/ tNH_3	2045	0.2473
HB	ELectricity	MWh ELec/ tNH_3	2050	0.2473
AmCr	ELectricity	$MWhEL/MWhNH_3$	2030	0.08
AmCr	ELectricity	$MWhEL/MWhNH_3$	2035	0.08
AmCr	ELectricity	$MWhEL/MWhNH_3$	2040	0.08
AmCr	ELectricity	$MWhEL/MWhNH_3$	2045	0.08
SmrCCTS	Gas	MWhGas / tH_2	2030	56.21
SmrCCTS	Gas	MWhGas / tH_2	2035	56.21
SmrCCTS	Gas	MWhGas / tH_2	2040	56.21
SmrCCTS	Gas	MWhGas / tH_2	2045	56.21
SmrCCTS	Gas	MWhGas / tH_2	2050	56.21
BTM	Biomass	tBio/tMeOH	2030	24.26
BTM	Biomass	tBio/tMeOH	2035	23.47
BTM	Biomass	tBio/tMeOH	2040	22.78
BTM	Biomass	tBio/tMeOH	2045	22.78
BTM	Biomass	tBio/tMeOH	2050	22.09
BTM	Biomass	MWhELectricity/tMeOH	2030	0.13
BTM	Biomass	MWhELectricity/tMeOH	2035	0.13
BTM	Biomass	MWhELectricity/tMeOH	2040	0.13
BTM	Biomass	MWhELectricity/tMeOH	2045	0.13
BTM	Biomass	MWhELectricity/tMeOH	2050	0.13
FT	ELectricity	MWhELectricity/tFT	2030	0.08
FT	ELectricity	MWhELectricity/tFT	2035	0.08
FT	ELectricity	MWhELectricity/tFT	2040	0.08
FT	ELectricity	MWhELectricity/tFT	2045	0.08
FT	ELectricity	MWhELectricity/tFT	2050	0.08
FT	H_2	tH_2/tFT	2030	0.51

(Continued)

Process Source	Input	Unit	Year	Value
FT	H_2	tH_2/tFT	2035	0.5
FT	H_2	tH_2/tFT	2040	0.5
FT	H_2	tH_2/tFT	2045	0.5
FT	H_2	tH_2/tFT	2050	0.5
FT	LCH_2	tH_2/tFT	2030	0.51
FT	LCH_2	tH_2/tFT	2035	0.5
FT	LCH_2	tH_2/tFT	2040	0.5
FT	LCH_2	tH_2/tFT	2045	0.5
FT	LCH_2	tH_2/tFT	2050	0.5
FT	CO_2	tCO_2/tFT	2030	3.88
FT	CO_2	tCO_2/tFT	2035	3.73
FT	CO_2	tCO_2/tFT	2040	3.58
FT	CO_2	tCO_2/tFT	2045	3.43
FT	CO_2	tCO_2/tFT	2050	3.28
Jet Engine	JetA	tJetA/tAviation Fuel	2030	1
Jet Engine	JetA	tJetA/tAviation Fuel	2035	1
Jet Engine	JetA	tJetA/tAviation Fuel	2040	1
Jet Engine	JetA	tJetA/tAviation Fuel	2045	1
Jet Engine	JetA	tJetA/tAviation Fuel	2050	1
Jet Engine	HEFA	tHEFA/tAviation Fuel	2030	1
Jet Engine	HEFA	tHEFA/tAviation Fuel	2035	1
Jet Engine	HEFA	tHEFA/tAviation Fuel	2040	1
Jet Engine	HEFA	tHEFA/tAviation Fuel	2045	1
Jet Engine	HEFA	tHEFA/tAviation Fuel	2050	1
Jet Engine	E-Kerosene	tE-Kerosene/tAviation Fuel	2030	1
Jet Engine	E-Kerosene	tE-Kerosene/tAviation Fuel	2035	1
Jet Engine	E-Kerosene	tE-Kerosene/tAviation Fuel	2040	1
Jet Engine	E-Kerosene	tE-Kerosene/tAviation Fuel	2045	1
Jet Engine	E-Kerosene	tE-Kerosene/tAviation Fuel	2050	1
ESC	ELectricity	MWh ELec/tOlefins/Aromatics	2030	2.7
ESC	ELectricity	MWh ELec/tOlefins/Aromatics	2035	2.7

(Continued)

Process Source	Input	Unit	Year	Value
ESC	ELectricity	MWh ELec/tOlefins/Aromatics	2040	2.7
ESC	ELectricity	MWh ELec/tOlefins/Aromatics	2045	2.7
ESC	ELectricity	MWh ELec/tOlefins/Aromatics	2050	2.7
ESC	Naphtha	MWh ELec/tOlefins/Aromatics	2030	14.8
ESC	Naphtha	MWh ELec/tOlefins/Aromatics	2035	14.8
ESC	Naphtha	MWh ELec/tOlefins/Aromatics	2040	14.8
ESC	Naphtha	MWh ELec/tOlefins/Aromatics	2045	14.8
ESC	Naphtha	MWh ELec/tOlefins/Aromatics	2050	14.8

A.1.3. RFNBO Quotas

Table (7) shows the EU RFNBO quotas in % of total fuel consumption for each sector and year are based on report by the Agency for the Cooperation of Energy Regulators (ACER) (2024). 2

Table 7: RFNBO Quota

Sector	Year	Quota (%)
Industry	2030	42.00
Transport	2030	1.00
Maritime	2030	6.00
Aviation	2030	6.00
Industry	2035	48.00
Transport	2035	25.66
Maritime	2035	14.50
Aviation	2035	20.00
Industry	2040	54.00
Transport	2040	50.33

A.1.4. RFNBO Weights

Table (7) shows the weights the various fuels have in fulfilling the sectors quota.

Table 8: RFNBO Weights

Process	Input	Year	Value	Process	Input	Year	Value
Bof	Coal	2030	0	Bof	Gas	2030	0
Bof	Coal	2035	0	Bof	Gas	2035	0

(Continued)

Process	Input	Year	Value	Process	Input	Year	Value
Bof	Coal	2040	0	Bof	Gas	2040	0
Bof	Coal	2045	0	Bof	Gas	2045	0
Bof	Coal	2050	0	Bof	Gas	2050	0
DRI	Electricity	2030	0.7	DRI	HCH_2	2030	0
DRI	Electricity	2035	0.77	DRI	HCH_2	2035	0
DRI	Electricity	2040	0.84	DRI	HCH_2	2040	0
DRI	Electricity	2045	0.85	DRI	HCH_2	2045	0
DRI	Electricity	2050	0.9	DRI	HCH_2	2050	0
DRI	LCH_2	2030	0.8	DRI	LCH_2	2030	0.8
DRI	LCH_2	2035	0.85	DRI	LCH_2	2035	0.85
DRI	LCH_2	2040	0.89	DRI	LCH_2	2040	0.89
DRI	LCH_2	2045	0.85	DRI	LCH_2	2045	0.85
DRI	LCH_2	2050	0.9	DRI	LCH_2	2050	0.9
Fertilizer Synthesis	$LCNH_3$	2030	1	Fertilizer Synthesis	$LCNH_3$	2030	1
Fertilizer Synthesis	$LCNH_3$	2035	1	Fertilizer Synthesis	$LCNH_3$	2035	1
Fertilizer Synthesis	$LCNH_3$	2040	1	Fertilizer Synthesis	$LCNH_3$	2040	1
Fertilizer Synthesis	$LCNH_3$	2045	1	Fertilizer Synthesis	$LCNH_3$	2045	1
Fertilizer Synthesis	$LCNH_3$	2050	1	Fertilizer Synthesis	$LCNH_3$	2050	1
Fertilizer Synthesis	$HCNH_3$	2030	0	Fertilizer Synthesis	$HCNH_3$	2030	0
Fertilizer Synthesis	$HCNH_3$	2035	0	Fertilizer Synthesis	$HCNH_3$	2035	0
Fertilizer Synthesis	$HCNH_3$	2040	0	Fertilizer Synthesis	$HCNH_3$	2040	0
Fertilizer Synthesis	$HCNH_3$	2045	0	Fertilizer Synthesis	$HCNH_3$	2045	0
Fertilizer Synthesis	$HCNH_3$	2050	0	Fertilizer Synthesis	$HCNH_3$	2050	0
Fertilizer Synthesis	NH_3	2030	1	Fertilizer Synthesis	NH_3	2030	1
Fertilizer Synthesis	NH_3	2035	1	Fertilizer Synthesis	NH_3	2035	1
Fertilizer Synthesis	NH_3	2040	1	Fertilizer Synthesis	NH_3	2040	1
Fertilizer Synthesis	NH_3	2045	1	Fertilizer Synthesis	NH_3	2045	1
Fertilizer Synthesis	NH_3	2050	1	Fertilizer Synthesis	NH_3	2050	1
Hb	H_2	2030	1	Hb	H_2	2030	1
Hb	H_2	2035	1	Hb	H_2	2035	1
Hb	H_2	2040	1	Hb	H_2	2040	1
Hb	H_2	2045	1	Hb	H_2	2045	1
Hb	H_2	2050	1	Hb	H_2	2050	1

(Continued)

Process	Input	Year	Value	Process	Input	Year	Value
Hb	LCH_2	2030	0.8	Hb	LCH_2	2030	0.8
Hb	LCH_2	2035	0.85	Hb	LCH_2	2035	0.85
Hb	LCH_2	2040	0.89	Hb	LCH_2	2040	0.89
Hb	LCH_2	2045	0.85	Hb	LCH_2	2045	0.85
Hb	LCH_2	2050	0.9	Hb	LCH_2	2050	0.9
Hb	HCH_2	2030	0	Hb	HCH_2	2030	0
Hb	HCH_2	2035	0	Hb	HCH_2	2035	0
Hb	HCH_2	2040	0	Hb	HCH_2	2040	0
Hb	HCH_2	2045	0	Hb	HCH_2	2045	0
Hb	HCH_2	2050	0	Hb	HCH_2	2050	0
Hb	Electricity	2030	0.6	Hb	Electricity	2030	0.6
Hb	Electricity	2035	0.68	Hb	Electricity	2035	0.68
Hb	Electricity	2040	0.77	Hb	Electricity	2040	0.77
Hb	Electricity	2045	0.88	Hb	Electricity	2045	0.88
Hb	Electricity	2050	1	Hb	Electricity	2050	1
Hb	N	2030	1	Hb	N	2030	1
Hb	N	2035	1	Hb	N	2035	1
Hb	N	2040	1	Hb	N	2040	1
Hb	N	2045	1	Hb	N	2045	1
Hb	N	2050	1	Hb	N	2050	1
ASU	Electricity	2030	0.6	ASU	Electricity	2030	0.6
ASU	Electricity	2035	0.68	ASU	Electricity	2035	0.68
ASU	Electricity	2040	0.77	ASU	Electricity	2040	0.77
ASU	Electricity	2045	0.85	ASU	Electricity	2045	0.85
ASU	Electricity	2050	0.9	ASU	Electricity	2050	0.9
Smr	Gas	2030	0	Smr	Gas	2030	0
Smr	Gas	2035	0	Smr	Gas	2035	0
Smr	Gas	2040	0	Smr	Gas	2040	0
Smr	Gas	2045	0	Smr	Gas	2045	0
Smr	Gas	2050	0	Smr	Gas	2050	0
SmrCCTS	Gas	2030	0.8	SmrCCTS	Gas	2035	0.85
SmrCCTS	Gas	2040	0.89	SmrCCTS	Gas	2045	0.85
SmrCCTS	Gas	2050	0.9	NTO/NTA	Naphtha	2030	0

(Continued)

Process	Input	Year	Value	Process	Input	Year	Value
NTO/NTA	Naphtha	2035	0	NTO/NTA	Naphtha	2040	0
NTO/NTA	Naphtha	2045	0	NTO/NTA	Naphtha	2050	0
MTO/MTA	MeOH	2030	1	MTO/MTA	MeOH	2035	1
MTO/MTA	MeOH	2040	1	MTO/MTA	MeOH	2045	1
MTO/MTA	MeOH	2050	1	MTO/MTA	LCMeOH	2030	1
MTO/MTA	LCMeOH	2035	1	MTO/MTA	LCMeOH	2040	1
MTO/MTA	LCMeOH	2045	1	MTO/MTA	LCMeOH	2050	1
MTO/MTA	BMeOH	2030	1	MTO/MTA	BMeOH	2035	1
MTO/MTA	BMeOH	2040	1	MTO/MTA	BMeOH	2045	1
MTO/MTA	BMeOH	2050	1	MeOHSyn	H_2	2030	1
MeOHSyn	H_2	2035	1	MeOHSyn	H_2	2040	1
MeOHSyn	H_2	2045	1	MeOHSyn	H_2	2050	1
MeOHSyn	CO_2	2030	0	MeOHSyn	CO_2	2035	0
MeOHSyn	CO_2	2040	0	MeOHSyn	CO_2	2045	0
MeOHSyn	CO_2	2050	0	MeOHSyn	Electricity	2030	0.7
MeOHSyn	Electricity	2035	0.76	MeOHSyn	Electricity	2040	0.84
MeOHSyn	Electricity	2045	0.85	MeOHSyn	Electricity	2050	0.9
MeOHSyn	LCH_2	2030	0.8	MeOHSyn	LCH_2	2035	0.85
MeOHSyn	LCH_2	2040	0.89	MeOHSyn	LCH_2	2045	0.95
MeOHSyn	LCH_2	2050	1	Dac	Electricity	2030	0.7
Dac	Electricity	2035	0.76	Dac	Electricity	2040	0.84
Dac	Electricity	2045	0.85	Dac	Electricity	2050	0.9
Btm	Electricity	2030	0.7	Btm	Electricity	2035	0.76
Btm	Electricity	2040	0.8367	Btm	Electricity	2045	0.85
Btm	Electricity	2050	0.9	Btm	Biomass	2030	0
Btm	Biomass	2035	0	Btm	Biomass	2040	0
Btm	Biomass	2045	0	Btm	Biomass	2050	0
Conventional ICE	Biodiesel	2035	0	Conventional ICE	Biodiesel	2040	0
Conventional ICE	Biodiesel	2045	0	Conventional ICE	Biodiesel	2050	0
Conventional ICE	MGO	2030	0	Conventional ICE	MGO	2035	0
Conventional ICE	MGO	2040	0	Conventional ICE	MGO	2045	0
Conventional ICE	MGO	2050	0	H_2 ICE	H_2	2030	1
H_2 ICE	H_2	2035	1	H_2 ICE	H_2	2040	1

(Continued)

Process	Input	Year	Value	Process	Input	Year	Value
H_2 ICE	H_2	2045	1	H_2 ICE	H_2	2050	1
H_2 ICE	LCH_2	2030	1	H_2 ICE	LCH_2	2035	1
H_2 ICE	LCH_2	2040	1	H_2 ICE	LCH_2	2045	1
H_2 ICE	LCH_2	2050	1	MeOH ICE	MeOH	2030	1
MeOH ICE	LCMeOH	2035	1	MeOH ICE	LCMeOH	2040	1
MeOH ICE	LCMeOH	2045	1	MeOH ICE	LCMeOH	2050	1
NH_3 ICE	NH_3	2030	1	NH_3 ICE	NH_3	2035	1
NH_3 ICE	NH_3	2040	1	NH_3 ICE	NH_3	2045	1
NH_3 ICE	NH_3	2050	1	NH_3 ICE	$LCNH_3$	2030	1
NH_3 ICE	$LCNH_3$	2035	1	NH_3 ICE	$LCNH_3$	2040	1
NH_3 ICE	$LCNH_3$	2045	1	NH_3 ICE	$LCNH_3$	2050	1
LNG ICE	LNG	2030	0	LNG ICE	LNG	2035	0
LNG ICE	LNG	2040	0	LNG ICE	LNG	2045	0
LNG ICE	LNG	2050	0	FT	Electricity	2030	0.7
FT	Electricity	2035	0.76	FT	Electricity	2040	0.84
FT	Electricity	2045	0.85	FT	Electricity	2050	0.9
FT	H_2	2030	1	FT	H_2	2035	1
FT	H_2	2040	1	FT	H_2	2045	1
FT	H_2	2050	1	FT	CO_2	2030	0
FT	CO_2	2035	0	FT	CO_2	2040	0
FT	CO_2	2045	0	FT	CO_2	2050	0
JetEngine	JetA	2035	0	JetEngine	JetA	2040	0
JetEngine	JetA	2045	0	JetEngine	JetA	2050	0
JetEngine	HEFA	2030	0	JetEngine	HEFA	2035	0
JetEngine	HEFA	2040	0	JetEngine	HEFA	2045	0
JetEngine	HEFA	2050	0	JetEngine	E-Kerosene	2030	1
JetEngine	E-Kerosene	2035	1	JetEngine	E-Kerosene	2040	1
JetEngine	E-Kerosene	2045	1	JetEngine	E-Kerosene	2050	1
Esc	Naphtha	2030	1	Esc	Naphtha	2035	1
Esc	Naphtha	2040	1	Esc	Naphtha	2045	1
Esc	Naphtha	2050	1	Esc	Electricity	2030	0.7
Esc	Electricity	2035	0.76	Esc	Electricity	2040	0.84
Esc	Electricity	2045	0.85	Esc	Electricity	2050	0.9

(Continued)

Sector	Year	Quota (%)
Shipping	2040	31.00
Aviation	2040	34.00
Industry	2045	55.00
Transport	2045	56.00
Maritime	2045	62.00
Aviation	2045	42.00
Industry	2050	60.00
Transport	2050	75.00
Maritime	2050	80.00
Aviation	2050	70.00

A.1.5. Residual Capacity

Table 9: Residual Capacity

Industry	Good	Location	Country	Year	Residual Capacity (in kt)
Shipping	Conventional ICE	Hamburg	GER	2030	1713
Shipping	Conventional ICE	Hamburg	GER	2035	886
Shipping	Conventional ICE	Hamburg	GER	2040	214
Shipping	Conventional ICE	Hamburg	GER	2045	0
Shipping	Conventional ICE	Hamburg	GER	2050	0
Hvc	NTO/NTA	Leverkusen	GER	2030	1674
Hvc	NTO/NTA	Leverkusen	GER	2035	1877
Hvc	NTO/NTA	Leverkusen	GER	2040	284
Hvc	NTO/NTA	Leverkusen	GER	2045	0
Hvc	NTO/NTA	Leverkusen	GER	2050	0
Fertilizer	Smr	Ludwigshafen	GER	2030	1300
Fertilizer	Smr	Ludwigshafen	GER	2035	1300
Fertilizer	Smr	Ludwigshafen	GER	2040	0
Fertilizer	Smr	Ludwigshafen	GER	2045	0
Fertilizer	Smr	Ludwigshafen	GER	2050	0
Aviation	Jet Engine	Frankfurt	GER	2030	2800
Aviation	Jet Engine	Frankfurt	GER	2035	2800
Aviation	Jet Engine	Frankfurt	GER	2040	2800
Aviation	Jet Engine	Frankfurt	GER	2045	2800
Aviation	Jet Engine	Frankfurt	GER	2050	2800
Steel	Bof	Duisburg	GER	2030	2500
Steel	Bof	Duisburg	GER	2035	621
Steel	Bof	Duisburg	GER	2040	0

(Continued)

Industry	Good	Location	Country	Year	Residual Capacity (in kt)
Steel	Bof	Duisburg	GER	2045	0
Steel	Bof	Duisburg	GER	2050	0

A.1.6. Emission Factors

Table (10) shows the assumed emission factors fro each processes and input used. These are based on Hauser et al. (2021) for the BF-BOF route of steelmaking. The emissions of the Jet Engine running on JetA fuel are based on data from the European Environment Agency (2020). All other values are taken from Victoria et al. (2024).

Table 10: Emission Factors

Process	Input	Output	Year	Value
Conventional ICE	MGO	Conventional ICE	2030	0.27
Conventional ICE	MGO	Conventional ICE	2035	0.27
Conventional ICE	MGO	Conventional ICE	2040	0.27
Conventional ICE	MGO	Conventional ICE	2045	0.27
Conventional ICE	MGO	Conventional ICE	2050	0.27
LNG ICE	LNG	Conventional ICE	2030	0.61
LNG ICE	LNG	Conventional ICE	2035	0.61
LNG ICE	LNG	Conventional ICE	2040	0.61
LNG ICE	LNG	Conventional ICE	2045	0.61
LNG ICE	LNG	Conventional ICE	2050	0.61
Bof	Coal	Steel	2030	1.71
Bof	Coal	Steel	2035	1.71
Bof	Coal	Steel	2040	1.71
Bof	Coal	Steel	2045	1.71
Bof	Coal	Steel	2050	1.71
Bof	Gas	Steel	2030	1.71
Bof	Gas	Steel	2035	1.71
Bof	Gas	Steel	2040	1.71
Bof	Gas	Steel	2045	1.71
Bof	Gas	Steel	2050	1.71

(Continued)

Process	Input	Output	Year	Value
Smr	Gas	HCH_2	2030	2.1
Smr	Gas	HCH_2	2035	2.1
Smr	Gas	HCH_2	2040	2.1
Smr	Gas	HCH_2	2045	2.1
Smr	Gas	HCH_2	2050	2.1
NTO/NTA	Naphtha	Olefins/Aromatics	2030	0.85
NTO/NTA	Naphtha	Olefins/Aromatics	2035	0.85
NTO/NTA	Naphtha	Olefins/Aromatics	2040	0.85
NTO/NTA	Naphtha	Olefins/Aromatics	2045	0.85
NTO/NTA	Naphtha	Olefins/Aromatics	2050	0.85
SmrCCTS	Gas	LCH_2	2030	0.42
SmrCCTS	Gas	LCH_2	2035	0.32
SmrCCTS	Gas	LCH_2	2040	0.22
SmrCCTS	Gas	LCH_2	2045	0.11
SmrCCTS	Gas	LCH_2	2050	0
Esc	Naphtha	Olefins/Aromatics	2030	0.55
Esc	Naphtha	Olefins/Aromatics	2035	0.55
Esc	Naphtha	Olefins/Aromatics	2040	0.42
Esc	Naphtha	Olefins/Aromatics	2045	0.22
Esc	Naphtha	Olefins/Aromatics	2050	0
JetEngine	JetA	Aviation	2030	3.16
JetEngine	JetA	Aviation	2035	3.16
JetEngine	JetA	Aviation	2040	3.16
JetEngine	JetA	Aviation	2045	3.16
JetEngine	JetA	Aviation	2050	3.16

A.1.7. Pipeline Distance Matrix

Table (11) shows the distances for commodities by pipeline. The distance is calculated with GeoPy, and a 15% premium is added for them as pipelines may often not be constructed on the shortest path between two cities. Table (12) represents the distance between destinations connected by submarine pipelines. Additionally, table (13) shows the distance between ports which are connected through shipping routes. The Searoute python package by Gaffuri (2021) calculates these distances.

Table 11: Pipeline Distances

From/To	Duisburg	Ludw	Leve.	HH	Frankfurt	Rotterdam	Chan.	Ant	Teruel	Guel.	Agadir	Fiska
Duisburg	0.0	286	55	370	1385	192	0.0	0.0	0.0	0.0	0.0	0.0
Ludwigshafen	286	0.0	232	540	1223	449	0.0	0.0	0.0	0.0	0.0	0.0
Leverkusen	55	232	0.0	400	1345	231	0.0	0.0	0.0	0.0	0.0	0.0
Hamburg	370.3	540	400	0.0	1739	473	0.0	0.0	0.0	0.0	0.0	0.0
Frankfurt	1385	1223	1345	1739	0.0	1394	0.0	0.0	0.0	0.0	0.0	0.0
Rotterdam	192.05	449	231	473	1394	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chanaral	0.0	0.0	0.0	0.0	0.0	0.0	0.0	345.0	0.0	0.0	0.0	0.0
Antofagasta	0.0	0.0	0.0	0.0	0.0	0.0	345	0.0	0.0	0.0	0.0	0.0
Teruel	1542	1413	1507	1906	255	1523	0.0	0.0	0.0	0.0	0.0	0.0
Guelmim	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.45	0.0	0.0
Agadir	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.45	0.0	0.0
Fiska	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 12: Pipeline Distances

From/To	Duisburg	Ludw	Leve.	HH	Frankfurt	Rotterdam	Chan.	Ant	Teruel	Guel.	Agadir	Fiska
Duisb.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ludw.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Leverk.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hamb.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	861
Frankfurt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rott.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1040
Chan.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Anto.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Teruel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Guelmim	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Agadir	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fiska	0.0	0.0	0.0	861	0.0	1045	0.0	0.0	0.0	0.0	0.0	0.0

Table 13: Shipping Distance Matrix

From/To	Duisburg	Ludw	Leve.	HH	Frankfurt	Rotterdam	Chan.	Ant	Teruel	Guel.	Agadir	Fiska
Duisburg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ludw.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Leverk.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hamburg	0.0	0.0	0.0	0.0	0.0	585	0.0	13646	0.0	0.0	3088	0.0
Frankfurt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rotterdam	0.0	0.0	0.0	585	0.0	0.0	0.0	13187	0.0	0.0	2629	0.0
Chanaral	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Antofagasta	0.0	0.0	0.0	13646	0.0	13187	0.0	0.0	0.0	0.0	0.0	0.0
Teruel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Guelmim	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Agadir	0.0	0.0	0.0	3088	0.0	2629	0.0	0.0	0.0	0.0	0.0	0.0
Fiska	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

A.1.8. Cost Data for processes

The CAPEX presented in table (14), for OPEX in table (15) and FOM in table (**??**) for each process. The BF-BOF costs are taken from Hauser et al. (2021). The cost data for the various shipping ICE are taken from Sánchez, Rengel, and Martín (2023). The data for methanol synthesis is taken from Agora (2018), and Mayer et al. (2023) is the reference for data on fertilizer synthesis.

Table 14: Capital Cost

Process	Year	Unit	Value
ASU	2030	EUR/tN/a	102.58
ASU	2035	EUR/tN/a	93.24
ASU	2040	EUR/tN/a	83.90
ASU	2045	EUR/tN/a	74.11
ASU	2050	EUR/tN/a	64.33
Btm	2030	EUR/tMeOH/a	492
Btm	2035	EUR/tMeOH/a	425
Btm	2040	EUR/tMeOH/a	357
Btm	2045	EUR/tMeOH/a	302
Btm	2050	EUR/tMeOH/a	246
Dac	2030	EUR/tCO_2/a	818
Dac	2035	EUR/tCO_2/a	759
Dac	2040	EUR/tCO_2/a	701
Dac	2045	EUR/tCO_2/a	584
Dac	2050	EUR/tCO_2/a	467
El	2030	EUR/tH_2/a	1190
El	2035	EUR/tH_2/a	1041
El	2040	EUR/tH_2/a	893
El	2045	EUR/tH_2/a	744
El	2050	EUR/tH_2/a	595
Ft	2020	EUR/tH_2/a	734
Ft	2030	EUR/tH_2/a	631
Ft	2040	EUR/tH_2/a	549
Ft	2050	EUR/tH_2/a	466
Hb	2030	EUR/tNH_3/a	949
Hb	2035	EUR/tNH_3/a	863

(Continued)

Process	Year	Unit	Value
Hb	2040	EUR/tNH_3/a	776
Hb	2045	EUR/tNH_3/a	686
Hb	2050	EUR/tNH_3/a	595
MeOHSyn	2030	EUR/tMeOH/a	500
MeOHSyn	2035	EUR/tMeOH/a	375
MeOHSyn	2040	EUR/tMeOH/a	250
MeOHSyn	2045	EUR/tMeOH/a	275
MeOHSyn	2050	EUR/tMeOH/a	300
Mto/a	2020	EUR/tHVC/a	300
Mto/a	2030	EUR/tHVC/a	300
Mto/a	2040	EUR/tHVC/a	300
Mto/a	2050	EUR/tHVC/a	300
Smr	2020	EUR/tH_2/a	135.14
Smr	2030	EUR/tH_2/a	135.14
Smr	2040	EUR/tH_2/a	135.14
Smr	2050	EUR/tH_2/a	135.14
SmrCC	2020	EUR/tH_2/a	252.50
SmrCC	2030	EUR/tH_2/a	252.50
SmrCC	2040	EUR/tH_2/a	252.50
SmrCC	2050	EUR/tH_2/a	252.50
Esc	2030	EUR/tHVC/a	2225
Esc	2035	EUR/tHVC/a	2225
Esc	2040	EUR/tHVC/a	2225
Esc	2045	EUR/tHVC/a	2225
Esc	2050	EUR/tHVC/a	2225
DRI	2020	EUR/t_Steel/a	856
DRI	2030	EUR/t_Steel/a	856
DRI	2035	EUR/t_Steel/a	856
DRI	2040	EUR/t_Steel/a	856
DRI	2045	EUR/t_Steel/a	856
DRI	2050	EUR/t_Steel/a	856
Eaf	2020	EUR/t_Steel/a	368

(Continued)

Process	Year	Unit	Value
Eaf	2030	EUR/t_Steel/a	368
Eaf	2035	EUR/t_Steel/a	368
Eaf	2040	EUR/t_Steel/a	368
Eaf	2045	EUR/t_Steel/a	368
Eaf	2050	EUR/t_Steel/a	368
Conventional ICE	2025	EUR/tMGO/a	331
Conventional ICE	2030	EUR/tMGO/a	284
Conventional ICE	2035	EUR/tMGO/a	237
Conventional ICE	2040	EUR/tMGO/a	191
Conventional ICE	2045	EUR/tMGO/a	144
Conventional ICE	2050	EUR/tMGO/a	97
H_2 ICE	2030	EUR/tH_2/a	393
H_2 ICE	2035	EUR/tH_2/a	335
H_2 ICE	2040	EUR/tH_2/a	237
H_2 ICE	2045	EUR/tH_2/a	132
H_2 ICE	2050	EUR/tH_2/a	55
MeOH ICE	2025	EUR/tMeOH/a	2637
MeOH ICE	2030	EUR/tMeOH/a	2249
MeOH ICE	2035	EUR/tMeOH/a	1862
MeOH ICE	2040	EUR/tMeOH/a	1475
MeOH ICE	2045	EUR/tMeOH/a	1087
MeOH ICE	2050	EUR/tMeOH/a	700
NH_3 ICE	2025	EUR/tNH_3/a	2876
NH_3 ICE	2030	EUR/tNH_3/a	2249
NH_3 ICE	2035	EUR/tNH_3/a	1862
NH_3 ICE	2040	EUR/tNH_3/a	1475
NH_3 ICE	2045	EUR/tNH_3/a	1087
NH_3 ICE	2050	EUR/tNH_3/a	700
Offwind	2020	EUR/MW_Elec	1992
Offwind	2030	EUR/MW_Elec	1682
Offwind	2035	EUR/MW_Elec	1622
Offwind	2040	EUR/MW_Elec	1562

(Continued)

Process	Year	Unit	Value
Offwind	2045	EUR/MW_Elec	1543
Offwind	2050	EUR/MW_Elec	1523
Onwind	2020	EUR/MW_Elec	1183
Onwind	2030	EUR/MW_Elec	1095
Onwind	2035	EUR/MW_Elec	1065
Onwind	2040	EUR/MW_Elec	1034
Onwind	2045	EUR/MW_Elec	1026
Onwind	2050	EUR/MW_Elec	1019
Pv	2020	EUR/MW_Elec	562
Pv	2030	EUR/MW_Elec	383
Pv	2035	EUR/MW_Elec	352
Pv	2040	EUR/MW_Elec	320
Pv	2045	EUR/MW_Elec	306
Pv	2050	EUR/MW_Elec	292
H_2Eva	2020	EUR/tH_2/a	4370
H_2Eva	2030	EUR/tH_2/a	4370
H_2Eva	2035	EUR/tH_2/a	3708
H_2Eva	2040	EUR/tH_2/a	3046
H_2Eva	2045	EUR/tH_2/a	2384
H_2Eva	2050	EUR/tH_2/a	1722
H_2Liq	2020	EUR/tH_2/a	26486
H_2Liq	2030	EUR/tH_2/a	26486
H_2Liq	2035	EUR/tH_2/a	23838
H_2Liq	2040	EUR/tH_2/a	21189
H_2Liq	2045	EUR/tH_2/a	18540
H_2Liq	2050	EUR/tH_2/a	15892
AmCr	2020	EUR/tH_2	8982
AmCr	2030	EUR/tH_2	8982
AmCr	2035	EUR/tH_2	7852
AmCr	2040	EUR/tH_2	6722
AmCr	2045	EUR/tH_2	5030
AmCr	2050	EUR/tH_2	3339

Table 15: Operational expenditure OPEX

Process	Year	Unit	Value
Btm	2020	EUR/tMeOH/a	3.44
Btm	2030	EUR/tMeOH/a	2.29
Btm	2035	EUR/tMeOH/a	2.29
Btm	2040	EUR/tMeOH/a	2.29
Btm	2045	EUR/tMeOH/a	2.29
Btm	2050	EUR/tMeOH/a	2.29
FT	2020	EUR/tFT/a	0.47
FT	2030	EUR/tFT/a	0.38
FT	2035	EUR/tFT/a	0.33
FT	2040	EUR/tFT/a	0.29
FT	2045	EUR/tFT/a	0.24
FT	2050	EUR/tFT/a	0.19
Hb	2020	EUR/tNH_3/a	0.0042
Hb	2030	EUR/tNH_3/a	0.0042
Hb	2035	EUR/tNH_3/a	0.0042
Hb	2040	EUR/tNH_3/a	0.0042
Hb	2045	EUR/tNH_3/a	0.0042
Hb	2050	EUR/tNH_3/a	0.0042
MTO/MTA	2020	EUR/tHVC/a	31.75
MTO/MTA	2030	EUR/tHVC/a	31.75
MTO/MTA	2035	EUR/tHVC/a	31.75
MTO/MTA	2040	EUR/tHVC/a	31.75
MTO/MTA	2045	EUR/tHVC/a	31.75
MTO/MTA	2050	EUR/tHVC/a	31.75
NTO/NTA	2020	EUR/tHVC/a	190.48
NTO/NTA	2030	EUR/tHVC/a	190.48
NTO/NTA	2035	EUR/tHVC/a	190.48
NTO/NTA	2040	EUR/tHVC/a	190.48
NTO/NTA	2045	EUR/tHVC/a	190.48
NTO/NTA	2050	EUR/tHVC/a	190.48
Offwind	2020	EUR/MWh Elec/a	0.02
Offwind	2030	EUR/MWh Elec/a	0.02
Offwind	2035	EUR/MWh Elec/a	0.02

(Continued)

Process	Year	Unit	Value
Offwind	2040	EUR/MWh Elec/a	0.02
Offwind	2045	EUR/MWh Elec/a	0.02
Offwind	2050	EUR/MWh Elec/a	0.02
Onwind	2020	EUR/MWh Elec/a	1.59
Onwind	2030	EUR/MWh Elec/a	1.43
Onwind	2035	EUR/MWh Elec/a	1.37
Onwind	2040	EUR/MWh Elec/a	1.31
Onwind	2045	EUR/MWh Elec/a	1.30
Onwind	2050	EUR/MWh Elec/a	1.29
DRI	2030	tStahl/a	337.00
DRI	2035	tStahl/a	337.00
DRI	2040	tStahl/a	337.00
DRI	2045	tStahl/a	337.00
DRI	2050	tStahl/a	337.00
Bof	2030	tStahl/a	200.00
Bof	2035	tStahl/a	200.00
Bof	2040	tStahl/a	200.00
Bof	2045	tStahl/a	200.00
Bof	2050	tStahl/a	200.00
Smr	2030	EUR/tH_2/a	736.36
Smr	2035	EUR/tH_2/a	736.36
Smr	2040	EUR/tH_2/a	736.36
Smr	2045	EUR/tH_2/a	736.36
Smr	2050	EUR/tH_2/a	736.36
SmrCCTS	2030	EUR/tLCH_2/a	936.36
SmrCCTS	2035	EUR/tLCH_2/a	936.36
SmrCCTS	2040	EUR/tLCH_2/a	936.36
SmrCCTS	2045	EUR/tLCH_2/a	936.36
SmrCCTS	2050	EUR/tLCH_2/a	936.36
LNG ICE	2030	EUR/tLNG/a	66
LNG ICE	2035	EUR/tLNG/a	66
LNG ICE	2040	EUR/tLNG/a	66
LNG ICE	2045	EUR/tLNG/a	66

(Continued)

Process	Year	Unit	Value
LNG ICE	2050	EUR/tLNG/a	66
MeOH ICE	2030	EUR/tMeOH/a	47
MeOH ICE	2035	EUR/tMeOH/a	47.2
MeOH ICE	2040	EUR/tMeOH/a	47.2
MeOH ICE	2045	EUR/tMeOH/a	47.2
MeOH ICE	2050	EUR/tMeOH/a	47.2
Conventional ICE	2030	EUR/tMeOH/a	45.43
Conventional ICE	2035	EUR/tMeOH/a	45.43
Conventional ICE	2040	EUR/tMeOH/a	45.43
Conventional ICE	2045	EUR/tMeOH/a	45.43
Conventional ICE	2050	EUR/tMeOH/a	45.43
NH_3 ICE	2030	EUR/tMeOH/a	92.512
NH_3 ICE	2035	EUR/tMeOH/a	92.512
NH_3 ICE	2040	EUR/tMeOH/a	92.512
NH_3 ICE	2035	EUR/tMeOH/a	92.512
NH_3 ICE	2050	EUR/tMeOH/a	92.512

Table 16: FOM data

Process	Year	Unit	Value
AmCr	2020	% of capex/year	4.3
AmCr	2030	% of capex/year	4.3
AmCr	2035	% of capex/year	4.3
AmCr	2040	% of capex/year	4.3
AmCr	2045	% of capex/year	4.3
AmCr	2050	% of capex/year	4.3
ASU	2020	% of capex/year	3.0
ASU	2030	% of capex/year	3.0
ASU	2035	% of capex/year	3.0
ASU	2040	% of capex/year	3.0
ASU	2045	% of capex/year	3.0
ASU	2050	% of capex/year	3.0
Btm	2020	% of capex/year	1.1111
Btm	2030	% of capex/year	1.3333

(Continued)

Process	Year	Unit	Value
Btm	2035	% of capex/year	1.5708
Btm	2040	% of capex/year	1.8083
Btm	2045	% of capex/year	2.2375
Btm	2050	% of capex/year	2.6667
Dac	2020	% of capex/year	4.95
Dac	2030	% of capex/year	4.95
Dac	2035	% of capex/year	4.95
Dac	2040	% of capex/year	4.95
Dac	2045	% of capex/year	4.95
Dac	2050	% of capex/year	4.95
DRI	2020	% of capex/year	11.3
DRI	2030	% of capex/year	11.3
DRI	2035	% of capex/year	11.3
DRI	2040	% of capex/year	11.3
DRI	2045	% of capex/year	11.3
DRI	2050	% of capex/year	11.3
Eaf	2020	% of capex/year	30.0
Eaf	2030	% of capex/year	30.0
Eaf	2035	% of capex/year	30.0
Eaf	2040	% of capex/year	30.0
Eaf	2045	% of capex/year	30.0
Eaf	2050	% of capex/year	30.0
El	2020	% of capex/year	4.0
El	2030	% of capex/year	4.0
El	2035	% of capex/year	4.0
El	2040	% of capex/year	4.0
El	2045	% of capex/year	4.0
El	2050	% of capex/year	4.0
H_2Eva	2020	% of capex/year	2.5
H_2Eva	2030	% of capex/year	2.5
H_2Eva	2035	% of capex/year	2.5
H_2Eva	2040	% of capex/year	2.5
H_2Eva	2045	% of capex/year	2.5

(Continued)

Process	Year	Unit	Value
H_2Eva	2050	% of capex/year	2.5
H_2Liq	2020	% of capex/year	2.5
H_2Liq	2030	% of capex/year	2.5
H_2Liq	2035	% of capex/year	2.5
H_2Liq	2040	% of capex/year	2.5
H_2Liq	2045	% of capex/year	2.5
H_2Liq	2050	% of capex/year	2.5
Hb	2020	% of capex/year	3.0
Hb	2030	% of capex/year	3.0
Hb	2035	% of capex/year	3.0
Hb	2040	% of capex/year	3.0
Hb	2045	% of capex/year	3.0
Hb	2050	% of capex/year	3.0
MeOHT	2020	% of capex/year	5.0
MeOHT	2030	% of capex/year	5.0
MeOHT	2035	% of capex/year	5.0
MeOHT	2040	% of capex/year	5.0
MeOHT	2045	% of capex/year	5.0
MeOHT	2050	% of capex/year	5.0
MTO/MTA	2020	% of capex/year	3
MTO/MTA	2030	% of capex/year	3
MTO/MTA	2035	% of capex/year	3
MTO/MTA	2040	% of capex/year	3
MTO/MTA	2045	% of capex/year	3
MTO/MTA	2050	% of capex/year	3
NTO/NTA	2020	% of capex/year	3
NTO/NTA	2030	% of capex/year	3
NTO/NTA	2035	% of capex/year	3
NTO/NTA	2040	% of capex/year	3
NTO/NTA	2045	% of capex/year	3
NTO/NTA	2050	% of capex/year	3
Offwind	2020	% of capex/year	2.5093
Offwind	2030	% of capex/year	2.3185

(Continued)

Process	Year	Unit	Value
Offwind	2035	% of capex/year	2.24735
Offwind	2040	% of capex/year	2.1762
Offwind	2045	% of capex/year	2.17085
Offwind	2050	% of capex/year	2.1655
Onwind	2020	% of capex/year	1.2514
Onwind	2030	% of capex/year	1.2167
Onwind	2035	% of capex/year	1.20125
Onwind	2040	% of capex/year	1.1858
Onwind	2045	% of capex/year	1.18165
Onwind	2050	% of capex/year	1.1775
Pv	2020	% of capex/year	2.0089
Pv	2030	% of capex/year	2.4757
Pv	2035	% of capex/year	2.5002
Pv	2040	% of capex/year	2.5247
Pv	2045	% of capex/year	2.52695
Pv	2050	% of capex/year	2.5292
Smr	2020	% of capex/year	5
Smr	2030	% of capex/year	5
Smr	2035	% of capex/year	5
Smr	2040	% of capex/year	5
Smr	2045	% of capex/year	5
Smr	2050	% of capex/year	5
SmrCCTS	2020	% of capex/year	5
SmrCCTS	2030	% of capex/year	5
SmrCCTS	2035	% of capex/year	5
SmrCCTS	2040	% of capex/year	5
SmrCCTS	2045	% of capex/year	5
SmrCCTS	2050	% of capex/year	5
Esc	2030	% of capex/year	3
Esc	2035	% of capex/year	3
Esc	2040	% of capex/year	3
Esc	2045	% of capex/year	3
Esc	2050	% of capex/year	3

A.1.9. Cost Data for Transportation Modes

For the transportation of hydrogen and its derivatives, only CAPEX and FOM costs are considered due to the lack of data available and shown in table (17) and table (18) . The cost data for hydrogen, submarine pipelines, and all shipping costs are sourced from Victoria et al. (2024). The data for methanol pipelines are taken from DeSantis et al. (2021), while the ammonia pipeline costs are derived from Galimova et al. (2023). The costs for submarine methanol and ammonia pipelines are estimated by scaling the cost of hydrogen submarine pipelines in proportion to the costs of ammonia and methanol pipelines.

Table 17: Transportation CAPEX

Mode	Fuel	Year	Unit	Value
shipping	LH_2	2020	EUR/tH_2	35794
shipping	LH_2	2030	EUR/tH_2	35794
shipping	LH_2	2035	EUR/tH_2	35794
shipping	LH_2	2040	EUR/tH_2	35794
shipping	LH_2	2045	EUR/tH_2	35794
shipping	LH_2	2050	EUR/tH_2	35794
shipping	NH_3	2030	EUR/tNH_3	1531
shipping	NH_3	2035	EUR/tNH_3	1531
shipping	NH_3	2040	EUR/tNH_3	1531
shipping	NH_3	2045	EUR/tNH_3	1531
shipping	NH_3	2050	EUR/tNH_3	1531
shipping	MeOH	2030	EUR/tMeOH	467
shipping	MeOH	2035	EUR/tMeOH	467
shipping	MeOH	2040	EUR/tMeOH	467
shipping	MeOH	2045	EUR/tMeOH	467
shipping	MeOH	2050	EUR/tMeOH	467
pipeline	H_2	2030	EUR/tH_2/km	9.11
pipeline	H_2	2035	EUR/tH_2/km	9.11
pipeline	H_2	2040	EUR/tH_2/km	9.11
pipeline	H_2	2045	EUR/tH_2/km	9.11
pipeline	H_2	2050	EUR/tH_2/km	9.11
pipeline	NH_3	2030	EUR/tNH_3/km	16.36
pipeline	NH_3	2035	EUR/tNH_3/km	16.36
pipeline	NH_3	2040	EUR/tNH_3/km	12.42

(Continued)

Mode	Fuel	Year	Unit	Value
pipeline	NH_3	2045	EUR/tNH_3/km	12.42
pipeline	NH_3	2050	EUR/tNH_3/km	10.79
pipeline	MeOH	2030	EUR/tMeOH/km	11.82
pipeline	MeOH	2035	EUR/tMeOH/km	11.82
pipeline	MeOH	2040	EUR/tMeOH/km	8.97
pipeline	MeOH	2045	EUR/tMeOH/km	6.81
pipeline	MeOH	2050	EUR/tMeOH/km	4.49
submarine	H_2	2030	EUR/tH_2/km	456
submarine	H_2	2035	EUR/tH_2/km	456
submarine	H_2	2040	EUR/tH_2/km	456
submarine	H_2	2045	EUR/tH_2/km	456
submarine	H_2	2050	EUR/tH_2/km	456
submarine	NH_3	2030	EUR/tNH_3/km	819
submarine	NH_3	2035	EUR/tNH_3/km	819
submarine	NH_3	2040	EUR/tNH_3/km	621
submarine	NH_3	2045	EUR/tNH_3/km	621
submarine	NH_3	2050	EUR/tNH_3/km	540
submarine	MeOH	2030	EUR/tMeOH/km	592
submarine	MeOH	2035	EUR/tMeOH/km	592
submarine	MeOH	2040	EUR/tMeOH/km	449
submarine	MeOH	2045	EUR/tMeOH/km	341
submarine	MeOH	2050	EUR/tMeOH/km	225

Table 18: Transport fixed and maintenance cost data

Mode	Fuels	Unit	Value
pipeline	H_2	% of capex/year	4
pipeline	H_2	% of capex/year	3.1
pipeline	H_2	% of capex/year	2.75
pipeline	H_2	% of capex/year	2.34
pipeline	H_2	% of capex/year	1.91
pipeline	H_2	% of capex/year	1.5
pipeline	NH_3	% of capex/year	3.16
pipeline	NH_3	% of capex/year	2.75

(Continued)

Mode	Fuels	Unit	Value
pipeline	NH_3	% of capex/year	2.33
pipeline	NH_3	% of capex/year	1.91
pipeline	NH_3	% of capex/year	1.5
pipeline	MeOH	% of capex/year	3.16
pipeline	MeOH	% of capex/year	2.75
pipeline	MeOH	% of capex/year	2.33
pipeline	MeOH	% of capex/year	1.91
pipeline	MeOH	% of capex/year	1.5
shipping	LH_2	% of capex/year	4
shipping	LH_2	% of capex/year	4
shipping	LH_2	% of capex/year	4
shipping	LH_2	% of capex/year	4
shipping	LH_2	% of capex/year	4
shipping	LH_2	% of capex/year	4
shipping	NH_3	% of capex/year	4
shipping	NH_3	% of capex/year	4
shipping	NH_3	% of capex/year	4
shipping	NH_3	% of capex/year	4
shipping	NH_3	% of capex/year	4
shipping	NH_3	% of capex/year	4
shipping	MeOH	% of capex/year	5
shipping	MeOH	% of capex/year	5
shipping	MeOH	% of capex/year	5
shipping	MeOH	% of capex/year	5
shipping	MeOH	% of capex/year	5
shipping	MeOH	% of capex/year	5
submarine	H_2	% of capex/year	3
submarine	H_2	% of capex/year	3
submarine	H_2	% of capex/year	3
submarine	H_2	% of capex/year	3
submarine	H_2	% of capex/year	3
submarine	NH_3	% of capex/year	3
submarine	NH_3	% of capex/year	3

(Continued)

Mode	Fuels	Unit	Value
submarine	NH_3	% of capex/year	3
submarine	NH_3	% of capex/year	3
submarine	NH_3	% of capex/year	3
submarine	MeOH	% of capex/year	3
submarine	MeOH	% of capex/year	3
submarine	MeOH	% of capex/year	3
submarine	MeOH	% of capex/year	3
submarine	MeOH	% of capex/year	3

Technology Lifetime Table (19) shows the assumptions which are made regarding a process lifetime. If no information was available a default lifetime of 20 years was assumed.

Table 19: Process Lifetimes

Process	Lifetime (years)	Process	Lifetime (years)
MGO ICE	20	Hb	30
H_2 ICE	10	Msr	20
NH_3 ICE	10	Btm	20
MeOH ICE	10	Dac	20
Bio ICE	15	EL	25
LNG ICE	15	AmCr	25
MTO/MTA	10	H_2Eva	20
ASU	30	H_2Liq	20
MeOHSyn	10	Shipping	20
NTO/NTA	10	EXC	30

A.1.10. Exogenous Fuel Prices

Several sources derive the price paths for the exogenous fuels in the model shown in the table (20), like natural gas, electricity, and biomass derivatives. Electricity prices are taken from International Energy Agency (2020) and biomass and biobased CO_2 prices and assumed to stay constant until 2050. The prices for natural gas are taken from the Market Observatory for Energy (2024). The prices for biomass and biobased CO_2 are guesstimated based on Commission (2017) and Dees et al. (2017). The data for maritime fuels is derived from Statista (2024) and IEA (2020). The prices for sustainable aviation fuels (SAF) are taken from Strategy (2020) and IEA (2021).

Table 20: Fuel Prices Across Locations and Years

Item/Process	Fuel	Unit	Country	Year	Value
Fuel	Electricity	EUR/MWh Elec	GER	2030	17.13
Fuel	Electricity	EUR/MWh Elec	GER	2035	17.13
Fuel	Electricity	EUR/MWh Elec	GER	2040	17.13
Fuel	Electricity	EUR/MWh Elec	GER	2045	17.13
Fuel	Electricity	EUR/MWh Elec	GER	2050	17.13
Fuel	Electricity	EUR/MWh Elec	NOR	2030	5.31
Fuel	Electricity	EUR/MWh Elec	NOR	2035	5.31
Fuel	Electricity	EUR/MWh Elec	NOR	2040	5.31
Fuel	Electricity	EUR/MWh Elec	NOR	2045	5.31
Fuel	Electricity	EUR/MWh Elec	NOR	2050	5.31
Fuel	Electricity	EUR/MWh Elec	NLD	2030	13.26
Fuel	Electricity	EUR/MWh Elec	NLD	2035	13.26
Fuel	Electricity	EUR/MWh Elec	NLD	2040	13.26
Fuel	Electricity	EUR/MWh Elec	NLD	2045	13.26
Fuel	Electricity	EUR/MWh Elec	NLD	2050	13.26
Fuel	Gas	EUR/MWh Gas	GER	2030	60.00
Fuel	Gas	EUR/MWh Gas	GER	2035	60.00
Fuel	Gas	EUR/MWh Gas	GER	2040	60.00
Fuel	Gas	EUR/MWh Gas	GER	2045	60.00
Fuel	Gas	EUR/MWh Gas	GER	2050	60.00
Fuel	Gas	EUR/MWh Gas	NOR	2030	40.00
Fuel	Gas	EUR/MWh Gas	NOR	2035	40.00
Fuel	Gas	EUR/MWh Gas	NOR	2040	40.00
Fuel	Gas	EUR/MWh Gas	NOR	2045	40.00
Fuel	Gas	EUR/MWh Gas	NOR	2050	40.00
Fuel	Coal	EUR/tCoal	GER	2030	200.00
Fuel	Coal	EUR/tCoal	GER	2035	200.00
Fuel	Coal	EUR/tCoal	GER	2040	200.00
Fuel	Coal	EUR/tCoal	GER	2045	200.00
Fuel	Coal	EUR/tCoal	GER	2050	200.00
Fuel	Biodiesel	EUR/tBiodiesel	GER	2030	24.44
Fuel	Biodiesel	EUR/tBiodiesel	GER	2035	23.88

(Continued)

Item/Process	Fuel	Unit	Country	Year	Value
Fuel	Biodiesel	EUR/tBiodiesel	GER	2040	23.14
Fuel	Biodiesel	EUR/tBiodiesel	GER	2045	22.21
Fuel	Biodiesel	EUR/tBiodiesel	GER	2050	23.88
Fuel	LNG	EUR/tLNG	GER	2030	7.25
Fuel	LNG	EUR/tLNG	GER	2035	8.125
Fuel	LNG	EUR/tLNG	GER	2040	9.00
Fuel	LNG	EUR/tLNG	GER	2045	9.875
Fuel	LNG	EUR/tLNG	GER	2050	10.75
Fuel	MGO	EUR/tMGO	GER	2030	10.25
Fuel	MGO	EUR/tMGO	GER	2035	11.375
Fuel	MGO	EUR/tMGO	GER	2040	12.50
Fuel	MGO	EUR/tMGO	GER	2045	13.625
Fuel	MGO	EUR/tMGO	GER	2050	14.75
Fuel	Naphtha	EUR/tNaphtha	GER	2030	573.00
Fuel	Naphtha	EUR/tNaphtha	GER	2035	573.00
Fuel	Naphtha	EUR/tNaphtha	GER	2040	573.00
Fuel	Naphtha	EUR/tNaphtha	GER	2045	573.00
Fuel	Naphtha	EUR/tNaphtha	GER	2050	573.00
Fuel	Biomass	EUR/tBiomass	GER	2030	40.00
Fuel	Biomass	EUR/tBiomass	GER	2035	61.25
Fuel	Biomass	EUR/tBiomass	GER	2040	82.50
Fuel	Biomass	EUR/tBiomass	GER	2045	103.75
Fuel	Biomass	EUR/tBiomass	GER	2050	125.00
Fuel	JetA	EUR/tJetA	GER	2030	1000.00
Fuel	JetA	EUR/tJetA	GER	2035	1200.00
Fuel	JetA	EUR/tJetA	GER	2040	1300.00
Fuel	JetA	EUR/tJetA	GER	2045	1350.00
Fuel	JetA	EUR/tJetA	GER	2050	1400.00
Fuel	HEFA	EUR/tHEFA	GER	2030	3200.00
Fuel	HEFA	EUR/tHEFA	GER	2035	3056.00
Fuel	HEFA	EUR/tHEFA	GER	2040	2912.00
Fuel	HEFA	EUR/tHEFA	GER	2045	2768.00

(Continued)

Item/Process	Fuel	Unit	Country	Year	Value
Fuel	HEFA	EUR/tHEFA	GER	2050	2624.00
Fuel	CO_2	EUR/tCO_2	GER	2030	350.00
Fuel	CO_2	EUR/tCO_2	GER	2035	325.00
Fuel	CO_2	EUR/tCO_2	GER	2040	250.00
Fuel	CO_2	EUR/tCO_2	GER	2045	225.00
Fuel	CO_2	EUR/tCO_2	GER	2050	200.00

A.1.11. Transport Losses

The losses occurring in occurring in transportation are based on boil-offs and self-consumption. The losses are due to own consumption during the shipment. The losses due to self-consumption in shipment are based on Patonia and Poudineh (2022). The additional transformational boil-offs are based on Carels et al. (2023). Additional data on losses occurring during pipeline transpiration of ammonia are based on Galimova et al. (2023).

Table 21: Losses for Different Commodities and Modes of Transportation

Fuel	Mode	Losses
LH_2	shipping	0.0003
NH_3	shipping	0.0015
MeOH	shipping	0.0009
LH_2	pipeline	0.0010
NH_3	pipeline	0.1000
MeOH	pipeline	0.0146
H_2	pipeline	0.0010
LCMeOH	pipeline	0.0146
$LCNH_3$	pipeline	0.0010
LCH_2	pipeline	0.1000
NH_3	submarine	0.1000
MeOH	submarine	0.0146
H_2	submarine	0.0010
LCH_2	submarine	0.1000

(Continued)

Commodity	Mode	Losses
LCMeOH	submarine	0.0146
$LCNH_3$	submarine	0.0010
LCH_2	submarine	0.1000

A.2. Maps

A.2.1. Location industy mapping

Table (22) maps the different industries to their locations.

Table 22: Industry Locations and Values

Country Code	Location	Industry	Value
GER	Duisburg	Steel	1
GER	Ludwigshafen	Fertilizer	1
GER	Leverkusen	Hvc	1
GER	Hamburg	Shipping	1
GER	Frankfurt	Aviation	1
GER	Hamburg	Port	1
NLD	Rotterdam	Port	1
CHL	Chanaral	Producer	1
CHL	Antofagasta	Port	1
ESP	Teruel	Producer	1
MAR	Guelmim	Producer	1
MAR	Agadir	Port	1
NOR	Fiska	LC Producer	1

A.2.2. Process Output Map

Table (23) shows the mapping of outputs to processes as described in table (4).

Table 23: Process Output Map

Process	Output	Process	Output
Bof	Steel	DRI	Steel
Smr	H_2	HB	NH_3
Fertilizer Synthesis	Fertilizer	Conventional ICE	Shipping
H_2 ICE	Shipping	LNG ICE	Shipping
NH_3 ICE	Shipping	MeOH ICE	Shipping
MTO/MTA	Olefins/Aromatics	NTO/NTA	Olefins/Aromatics
MeOH Syn	MeOH	ASU	N
Dac	CO_2	BTM	MeOH
Pv	Electricity	Onwind	Electricity
Offwind	Electricity	MeOH Syn	MeOH
EL	H_2	Smr-HB	Fertilizer
EL-HB	Fertilizer	H_2Liq	LH_2
H_2Eva	H_2	ESC	Olefins/Aromatics
Jet Engine	Aviation		

A.2.3. Fuel Switch Map

Table (24) map indicates the processes that allow for fuel switching:

Table 24: Processes, Fuels, and Values

Process	Fuel	Value
Conventional ICE	MGO	1
Conventional ICE	Biodiesel	1
DRI	H_2	1
DRI	LCH_2	1
MeOH ICE	MeOH	1
MeOH ICE	BMeOH	1
MeOH ICE	LCMeOH	1
H_2ICE	H_2	1
H_2ICE	LCH_2	1
NH_3 ICE	NH_3	1

(Continued)

Process	Fuel	Value
NH_3 ICE	$LCNH_3$	1
Fertilizer Synthesis	NH_3	1
Fertilizer Synthesis	$LCNH_3$	1
Fertilizer Synthesis	$HCNH_3$	1
MTO/MTA	MeOH	1
MTO/MTA	LCMeOH	1
MTO/MTA	BMeOH	1
JetEngine	JetA	1
JetEngine	HEFA	1
JetEngine	LCFT	1
JetEngine	FT	1

A.2.4. Process Industry Map

Table (25) maps the processes to each industry.

Table 25: Process Industry Map

Process	SteEL	Fert.	Hvc	Ship.	Aviat.	Prod.	LC Prod.	Port
MeOH ICE	0	0	0	1	0	0	0	0
Conv. ICE	0	0	0	1	0	0	0	0
NH_3 ICE	0	0	0	1	0	0	0	0
H_2 ICE	0	0	0	1	0	0	0	0
LNG ICE	0	0	0	1	0	0	0	0
Smr	0	1	0	0	0	0	0	0
SmrCCTS	0	0	0	0	0	0	1	0
Fert. Synth.	0	1	0	0	0	0	0	0
Bof	1	0	0	0	0	0	0	0
DRI	1	0	0	0	0	0	0	0
MeOH Syn	0	0	1	0	0	1	1	0
NTO/NTA	0	0	1	0	0	0	0	0
MTO/MTA	0	0	1	0	0	0	0	0

(Continued)

Process	SteEL	Fertilizer	Hvc	Ship.	Aviation	Producer	LC Producer.	Port
FT	0	0	0	0	1	0	0	0
ESC	0	0	1	0	0	0	0	0
EL	0	0	0	0	0	1	1	0
Dac	0	0	1	0	1	1	1	0
ASU	0	1	0	0	0	1	1	0
HB	0	1	0	0	0	1	1	0
BTM	0	0	1	0	0	1	1	0
Pv	0	0	0	0	0	1	1	0
Onwind	0	0	0	0	0	1	1	0
Offwind	0	0	0	0	0	0	0	0
AmCr	0	0	0	0	0	0	0	1
H_2Liq	0	0	0	0	0	0	0	1
H_2Eva	0	0	0	0	0	0	0	1
H_2gP	0	0	0	0	0	0	0	0
NH_3lP	0	0	0	0	0	0	0	0
MeOHlP	0	0	0	0	0	0	0	0
Jet Engine	0	0	0	0	1	0	0	0

A.2.5. Fuel Process Map

Table (26) maps the Fuels to each process.

Table 26: Fuel Process Map (Part 1)

Fuel	LNG ICE	MeOH ICE	NH_3 ICE	Conv ICE	H_2 ICE	DRI	BOF	HB	SMR	SMR CCTs	Fert. Synth.	ESC	NTO/NTA	MTO/MTA
H_2	0	0	0	0	1	1	0	1	0	0	0	0	0	0
NH_2	0	0	1	0	0	0	0	0	0	0	1	0	0	0
MeOH	0	1	0	0	0	0	0	0	0	0	0	0	1	0
E-Kerosene	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FT	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gas	0	0	0	0	0	0	1	0	1	1	0	1	0	0
Coal	0	0	0	0	0	0	1	0	0	0	0	0	0	0
MGO	0	0	0	1	0	0	0	0	0	0	0	0	0	0
LNG	1	0	0	0	0	0	0	0	0	0	0	0	0	0
BiodiesEL	0	0	0	1	0	0	0	0	0	0	0	0	0	0
HEFA	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JetA	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Naphtha	0	0	0	0	0	0	0	0	0	0	0	0	1	0
ELectricity	0	0	0	0	0	1	0	1	1	0	0	1	0	0
CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Biomass	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N	0	0	0	0	0	0	0	1	0	0	0	0	0	0
LH_2	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Power	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(Continued)

Fuel	LNG ICE	MeOH ICE	NH_3 ICE	Conv ICE	H_2 ICE	DRI	BOF	HB	SMR	SMR CCTs	Fert. Synth.	ESC	NTO/NTA	MTO/MTA
HCH_2	0	0	0	0	0	0	0	1	0	0	0	0	0	1
LCH_2	0	0	0	0	0	0	0	1	0	0	0	0	0	1
$HCNH_3$	0	0	0	0	0	0	0	0	0	0	1	0	0	0
$LCNH_3$	0	0	0	0	0	0	0	0	0	0	1	0	0	0
BMeOH	0	1	0	0	0	0	0	0	0	0	0	0	1	0
LCMeOH	0	1	0	0	0	0	0	0	0	0	0	0	1	0

Table 27: Fuel Process Map (Part 2)

Fuel	MTO/MTA	MeOH Syn	ASU	BTM	FT	Jet Eng.	EL	PV	Onwind	Offwind	DAC	AMCR	H_2 Liq.	H_2 Eva.
H_2	0	0	1	0	0	1	0	0	0	0	0	1	0	1
NH_3	0	0	0	0	0	0	0	0	0	0	1	0	0	0
MeOH	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E-Kerosene	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FT	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MGO	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LNG	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BiodiesEL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HEFA	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JetA	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Naphtha	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ELectricity	0	0	0	0	0	1	0	1	1	0	0	1	0	1
CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biomass	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N	0	0	0	0	0	0	0	1	0	0	0	0	0	0
LH_2	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Power	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(Continued)

Fuel	MTO/MTA	MeOH Syn	ASU	BTM	FT	Jet Eng.	EL	PV	Onwind	Offwind	DAC	AMCR	H_2 Liq.	H_2 Eva.
HCH_2	0	0	0	0	0	0	0	1	0	0	0	0	0	0
LCH_2	0	0	0	0	0	0	0	1	0	0	0	0	0	0
$HCNH_3$	0	0	0	0	0	0	0	0	0	0	1	0	0	0
$LCNH_3$	0	0	0	0	0	0	0	0	0	0	1	0	0	0
BMeOH	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LCMeOH	0	0	0	0	0	0	0	0	0	0	0	0	0	0

A.2.6. Fuel Industry Map

Table (28) maps each fuel to an industry that uses it. 2

Table 28: Fuel Industry Map

Fuel	Industry	Indicator
Biodiesel	Aviation	1
FT	Aviation	1
H_2	Aviation	1
JetA	Aviation	1
LNG	Aviation	1
MGO	Aviation	1
Electricity	Fertilizer	1
Gas	Fertilizer	1
H_2	Fertilizer	1
HCH_2	Fertilizer	1
LCH_2	Fertilizer	1
N	Fertilizer	1
NH_3	Fertilizer	1
Biomass	Hvc	1
BMeOH	Hvc	1
CO	Hvc	1
CO_2	Hvc	1
Electricity	Hvc	1
H_2	Hvc	1
LCH_2	Hvc	1
LCMeOH	Hvc	1
MeOH	Hvc	1
Naphtha	Hvc	1
H_2	Port	1
LH_2	Port	1
MeOH	Port	1

(Continued)

Fuel	Industry	Indicator
NH_3	Port	1
H_2	Port	1
HCH_2	Port	1
LCH_2	Port	1
LCMeOH	Port	1
LH_2	Port	1
Electricity	Producer	1
H_2	Producer	1
Biomass	Producer	1
CO_2	Producer	1
NH_3	Producer	1
MeOH	Producer	1

A.2.7. Fuel Supplier Map

Table (30) maps each fuel to its supplier. Hydrogen and its derivatives in their carbon-free and low-carbon versions are supplied either directly from the producer or via a port. For convenience, fuels exogenous to the model are assumed to be purchased from an external market. 2

Table 30: Supplier Fuel Mapping

Supplier	Fuel	Value
Producer	H_2	1
Producer	NH_3	1
Producer	MeOH	1
LC Producer	LCH_2	1
LC Producer	$LCNH_3$	1
LC Producer	LCMeOH	1
Port	LH_2	1
Port	H_2	1
Port	NH_3	1
Port	MeOH	1
Port	LCH_2	1
Port	$LCNH_3$	1

Supplier	Fuel	Value
Port	LCMeOH	1
Market	Electricity	1
Market	Gas	1
Market	Coal	1
Market	MGO	1
Market	LNG	1
Market	Biodiesel	1
Market	HEFA	1
Market	JetA	1
Market	Naphtha	1
Market	Biomass	1
Market	CO_2	1