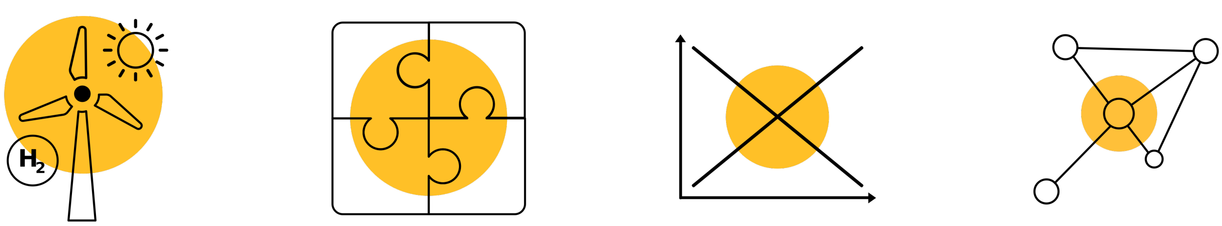
Energiewirtschaftliches Institut
an der Universität zu Köln

EWI Global PtX Cost Tool Documentation

Version 2.0

May 2024



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1 Introduction

The EWI Global PtX Cost Tool provides scenarios for the global supply side of green hydrogen and hydrogen derivatives from wind and solar energy. The tool enables the analysis of production costs and production potential from 117 origin countries, as well as the transportation costs from these origin countries to 19 destination countries.

The production systems are greenfield integrated plants powered by a single dedicated renewable energy source located at the site. The renewable energy source can be PV, onshore wind, or offshore wind.[1]

The tool provides analyses of the supply side for annual and hourly demand profiles. In the volatile delivery profile, the production system is designed to cover an annual demand at minimal costs. This profile can be analyzed in monthly resolution. In the baseload delivery profile, the production system is designed to cover a constant hourly demand at minimal costs, with all necessary storage located in the origin country.

The tool contains two scenarios for cost projections of the production systems and transport costs for the years 2025 to 2050 in five year steps. Regarding transport costs, the tool provides multiple scenarios for hydrogen pipeline costs and shipping charter rates, as well as customizable default assumptions for further key parameters.

Country-specific RES input parameters include hourly capacity factor profiles and potentials. Country-specific economic inputs include weighted average costs of capital (WACC), labour costs, and investment costs.

The EWI Global PtX Cost Tool contains sheets with the following functionalities:

- **Overview:** contains credits and a navigation pane
- **Scenario settings:** contains general and expert settings for the production and transport cost scenario
- **Global analysis:** contains a simplified global supply analysis for one destination country
- **Country-to-country:** contains a detailed supply analysis from one origin to one destination country
- **Modellers sheet:** contains data structured for export for use in other models
- **Input data sheets:** contain input data structured as data table

The rest of this documentation explains the user interface (section 2), shows the modelling equations of production and transport costs (section 3) and describes how the input parameters for the modelling were derived (section 4).

[1] For offshore wind, downstream processes like electrolysis occur onshore.

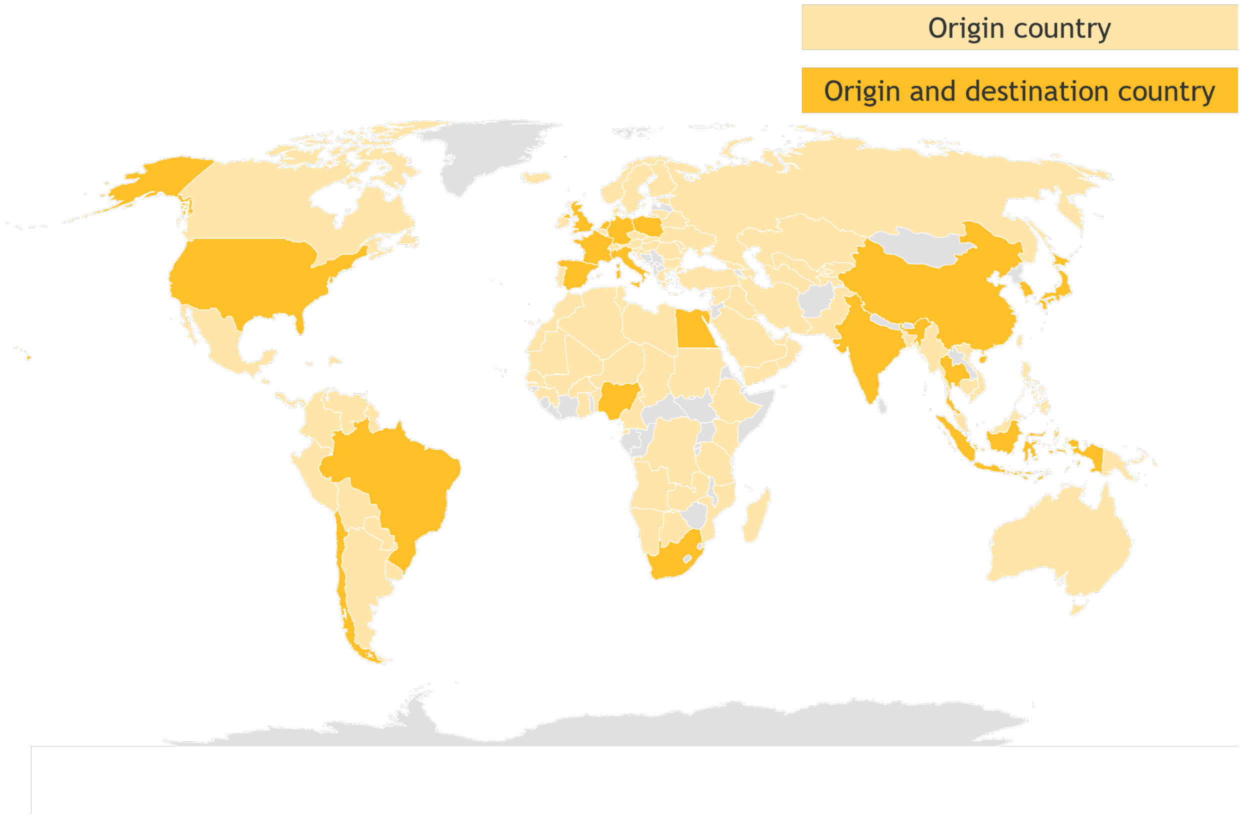

Figure 1: Origin and destination countries analyzed in the EWI Global Power-to-X tool.

1.1 Changelog

The following changes have been made to version 1.3 of the tool:

- Model
  - Introduction of the volatile and baseline delivery profiles including information on the profiles. Reason: The costs in version 1.3 represented the volatile delivery profile without explicitly providing information about the profile.
  - Introduction of hydrogen derivative storages to the production system.
  - Introduction of compressors to the hydrogen and CH_4 storages.
  - Introduction of the CO_2 Direct Air Capturing (DAC) process into the optimization model.
  - Liquefied organic hydrogen carriers (LOHC) as a hydrogen transport option has been added.
  - Implementation of the tool has been completely redone so that no VBA macros are necessary anymore.
- Input data
  - Techno-economic input data has been revised.
  - 18 new destination countries and 4 new origin countries have been added.

  - New country-specific RES time series for all countries.
  - New source for offshore potentials now includes water depths up to 40 m (before 25 m) for class 1 and 40-60 m (before 25-55 m).
  - New methodology and sources for the calculation of the country-specific weighted average costs of capital for hydrogen projects.
  - The cost of losses in the transport chain are accounted for in greater detail and are shown as a separate cost item.
  - Diesel, Kerosene and Gasoline are summed up to Fischer-Tropsch fuels.
  - Country-specific labour costs and their impact on construction and fixed operation and maintenance costs are now considered.

- Analysis
  - A modeller-friendly results export sheet is added for further analyses outside the Excel tool.
  - The country-to-country sheet now contains a visualization of the value chain and a more detailed cost structure of the production costs.

2 User interface

This section explains the user interface and the functionality of each selection field.

2.1 Scenario settings

On the sheet *scenario settings*, the user can set different settings for production costs, transportation costs, and the year of the cost projection. The following settings can be made in the *General settings* box:

- **Investment costs** (baseline/optimistic): Affects the investment cost projection of all components of the production systems in the origin countries. In the optimistic scenario, the investment cost decreases more strongly over time due to higher scale effects and learning.

- **Hydrogen pipeline costs** (high cost new/low cost new/retrofitted): Affects the investment cost of hydrogen pipelines. *High cost new* has the highest costs and represents transport costs in newly constructed 700 mm pipelines. *Low cost new* has medium costs and represents transport costs in newly constructed 950 mm pipelines. *Retrofitted* has the lowest costs and represents transport costs in retrofitted natural gas pipelines.

- **Shipping charter rates** (high/medium/low): Affects the charter rates of ships. Charter rates can vary significantly over time. *high* represents the highest charter rate, *medium* the medium charter rate, and *low* the lowest charter rate found between 2021 and 2023 for each ship type.

- **Infrastructure** (greenfield/brownfield): Affects the CAPEX of transport infrastructure like pipelines, import or export terminals. *greenfield* assumes that transport infrastructure costs are calculated as greenfield investments, including CAPEX and OPEX. *brownfield* assumes existing, fully depreciated transport infrastructure and only considers OPEX.
- **Prioritize power generation over PtX production** (yes/no): Affects the available RES potential in the origin countries. *yes* assumes, that origin countries use their best RES potentials to cover their own electricity demand. This priority reduces the available RES potential for PtX production. *no* assumes all RES potential is available for PtX production.
- **Year** (2025-2050): The year of projection affects the investment costs and technical parameters like efficiencies and energy demands of production plants and transport infrastructure.

The *Expert settings* box shows the default assumptions of various technical and economic parameters and allows expert users to tweak these assumptions. *Economical parameters* include:

- **Renewable electricity prices for liquefaction, regasification, and reconversion affect the electricity price of terminals**: by default, these terminals use country-specific electricity prices. The user can choose a uniform electricity price by selecting the method *customized* and entering a price in *Customized electricity price*.
- Pipeline transport
  - **WACC**: Affects the weighted average costs of capital in the pipeline cost calculations. The WACC for pipelines is uniform across all countries.
  - **Economic lifetime in years**: Affects the economic lifetime of pipelines in the calculation of the annuity.
  - **Maximal utilization**: Affects the pipeline utilization. In destination and transit countries, the parameter sets the average pipeline utilization. In origin countries, the parameter sets the maximal pipeline utilization. The actual utilization in origin countries can be lower than the maximal utilization if the *delivery profile* is set to *volatile*.
  - **Offshore vs onshore pipeline cost factor**: Sets the investment costs ratio between offshore and onshore pipelines. The higher the factor, the more expensive offshore pipelines are.
- Shipping
  - **Fuel price green methanol in USD/t**: Affects the fuel cost of all ships. We assume that all ships use green methanol to guarantee a climate-neutral value chain as fuel.
  - **Fuel consumption in t/day**: Affects the shipping fuel consumption.
  - **Refueling costs in USD**: Affects the cost of a bunkering operation in port. We assume that each ship's bunkers once in the origin and once in the destination country.

  - **Terminal costs in USD/terminal**: Affects the cost of docking permit in port. We assume that ships run in shuttle mode between the origin and destination country with two port calls per roundtrip.
  - **Berthing time (loading and unloading) in hours**: Affects the time required for loading and unloading cargo when in port.
  - **Total waiting time in hours**: Affects the total waiting time of a ship before all port calls. The parameter reflects that ports are often at capacity, and ships have to line up and wait before entering the port.
  - **Speed in km/h**: Affects the average cruise speed of the ships.

- **LOHC Route**: Defines economic parameters of liquid organic hydrogen carriers (LOHC)
  - **Toluene costs in USD/kg tol**: Affects the toluene costs. Toluene is a circulated carrier medium to transport hydrogen. Hydrogenated, it transports hydrogen from the origin to the destination country. Dehydrogenated, it is transported back to the origin country.
  - **Toluene cycles**: Affects the number of toluene cycles before the toluene has to be replaced.

- Infrastructure
  - **Maximal utilization of liquefaction, regasification, and reconversion terminals**: Affects the utilization of liquefaction, regasification, and reconversion terminals. In destination countries, the parameter sets the average pipeline terminal utilization. In origin countries, the parameter sets the maximal terminal utilization. The actual utilization in origin countries can be lower than the maximal utilization if the *delivery profile* is set to *volatile*.

The *Technical parameters* box include:

- Hydrogen pipelines
  - **Hydrogen losses in compressor**: Affects the hydrogen losses in compressors due to leakage.
  - **Distance between compressors in km**: Affects the distance between compressor stations along a pipeline. The lower the distance, the higher the number of compressor stations necessary, which leads to higher pipeline transport costs.

- LH_2 shipping
  - **Boil-off losses during LH_2 transport per day**: Affects the hydrogen boil-off rate. Boil-off refers to the process where liquefied hydrogen stored in an insulated tank at extremely low temperatures evaporates into gaseous hydrogen due to heat transfer. The higher the boil-off rate, the higher the losses, which leads to higher transport costs.

- **Losses during liquefaction**: Affects the hydrogen losses during liquefaction due to leakage.
- **Electricity demand for liquefaction in $kWh_{el}/kWhH_2$**: Affects the electricity demand of hydrogen liquefaction due to cooling.
- **Electricity demand for regasification in $kWh_{el}/kWhH_2$**: Affects the electricity demand of hydrogen regasification due to pumps and auxiliaries.

- Ammonia shipping
  - **Boil-off losses during ammonia transport per day**: Affects the ammonia boil-off per day. Higher boil-off means higher losses and, thus, higher transport costs.
  - **Electricity demand for Ammonia cracking in kWh_{th}/kWh_{H2}**: Affects the electricity demand of the ammonia cracker per kWh hydrogen produced. Electricity is purchased at the country-specific price in the destination country.
  - **Heat demand for Ammonia cracking in kWh_{th}/kWh_{H2}**: Affects the heat demand of the ammonia cracker per kWh hydrogen produced. The heat demand is covered by the combustion of ammonia.
  - **Efficiency of heat supply for Ammonia cracking**: Affects the thermal efficiency of ammonia combustion.
- LOHC Shipping
  - **Electricity demand for dehydrogenation in kW_{el}/kW_{H2}**: Affects the electricity demand of the dehydrogenation due to pumping and subsequent compression of the hydrogen to 30 bar.
  - **Heat demand for dehydrogenation in kW_{th}/kW_{H2}**: Affects the heat demand of the dehydrogenation caused by the endothermic reaction. The heat demand is covered by the combustion of hydrogen.
  - **Efficiency of heat supply for dehydrogenation**: Affects the thermal efficiency of hydrogen combustion.
- Methane shipping
  - **Boil-off losses during methane transport per day**: Affects the ammonia boil-off per day. Higher boil-off means higher losses and, thus, higher transport costs.
  - **Electricity demand for liquefaction in kWh_{el}/kWh_{CH4}**: Affects the electricity demand of the liquefaction due to cooling.
  - **Electricity demand for regasification in kWh_{el}/kWh_{CH4}**: Affects the electricity demand of hydrogen regasification due to pumps and auxiliaries.

2.2 Global analysis

The global analysis sheet shows a global analysis of costs and delivery profiles using maps. The user can specify which results are to be displayed in the *control panel* box. The *scenario information* box shows the general settings from the scenario setting sheet. The *visualization* sheet shows the results in four maps. The data table box shows the data plotted on the maps.

The user can make the following settings in the control panel:

- **Destination country**: Sets the destination country of delivery.
- **Commodity**: Sets the end-use commodity in the destination country.
- **Delivery profile** (baseload/volatile): Affects the delivery profile. In *baseload*, the origin countries deliver a baseload profile to the destination country. Storage to compensate for a volatile production profile takes place in the country of origin. In *volatile*, the delivery profile is volatile. The profile is a result of the cost-optimal production of an annually delivered quantity.
- **Annual supply volume in TWh**: Affects the annual supply volume delivered by each origin country. The supplied volume affects the supply costs from each origin country, which are calculated by a weighted average of the origin countries' RES classes. See subsection 3.4 for more information on the calculation of weighted average cost.
- **Month of delivery profile analysis**: Affects the month shown in the bottom right map. The delivery profile shows the share of the annual delivered quantity delivered in the selected month.

The results are visualized on four world maps in the *Visualization* box. The corresponding values can be found in the *Data table*.

- **Commodity supply costs from origin country to destination country**: This world map shows the supply costs from all origin countries for the selected commodity to the selected destination country. Supply costs include hydrogen production costs, storage costs and, if required, conversion and CO_2 direct air capturing costs, as well as transportation costs from the origin to the destination country. Countries with lower production potential than the selected annual supply volume are not shown. The values are shown in the column Supply costs in USD/MWh of the data table. In general, the values reflect the supply costs of the cheapest possible transportation method, which is shown in the column Cheapest transportation method. Other transportation methods can be analyzed in the sheet *Country-to-country-analysis*
- **Commodity production costs in origin countries**: This world map shows the production costs of the selected commodity in all origin countries. Production costs include hydrogen production costs, storage costs and if required conversion and direct air capturing costs in

the origin country. Countries with less production potential than the annual supply volume are not shown. The values are shown in the column *Production costs in USD/MWh* of the data table.

- **Deviation of supply costs to production costs in the destination country**: This world map shows the relative deviation of the supply costs of all origin countries to the production costs in the destination country for the selected commodity. Origin countries marked in *red* have higher supply costs than the production costs of the same commodity in the destination country. Origin countries marked in *green* have lower supply costs. The values are shown in the column *Relative supply cost difference* of the data table.
- **Delivery profile in the selected month**: This world map shows the supply share of the selected month of the annual supply volume for all origin countries. If the delivery profile is set to *volatile*, the annual supply volume is not delivered evenly over all months of the year due to seasonal characteristics of renewable energies. For instance, if the annual supply volume is set to *100 TWh* and *10 TWh* would be delivered in June whereas only *5 TWh* would be delivered in February, the monthly supply share of June would be *10%* and the monthly supply share of February would be *5%*. The average supply share of all months has to be 8.33% which equals 1/12 and which is the supply share for all months if the delivery profile is selected to *baseload*. If the delivery profile is selected to *volatile*, countries with a supply share higher than the monthly average annual supply for the selected month are marked in *green*, whereas countries with a lower supply share than the annual average are marked in *red*. The values of the selected month are shown in the last column of the data table.

2.3 Country-to-country analysis

The *country-to-country analysis* sheet shows supply from a specific origin to a specific destination country in greater detail. As in the global analysis sheet, the user can specify which results are to be displayed in the *control panel* box. The *scenario information* box shows the general settings from the scenario setting sheet. The *country specific information* box shows economic parameters of the origin and destination country, as well as information about the transport route. The *Value chain visualization* shows the steps of the value chain from production to end-use and where these steps are located. The *Visualization of supply costs* box shows a cost breakdown of the supply costs of each RES class of the origin country in bars. The RES classes of the bars are classified by the capacity factor in the case of PV and wind onshore, and by the water depth in the case of wind onshore. The *Legend RES classes* box shows the exact classification of the RES classes. The bars refer to the left y-axis. Moreover, the figure shows the production potential of each class indicated by a diamond marker which refers to the right y-axis. The *Visualization of delivery profile* box shows the supply profile of each RES class in monthly resolution. The *Data table of supply costs* box shows the data plotter in the *Visualization of supply costs* box. The *Data table of delivery profile* box shows the data plotter in the *Visualization of delivery profile* box.

The control panel allows the following settings:

- **Origin country**: Sets the origin country.
- **Destination country**: Sets the destination country of delivery.
- **Delivery profile** (baseload/volatile): Affects the delivery profile. In *baseload*, the origin countries deliver a baseload profile to the destination country. Storage to compensate for a volatile production profile takes place in the country of origin. In *volatile*, the delivery profile is volatile. The profile is a result of the cost-optimal production of an annually delivered quantity.
- **Commodity**: Sets the end-use commodity in the destination country.
- **Transportation method**: The possible transportation methods are dependent on the selected commodity as well as the origin and the destination country. In case of hydrogen, the transportation method can be selected to *Cheapest*, *Ship (LH2)*, *Ship (Ammonia)*, *Ship (LOHC)* and *Pipeline (H2)*. *Cheapest* automatically selects the cheapest of all delivery methods. *Ship (LH2)* shows transport via the liquefied hydrogen shipping route only, which includes regasification in the destination country. *Ship (Ammonia)* shows transport via ammonia shipping only, which includes ammonia cracking in the destination country. *Ship (LOHC)* shows transport via LOHC shipping only, which includes dehydrogenation in the destination country. *Pipeline* shows pipeline transport only, which is only selectable if a pipeline connection between the origin and the destination country exists. In the case of all other commodities, the transportation method can be selected to *Ship (selected commodity)* and *Pipeline (selected commodity)* if a pipeline connection exists.
- **Annual supply volume in TWh**: Affects the annual supply volume delivered by each origin country. The supplied volume affects the supply costs of the weighted average bar. See subsection 3.4 for more information on the calculation of weighted average cost.

3 Methods

This section describes the modelling of production and transport costs. Figure 2 gives an overview of input parameters and modelling of production and transport costs.

3.1 Production of hydrogen or derivatives

The production costs for each RES class in each origin country are calculated in an optimization model. The model determines the optimal capacities and operation of a production system using a dedicated RES to achieve minimal production costs to cover an inelastic demand. The model is

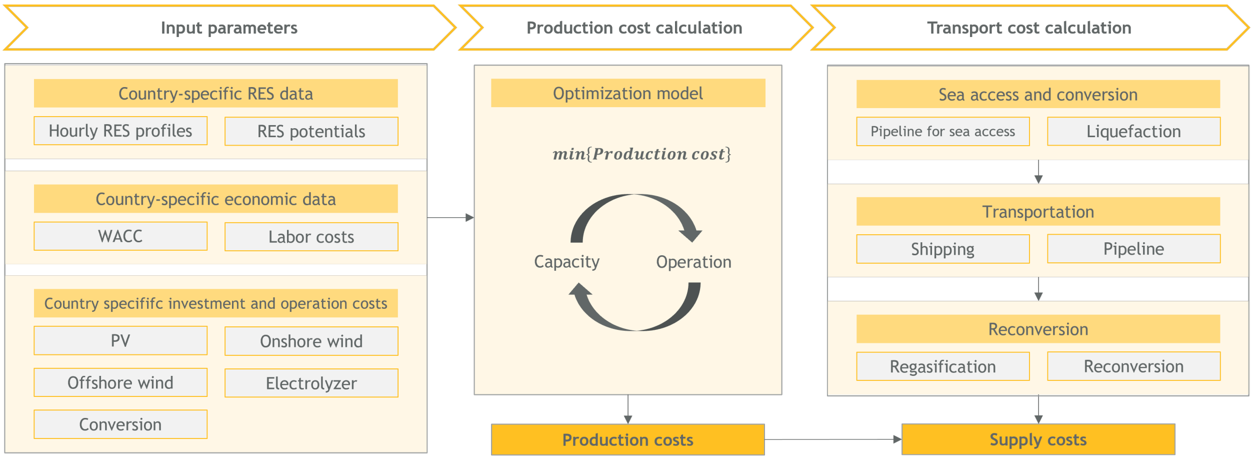

Figure 2: Overview on the methodology for the supply cost calculation.

described by equations 1 to 15. Figure 3 shows a flowsheet of the processes and energy flows in the model. Figure 3.1 shows a list of all sets, parameters and variables of the model, including units and explanation.

$$\min_{Cap,P,S,Sin,Sout} TC_{n,r,c,p,y} \tag{1}$$

s.t.

$$P^{H2}_{n,r,y,h} = \frac{P^{Der}_{r,c,p,h}}{\eta^{Der}_{p,y}} + Sin^{H_2}_{r,c,p,h} - Sout^{H_2}_{r,c,p,h} \tag{2}$$

$$P^{H2}_{n,r,y,h} \leq Cap^{H_2}_{n,r,c,p,y}\eta^{H_2}_{y} \tag{3}$$

$$S^{H_2}_{r,c,p,h} = \begin{cases} 0, & \text{if } h = 0 \\ S^{H_2}_{r,c,p,h-1} + Sin^{H_2}_{r,c,p,h} - Sout^{H_2}_{r,c,p,h}, & \text{otherwise} \end{cases} \tag{4}$$

$$Sin^{H_2}_{r,c,p,h} \leq \frac{Cap^{H_2comp}_{n,r,c,p,y}}{\mathsf{e}^{H_2stor}_{y}} \tag{5}$$

$$S^{H_2}_{r,c,p,h-1} \leq Cap^{H_2stor}_{n,r,c,p,y} \tag{6}$$

$$\frac{P^{H_2}_{r,c,p,h}}{\eta^{H_2}_{y}} + \frac{P^{Der}_{r,c,p,h}}{\mathsf{e}^{Der}_{p,y}} + \frac{P^{CO_2}_{r,c,p,h}}{\mathsf{e}^{CO_2}_{p,y}} + \frac{Sin^{H_2}_{r,c,p,h}}{\mathsf{e}^{H_2stor}_{y}} + \frac{Sin^{Der}_{r,c,p,h}}{\mathsf{e}^{Derstor}_{y}} \leq Cap^{RES}_{n,r,c,p,y}\mathsf{cf}_{n,r,c,h} \tag{7}$$

$$P^{Der}_{r,c,p,h} \leq Cap^{Der}_{n,r,c,p,y}\eta^{Der}_{p,y} \tag{8}$$

$$S^{Der}_{r,c,p,h} = \begin{cases} 0, & \text{if } h = 0 \\ S^{Der}_{r,c,p,h-1} + Sin^{Der}_{r,c,p,h} - Sout^{Der}_{r,c,p,h}, & \text{otherwise} \end{cases} \quad (9)$$

The following equation is only active if methane is the produced derivative. All other derivatives do not require compression for storage.

$$Sin^{Der}_{r,c,p,h} \leq \frac{Cap^{Dercomp}_{n,r,c,p,y}}{\mathsf{e}^{Derstor}_{y}} \quad (10)$$

$$Cap^{CO_2}_{n,r,c,p,y} = Cap^{Der}_{n,r,c,p,y}\mathsf{m}^{Der}_{p,y} \quad (11)$$

$$P^{CO_2}_{r,c,p,h} = P^{Der}_{r,c,p,h}\mathsf{m}^{Der}_{p,y} \quad (12)$$

The model has two different demand specifications, of which only one can be active. The production system must either cover an hourly baseload demand (Equation 13) or an annual demand (Equation 14).

$$P^{Der}_{r,c,p,h} = \mathsf{d}_h + Sin^{H_2}_{r,c,p,h} - Sout^{H_2}_{r,c,p,h} \quad (13)$$

$$\sum_{h}^{H} P^{Der}_{r,c,p,h} = \sum_{h}^{H} \mathsf{d}_h \quad (14)$$

$TC_{n,r,y}$ is the objective function and represents the total cost of production of commodity p by the combination of the RES technology res, the electrolyser H_2. hydrogen conversion process to a derivative Der, hydrogen compressor H_2comp, hydrogen storage H_2stor, derivative compressor $Dercomp$, derivative storage $Derstor$ and direct air capture plant for CO_2 production CO_2 in year y, country n and resource class r, defined by:

$$\begin{aligned} TC_{n,r,c,p,y} = \\ &+ \underbrace{(ic^{RES}_{y} * a_n + fom^{RES}_{y}) * Cap^{RES}_{n,r,c,p,y}}_{\text{RES cost}} + \underbrace{(ic^{H_2}_{y} * a_n + fom^{H_2}_{y}) * Cap^{H_2}_{n,r,c,p,y}}_{\text{Electrolysis cost}} \\ &+ \underbrace{(ic^{Der}_{y} * a_n + fom^{Der}_{y}) * Cap^{Der}_{n,r,c,p,y}}_{\text{Conversion cost}} + \underbrace{(ic^{H_2comp}_{y} * a_n + fom^{H_2comp}_{y}) * Cap^{H_2comp}_{n,r,c,p,y}}_{H_2 \text{ compressor cost}} \\ &+ \underbrace{(ic^{H_2stor}_{y} * a_n + fom^{H_2stor}_{y}) * Cap^{H_2stor}_{n,r,c,p,y}}_{H_2 \text{ storage cost}} + \underbrace{(ic^{Dercomp}_{y} * a_n + fom^{Dercomp}_{y}) * Cap^{Dercomp}_{n,r,c,p,y}}_{\text{Derivative compressor cost}} \\ &+ \underbrace{(ic^{Derstor}_{y} * a_n + fom^{Derstor}_{y}) * Cap^{Derstor}_{n,r,c,p,y}}_{\text{Derivative storage cost}} + \underbrace{(ic^{CO_2}_{y} * a_n + fom^{CO_2}_{y}) * Cap^{CO_2}_{n,r,c,p,y}}_{\text{Direct air capture cost}} \end{aligned} \quad (15)$$

In the cost components shown in the *Country-to-country analysis sheet*, RES costs are allocated as electricity costs to the electricity-consuming processes in proportion to their electricity consumption.

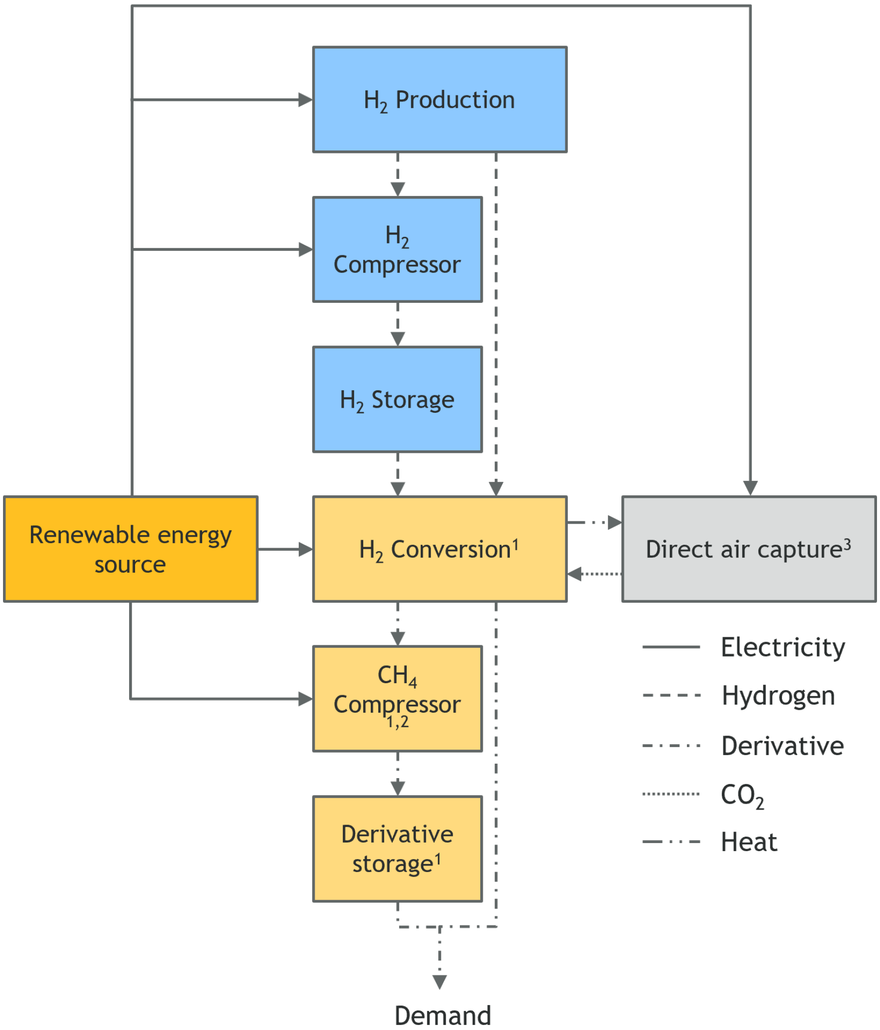

Figure 3: Flowsheet of the modelled integrated production system.
[1]Only active if a hydrogen derivative is the product. [2]Only active if methane is the product. [3]Only active if methane, methanol or FT-Fuel is the product.

Sets		
$r \in R$		Renewable energy source
$c \in C$		Renewable energy class
$p \in P$		Power-to-X technology
$y \in Y$		Year
$h \in H$		Hour
Parameters		
d_h	MWh	Hourly demand
wacc_n	-	Weighted average cost of capital
$textl$	years	technology lifetime
a_n	1/yr	annuity factor
$\mathrm{cf}_{n,r,c,h}$	-	hourly capacity factor profile of renewable energy class
η_y^H	MWh H_2 / MWh el	Energy efficiency of the electrolyzer
$\eta_{p,y}^{Der}$	MWh derivative / MWh H_2	Hydrogen to derivative conversion efficiency
$\mathrm{e}_{p,y}^{Der}$	MWh el / MWh derivative	Specific electricity demand of the hydrogen conversion plant
$\mathrm{e}_{p,y}^{CO}$	MWh el / t CO_2	Specific electricity demand of the direct air capture plant
e_y^{Hstor}	MWh el / MWh H_2	Specific electricity demand of the hydrogen storage compressor
$\mathrm{e}_y^{Derstor}$	MWh el / MWh H_2	Specific electricity demand of the derivative storage compressor
$\mathrm{m}_{p,y}^{Der}$	t CO_2 / MWh derivative	Specific CO_2 demand of hydrogen conversion plant
$\mathrm{ic}_{n,r,y}^{RES}$	TUSD/MW el	Specific investment cost of the renewable energy source
$\mathrm{ic}_{n,y}^{H2}$	TUSD/MW el	Specific investment cost of the electrolyzer
$\mathrm{ic}_{n,y}^{comp}$	TUSD/MW el	Specific investment cost of a compressor
$\mathrm{ic}_{n,y}^{Hstor}$	TUSD/MWh H_2	Specific investment cost of a hydrogen storage tank
$\mathrm{ic}_{n,p,y}^{Der}$	TUSD/MW derivative	Specific investment cost of the hydrogen conversion plant
$\mathrm{ic}_{n,p,y}^{Derstor}$	TUSD/MWh derivative	Specific investment cost of the derivative storage tank
$\mathrm{ic}_{n,p,y}^{CO}$	TUSD/(t CO_2/h)	Specific investment cost of the direct air capture plant
$\mathrm{fom}_{n,r,y}^{RES}$	TUSD/MW el/yr	Fixed operation and maintenance cost of the renewable energy source
$\mathrm{fom}_{n,y}^{H2}$	TUSD/MW el/yr	Fixed operation and maintenance cost of the electrolyzer
$\mathrm{fom}_{n,y}^{comp}$	TUSD/MW el/yr	Fixed operation and maintenance cost of a compressor
$\mathrm{fom}_{n,y}^{Hstor}$	TUSD/MWh H_2/yr	Fixed operation and maintenance cost of a hydrogen storage tank
$\mathrm{fom}_{n,p,y}^{Der}$	TUSD/MW derivative/yr	Fixed operation and maintenance cost of the hydrogen conversion plant
$\mathrm{fom}_{n,p,y}^{Derstor}$	TUSD/MWh derivative/yr	Fixed operation and maintenance cost of the derivative storage tank
$\mathrm{fom}_{n,p,y}^{CO}$	TUSD/(t CO_2/h)/yr	Fixed operation and maintenance cost of the direct air capture plant
Variables		
$Cap_{n,r,c,p,y}^{RES}$	MW el	Installed renewable energy source power generation capacity
$Cap_{n,r,c,p,y}^{H}$	MW el	Installed hydrogen production capacity
$Cap_{n,r,c,p,y}^{Hcomp}$	MW el	Installed hydrogen compressor capacity
$Cap_{n,r,c,p,y}^{Hstor}$	MWh H_2	Installed hydrogen storage capacity
$Cap_{n,r,c,p,y}^{Der}$	MWh/h H_2	Installed hydrogen-to-derivative conversion capacity
$Cap_{n,r,c,p,y}^{Dercomp}$	MW el	Installed derivative compressor capacity
$Cap_{n,r,c,p,y}^{Derstor}$	MWh derivative	Installed derivative storage capacity
$Cap_{n,r,c,p,y}^{CO}$	t/h	Installed CO_2 production capacity
$P_{r,c,p,h}^{H}$	MWh/h	Hydrogen production at hour h
$P_{r,c,p,h}^{Der}$	MWh/h	Derivative production at hour h
$P_{r,c,p,h}^{CO}$	t/h	CO_2 production at hour h
$S_{r,c,p,h}^{H}$	MWh	Hydrogen storage volume at hour h
$Sin_{r,c,p,h}^{H}$	MWh/h	Hydrogen storage inflow at hour h
$Sout_{r,c,p,h}^{H}$	MWh/h	Hydrogen storage withdrawal at hour h
$S_{r,c,p,h}^{Der}$	MWh	Derivative storage volume at hour h
$Sin_{r,c,p,h}^{Der}$	MWh/h	Derivative storage inflow at hour h
$Sout_{r,c,p,h}^{Der}$	MWh/h	Derivative storage withdrawal at hour h

3.2 Calculation of weighted average cost of capital

We calculate the country-specific weighted average cost of capital for Power-to-X projects in the origin countries by:

$$WACC_c = DR_c * cost\,of\,debt_c + (1 - DR_c) * cost\,of\,equity_c \tag{16}$$

The DR_c is the debt rate of the Power-to-X project investment in the origin country and varies between advanced and developing economies. We calculate the $cost\,of\,debt_c$ for Power-to-X projects in the origin countries by:

$$cost\,of\,debt_c = BIR + CRP_{debt,c} + TRP \tag{17}$$

The BIR states for the base interest rate and is derived from the yield curve of AAA rated government bonds for the United States. $CRP_{debt,c}$ states for the country risk premium for debt capital and is calculated based on the Moody's rating for each origin country as shown by Damodaran (2024). An average credit default swap (CDS) spread is calculated for every Moody's rating and then assigned to every country. The difference of the CDS spread and the US CDS spread then reflects the country risk premium for debt capital. The TRP states for the technology risk premium as the Power-to-X value chain is still on a early stage. The $cost\,of\,equity_c$ is calculated by:

$$cost\,of\,equity_c = BIR + CRP_{equity,c} + TRP + ERP \tag{18}$$

The base interest rate and technology risk premium are calculated as in the costs of debt. For the country risk premium for equity, the country risk premium for debt capital is multiplied with the relative equity market volatility as shown in Damodaran (2024). The ERP states for the equity risk premium which is derived from the S&P 500.

All values and sources can be found in Table 1.

Parameter	Value	Source
Risk-free rate	4.46 %	Risk free rate in the US in Jan 2024 (Fenebris, 2024)
Country risk premium	country-specific	Damodaran (2024)
Debt ratio	64-67 %	For low-carbon generation (IEA, 2023a)
Equity risk premium	4.7 %	Damodaran (2024)
Technology risk premium	4 %	IRENA (n.d.)

Table 1: Assumptions for the calculation of country-specific weighted average costs of capital for hydrogen projects.

3.3 Transport of hydrogen or derivatives

Transportation costs are calculated ex post to the production costs, depending on the selected supply routes in the tool. In general, all possible transportation methods can be analyzed in the *country-to-country-analysis* sheet, whereas only the supply costs of the cheapest transportation methods are displayed on the *global analysis* sheet. We designate the capital of the origin country as the starting point of transportation and the capital of the destination country as the final destination.

The following transportation methods for the following commodites are analyzed in the tool. The commodities reflect the end product for the customer and are at the beginning of the list. The transportation methods describe how the commodities get from origin to destination and are listed after each commodity.

- **Hydrogen**: Hydrogen pipeline, hydrogen shipping (via LH_2), hydrogen shipping (via ammonia) and hydrogen shipping (via LOHC)
- **Ammonia**: Ammonia pipeline and ammonia shipping
- **Methane**: Methane pipeline and methane shipping (via LSNG)
- **Methanol**: Methanol pipeline and methanol shipping
- **Fischer-Tropsch-Fuel**: FT-Fuel pipeline and FT-Fuel shipping

All resulting transportation chains can be seen in figure 4.

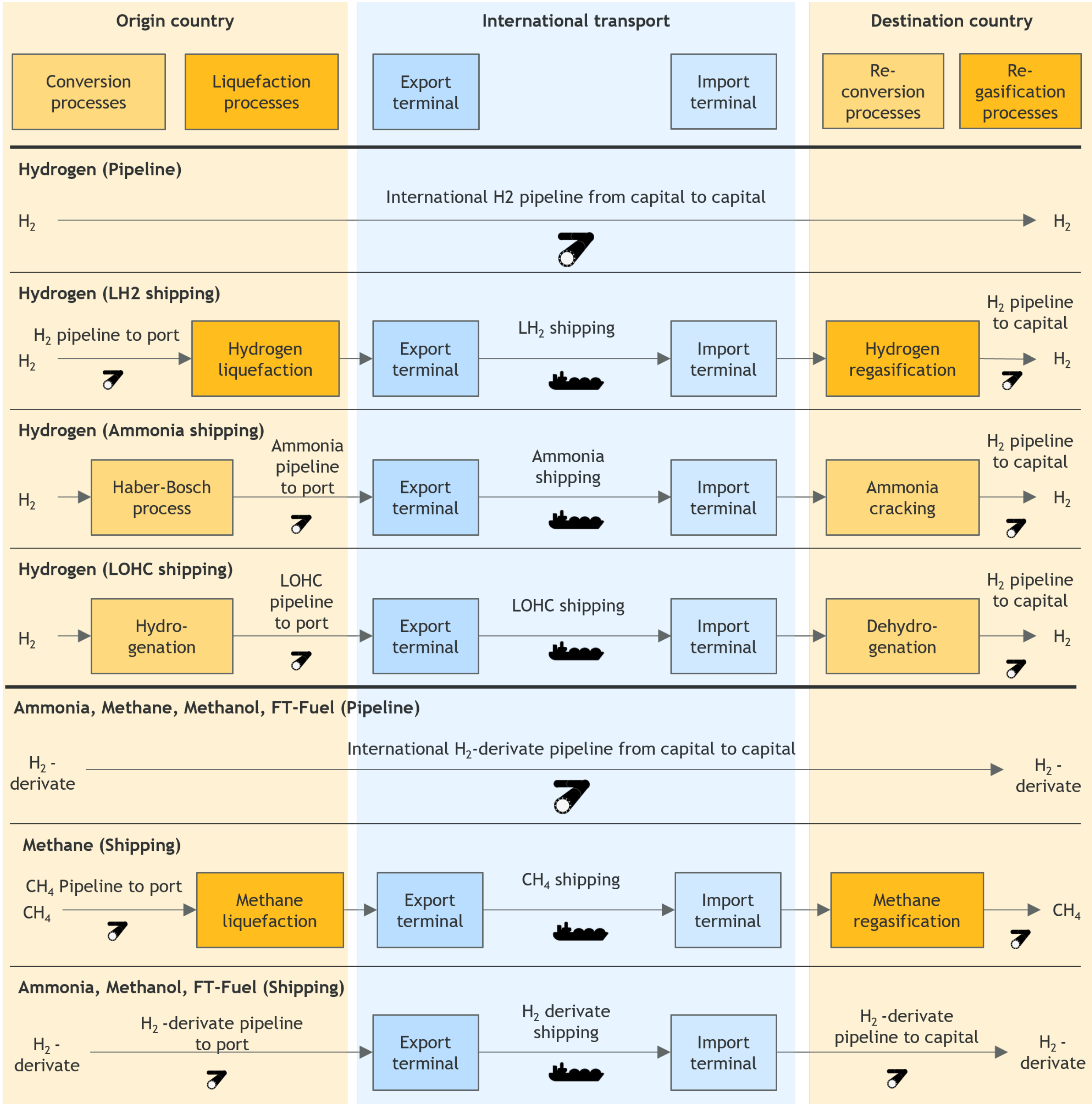

Figure 4: Visualization of transportation methods in the model.

We calculate the total transportation costs $C^{transp}_{c,tm,dp,od}$ for every commodity c, every transportation method tm, every delivery profile dp from every origin country to every destination country od. The delivery profile can be *baseload* or *volatile*. The transportation costs are calculated in $USD/MWh\, end\, product$.

In the following equations, the commodities hydrogen, ammonia, methane, methanol, and FT-Fuel are abbreviated to H_2, NH_3, CH_4, MeOH, and ftfuel. For hydrogen, the transportation methods hydrogen pipeline, hydrogen shpping (via LH_2), hydrogen shpping (via ammonia), and hydrogen shipping (via LOHC) are abbreviated to pipe, LH_2, NH_3, and LOHC. For all other commodities, the transportation methods shipping and pipeline are abbreviated to ship and pipe. The total transportation costs are calculated by:

$$C^{transp}_{c,tm,dp,od} = C^{conv}_{c,tm,dp,od} + C^{liq}_{c,tm,dp,od} + C^{ship}_{c,tm,dp,od} + C^{recon}_{c,tm,dp,od} + C^{regas}_{c,tm,dp,od} + C^{pipe}_{c,tm,dp,od} + C^{losses}_{c,tm,dp,od} \tag{19}$$

$C^{conv}_{c,tm,dp,od}$ are conversion costs which may be required before transportation and are calculated by:

$$C^{conv}_{c,tm,dp,od} = \begin{cases} 0, & \text{if } c = \text{NH}_3, \text{CH}_4, \text{MeOH}, \text{FT-fuel} \\ 0, & \text{if } c = \text{H}_2 \text{ and } tm = \text{pipe}, \text{H}_2 \\ \frac{ic^{conv}_{H_2,tm,o} * a_o + fom^{conv}_{H_2,tm,o}}{util^{conv}_{H_2,tm,dp,o}} + c^{conv,el}_{H_2,tm,dp,o}, & \text{if } c = \text{H}_2 \text{ and } tm = \text{NH}_3, \text{LOHC} \end{cases} \tag{20}$$

For the hydrogen derivates ammonia, methane, methanol, and T-Fuel the costs for the conversion from hydrogen to the derivate are already included in the production costs and not allocated to the transportation costs. If hydrogen is transported by pipeline or LH_2, no conversion processes are required. If hydrogen is transported via ammonia shipping the Haber-Bosch process is required to convert hydrogen to ammonia. If hydrogen is transported via LOHC shipping a hydrogenation process is required. For both cases, the conversion costs consist of investment costs $ic^{conv}_{H_2,tm,o}$, fixed operations and maintenance costs $fom^{conv}_{H_2,tm,o}$, and electricity costs $c^{conv,el}_{H_2,tm,dp,o}$. $ic^{conv}_{H_2,tm,o}$ and $fom^{conv}_{H_2,tm,o}$ depend on country specif labor costs and vary between the origin coutries o. $ic^{conv}_{H_2,tm,o}$ are multiplied with the annuity a_o which is dependent on the WACC in the origin country. It is assumed that the conversion process takes place at the hydrogen production site. Therefore, the utilization $util^{conv}_{H_2,tm,dp,o}$ and the electricity costs $cc^{conv,el}_{H_2,tm,dp,o}$ are defined by the optimization model which is described in section 3.1.

$C^{liq}_{c,tm,dp,od}$ are the liquefaction costs which may be required before transportation and are calculated by:

$$C^{liq}_{c,tm,dp,od} = \begin{cases} \frac{ic^{liq}_{H_2,LH_2,o} * a_o + fom^{liq}_{H_2,LH_2,o}}{util^{liq}_{H_2,LH_2,dp,o}} + c^{liq,el}_{H_2,LH_2,o}, & \text{if } c = \text{H}_2 \text{ and } tm = \text{LH}_2 \\ \frac{ic^{liq}_{CH_4,ship,o} * a_o + fom^{liq}_{CH_4,ship,o}}{util^{liq}_{CH_4,ship,dp,o}} + c^{liq,el}_{CH_4,ship,o}, & \text{if } c = \text{CH}_4 \text{ and } tm = \text{ship} \\ 0, & \text{otherwise} \end{cases} \tag{21}$$

A separate liquefaction process is only necessary if hydrogen is transported via LH_2 shipping or methane is transported via shipping. As the transportation from the production site to the port in a gaseous state might be beneficial, the liquefaction takes place at the export terminal and not at the hydrogen production site. Country-specific parameters, such as labor costs, affecting investment costs, refer to the country where the export terminal is located which is in most cases identical to the origin country. Therefore, the liquefaction costs are calculated independently of the optimization model which defines the production and conversion costs. As a result, the utilization and the electricity costs of the liquefaction process are not dependent on the production process. The utilization for the baseload delivery profile is constant within the year.

The utilization of the volatile delivery profile varies within the year and achieves its maximum in the month where the most hydrogen is produced. The average utilization of the year is used for the cost calculation. The electricity costs are a product of the electricity consumption for liquefaction and the electricity price. The electricity price is a price for baseload renewable electricity in the country where the export terminal is located.

$C^{ship}_{c,tm,dp,od}$ are the shipping costs which are incurred for every maritime route:

$$C^{ship}_{ship,c,tm,dp,od} = \begin{cases} 0, & \text{if } tm = \text{pipe} \\ \underbrace{(t_{time,od} * f_{cons} * f_{price}}_{\text{fuel costs}} + \underbrace{(t_{time_{od}} + w_{time}) * cr_{c,tm}}_{\text{charter costs}} \\ + \underbrace{c_{term} + c_{ref})}_{\text{terminal costs}} * \underbrace{\frac{1}{cap_{c,tm}}}_{\text{ship capacity}} * \underbrace{2}_{\text{shuttle}} + \underbrace{c^{tol}_{c,tm}}_{\text{LOHC costs}}, & \text{otherwise} \end{cases} \tag{22}$$

The shipping costs include fuel costs, charter costs, terminal costs, and, in the case of hydrogen transportation via LOHC shipping, LOHC costs. Fuel costs and Charter costs are dependent on the travel time $t_{time,od}$ between the export and import terminal which is a product of the distance and the shipping speed. f_{cons} stands for the daily fuel consumption and f_{price} for the corresponding fuel price. We use green methanol as shipping fuel. The charter costs are the product of the daily charter rate $cr_{c,tm}$ and the total charter time. The *daily charter rate* for LPG-tanker (in the case of ammonia shipping), LNG-tanker (methane shipping) and oil-tanker (ethanol, FT-fuel, and LOHC shipping) are derived from historical data and can be varied in scenarios. For LH_2 shipping, a technology premium is added to the LNG charter rate. The total charter time consists of the travel time and the waiting time which includes time for berthing (loading and unloading), as well as waiting times on the sea. Terminal costs include costs for terminal docking c_{term} and costs for refueling c_{ref}. All costs are divided by the shipping capacity $cap_{c,tm}$. The capacity is calculated based on Suez-max-tankers and the energy density of the transported commodities. The shipping costs are doubled as we assume a shuttle operation between the export and import terminal.

In the case of hydrogen transportation via LOHC shipping, toluene is hydrogenated with hydrogen to transport hydrogen in the form of hydrogenated LOHC as a liquid fuel. Therefore, the purchase of toluene is required in the case of hydrogen transportation via LOHC shipping which is accounted by $c^{tol}_{c,tm}$. The costs for the required toluene are a product of the toluene price and the possible LOHC cycles after the toluene is degraded. All other shipping routes do not require toluene.

$C^{recon}_{c,tm,dp,od}$ are the reconversion costs which may be required after transportation and are calculated by:

$$C^{recon}_{c,tm,dp,od} = \begin{cases} \frac{ic^{recon}_{H_2,tm,d} * a_d + fom^{recon}_{H_2,tm,d}}{util^{recon}_{H_2,tm}} + c^{recon,el}_{H_2,tm,d} + c^{recon,fuel}_{H_2,tm,dp,od}, & \text{if } c = \text{H}_2 \text{ and } tm = \text{NH}_3, \text{LOHC} \\ 0, & \text{otherwise} \end{cases} \tag{23}$$

A reconversion process is only required when hydrogen is the end product and transported in the form of ammonia shipping or LOHC shipping. The reconversion costs $C^{recon}_{c,tm,dp,od}$ then include investment costs $ic^{recon}_{H_2,tm,d}$, fixed operations and maintenance costs $fom^{recon}_{H_2,tm,d}$, electricity costs $c^{recon,el}_{H_2,tm,d}$, and fuel costs $c^{recon,fuel}_{H_2,tm,dp,od}$. $ic^{recon}_{H_2,tm,d}$ and $fom^{recon}_{H_2,tm,d}$ vary with the labor costs in the destination country d. Moreover, the annuity a_d varies with the WACC. A uniform utilization is assumed for both delivery profiles as the reconversion terminal in the destination country can also be used for other deliveries if the delivery profile is volatile. $c^{recon,el}_{H_2,tm,d}$ are a product of the electricity demand of the reconversion process and the price for baseload renewable electricity in the destination country. The required heat for the endothermic reconversion processes is provided by the combustion of hydrogen. The resulting fuel costs are derived from the hydrogen production costs, all transportation costs that occur before, and the efficiency of the combustion.

$C^{reg}_{c,tm,d}$ are the regasification costs which may be required after transportation and are calculated by:

$$C^{c,tm}_{c,tm,d} = \begin{cases} \frac{ic^{reg}_{H_2,LH_2,d} * a_d + fom^{reg}_{H_2,LH_2,d}}{util^{reg}_{H_2,LH_2,d}} + c^{reg,el}_{H_2,LH_2}, & \text{if } c = \text{H}_2 \text{ and } tm = \text{LH}_2 \\ \frac{ic^{reg}_{CH_4,ship,d} * a_o + fom^{reg}_{CH_4,ship,d}}{util^{reg}_{CH_4,ship,d}} + c^{reg,el}_{CH_4,ship,d}, & \text{if } c = \text{CH}_4 \text{ and } tm = \text{ship} \\ 0, & \text{otherwise} \end{cases} \tag{24}$$

A separate regasification process is only necessary if hydrogen is transported via LH_2 shipping or methane is transported via shipping. All cost components are analogous to the reconversion costs. However, no fuel is required for regasification resulting in fuel costs of zero.

$C^{pipe}_{c,tm,dp,od}$ are the costs for pipeline transportation and are calculated by:

$$C^{pipe}_{c,tm,dp,od} = \begin{cases} \underbrace{dist_{od} * \frac{ic^{pipe}_{c,tm} * a + fom^{pipe}_{c,tm} *}{util^{pipe}}}_{\text{international pipeline transport}}, & \text{if } tm = \text{pipe} \\ \underbrace{dist_o * \frac{ic^{pipe}_{c,tm} * a + fom^{pipe}_{c,tm} *}{util^{pipe}_{c,tm,dp,o}}}_{\text{capital to port origin country}} + \underbrace{dist_d * \frac{ic^{pipe}_{c,tm} * a + fom^{pipe}_{c,tm} *}{util^{pipe}}}_{\text{port to capital destination country}}, & \text{otherwise} \end{cases} \tag{25}$$

In the case of transportation via pipeline, the pipeline costs are the cost for the international pipeline transport between the capitals of the origin and destination country. For all maritime transportation routes, the pipeline costs are the costs for the pipeline transport between the capital and the port of the origin and the destination country. The transportation distance for international pipeline transport is derived from the existing natural gas pipeline network. It is assumed that new pipelines are constructed near existing natural gas pipelines and that no international pipeline transport will be possible if there are currently no natural gas pipelines between the countries. Transport to a shipping terminal is always possible.

We assume three investment cost scenarios for the construction of hydrogen pipelines to vary the investment costs $ic^{pipe}_{H_2,tm}$ (see section 4.5.1). The annuity a is based on the WACC for pipeline investments and pipeline lifetime. Fixed operations and maintenance costs $fom^{pipe}_{c,tm}$ include operations and maintenance costs for the pipeline and the compressor. We assume a uniform utilization of the pipeline $util^{pipe}$ for international pipeline transport and pipeline transport in the transportation country. If the delivery profile is *volatile*, we assume a maximum utilization for the month with the highest production and then calculate the average utilization for the cost calculation in the origin country. In the case of hydrogen transportation via ammonia shipping or LOHC shipping, we assume the pipeline transport of ammonia and LOHC in the origin country, as the reconversion process takes place at the production site. For all other cases, we calculate the pipeline transportation costs of the commodity itself.

$C^{losses}_{c,tm,dp,od}$ are the costs accounted for losses that occur during transportation. We consider losses during the transportation of hydrogen via pipeline, during hydrogen liquefaction, and boil-off losses during LH_2 shipping, ammonia shipping, and methane shipping. Hydrogen pipeline losses occur during compression and are defined by the distance between hydrogen compressors and the losses during compression. Hydrogen liquefaction losses are defined by the flash rate of the liquefaction. Boil-off losses are defined by the daily boil-off gas rate and the total traveling time between the origin and destination country. The loss costs include the costs for additional production and all processes including their losses until the losses occur.

Moreover, we calculate the total transportation costs for a *greenfield* and a *brownfield scenario*. The *greenfield scenario* includes all transportation costs. The *brownfield scenario* does not include investment cost components for all parts of the transportation value chain.

3.4 Calculation of weighted average costs

We estimate country-specific costs for a commodity's discrete production or import volume V by calculating a weighted average of the resource classes. Equation 26 shows the calculation of a weighted average production costs $\overline{PC}_V$.

$$\overline{PC}_V = \frac{\sum_{r \in R} PC_r P_r}{\sum_{r \in R} P_r} \tag{26}$$

$$P_r \leq \hat{P}_r - P_{e_r} \tag{27}$$

$$\sum_{r \in R} P_r = V \tag{28}$$

, where R is the set of resource classes, P_r is the allocated potential, $\hat{P}_r$ is the maximal potential of class r and PC$_r$ are the levelized production costs of class r in the respective country. P_r is allocated to the RES-classes starting with the RES-class with the lowest production costs, ascending until the conditions in equations 27 and 28 are met. Weighted averages for supply costs are calculated in the same fashion. Moreover, we assume that countries prior their RES potentials for their electricity demand. Thus, RES potentials with the lowest production costs are used for covering a country's electricity demand D. We allocate potentials to cover the electricity demand P_{e_r} to resource classes starting with the class with the lowest production costs, ascending while conditions of equations 29 and 30 must hold.

$$P_{e_r} \leq \hat{P}_r \tag{29}$$

$$\sum_{r \in R} P_{e_r} = D \tag{30}$$

4 Input parameters

This chapter shows how the input parameters for the modelling of the production and transport costs were derived.

4.1 Renewable energy sources

Renewable energy sources are classified in an approach adopted from Brändle et al. (2021). PV and wind onshore potentials are classified by their capacity factor. The capacity factor drives the LCOE and is a measure of the suitability of a location for RES. Wind offshore potentials are classified by the water depth, as the depth drives the investment costs, as Figure 5 shows. We exclude potentials below certain capacity factor thresholds or, in the case of wind offshore, above a water depth of 60 m because production from these potentials would hardly be economical. Country-level PV capacity factors and potentials (installable capacity) are taken from Pietzcker et al. (2014). Remote potentials with a distance of more than 50 km to the next settlement are excluded. Capacity factors and potentials for wind onshore are taken from Bosch et al. (2017). Capacity factors and potentials by water depth for wind offshore are taken from Bosch et al. (2018).

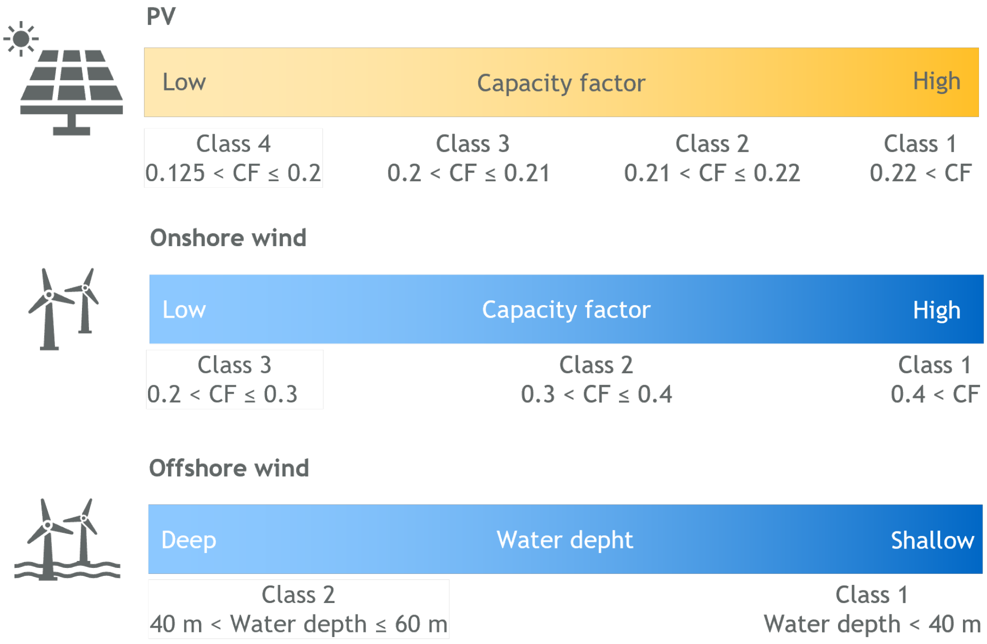

Figure 5: Classification of RES potentials.

In this analysis, the RES potential is the technical production potential. The technical potential reflects the maximum achievable production potential, considering technical constraints. It often represents an upper limit. The actual market potential might be lower due to practical, economic, social and policy-related constraints.

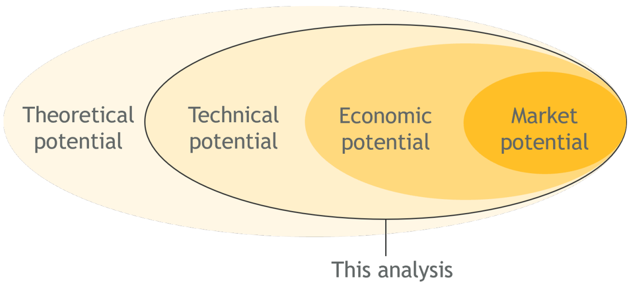

Figure 6: Classification of potentials.

We construct country-specific synthetic hourly capacity factor profiles over a full year for each RES class by the following steps: First, we choose a location in the respective country using Gobal-Wind-Atlas (2024) and Gobal-Solar-Atlas (2024), where the annual capacity equals the average capacity factor of all classes of a RES type (PV, wind onshore or wind offshore). Second, hourly capacity profiles for these locations are taken from Ninja[2]. Third, we scale the real profiles to get a synthetic profile for each RES class, which has the same annual capacity factor as the potential of this class. Details on the scaling procedure can be found in Brändle et al. (2021). Finally, we set the capacity factor to zero in all hours when it is less than 1 % to improve the

[2]Hourly are based on weather data of 2019. For wind onshore and offshore, profiles are taken for a hub height of 100 m

performance of the optimization model.

There is a large body of literature on investment cost projections. We develop two cost scenarios to be able to show a range of possible developments. The *baseline* scenario assumes a weaker investment cost degression and is in the middle to upper range of the scenarios found in the literature. The *optimistic* scenario assumes a stronger investment cost degression and is in the lower range of the scenarios found in the literature. The scenarios are constructed using a learning rate approach:

$$IC = IC_0\left(\frac{C}{C_0}\right)^{-LR} \tag{31}$$

IC_0 are the average investment costs from the literature, and C_0 is the cumulative deployment of a technology in the year 2022. C is the cumulative deployment in the future, where *baseline* refers to the STEPS scenario and *optimistic* refers to the NZE scenario from IEA (2023). Learning rates are varied within ranges found in the literature to construct the scenarios. Figure 7 shows the RES investment cost scenarios for Europe in relation to scenarios from the literature.

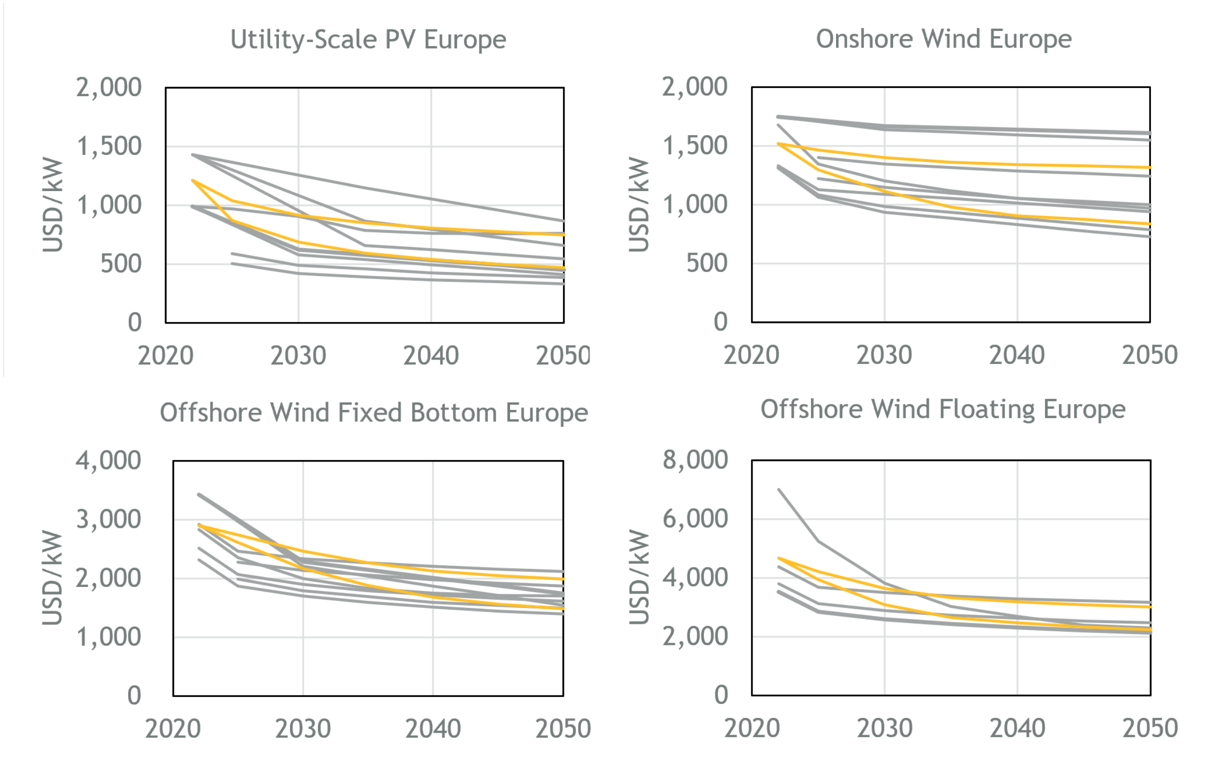

Figure 7: RES investment cost scenarios. The upper golden line refers to the baseline scenario, the lower golden line refers to the optimistic scenario. Grey lines refer to scenarios found in literature (IEA, 2023; DNV, 2023; NREL, 2023; ENTSOG & ENTSO-E, 2022)

RES investment costs vary between countries due to differences in labour costs and exchange rates (IRENA, 2020b). DNV (2023) differentiates RES investment costs by region. We use the RES investment costs for Europe and the cost factor between Europe and other world regions to construct region-specific RES investment costs [3]. Table 2 shows the regional RES investment

[3] The regional factors in DNV (2023) vary slightly over time. For simplicity, we assume the factors of the year 2024

costs in relation to Europe.

Region	Wind onshore	Wind offshore fixed-bottom	Wind offshore floating	PV
EUR	1	1	1	1
NAM	1.17	1.57	1.42	0.96
LAM	0.97	1.43	1.33	0.84
MEA	0.85	1.43	1.35	0.80
NEE	0.90	1.43	1.35	0.81
CHN	0.50	0.79	0.87	0.71
IND	0.69	1.23	1.33	0.67
SEA	0.77	1.43	1.33	0.74
OPA	1.06	1.43	1.16	0.95
SSA	1.12	1.42	1.35	1.00

Table 2: Regional RES investment cost factors in relation to Europe.

4.2 Hydrogen production

We consider hydrogen production by water electrolysis. Among existing water electrolysis types, we focus on alkaline (AEL) and proton-exchange-membrane electrolyzers (PEMEL) as they are mature technologies. Both electrolyzer types are projected to have similar investment costs and energy efficiencies. Therefore, we do not distinguish between AEL and PEMEL and speak of both as low-temperature electrolysis.

For the estimation of the electrolyzer investment cost development, we split the investment costs into investment costs for the stack and the balance of plant (BOP). We use Fraunhofer ISE (2021) for the starting value in 2020 and apply learning rates according to IEA (2023b). The stack benefits from higher learning rates than the BOP. Moreover, we assume cost reductions due to economies of scale for the BOP and a labor costs share of 20% (see next chapter for the explanation of the economies of scale and labor cost calculation). The resulting investment costs and values from the literature can be found in figure 8.

for all years of our analysis.

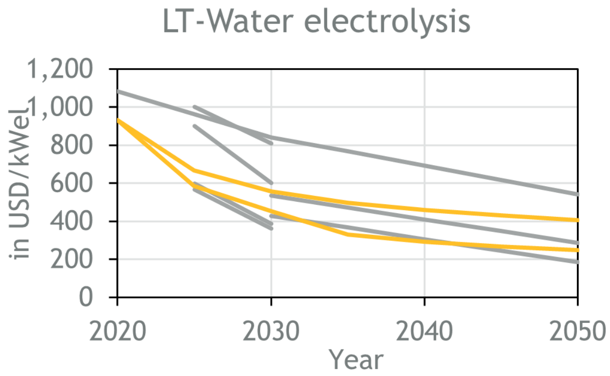

Figure 8: Specific investment costs of low-temperature water electrolysis over time. The upper golden line refers to the baseline scenario, the lower golden line refers to the optimistic scenario. Grey lines refer to scenarios found in literature (IRENA, 2020a; Fraunhofer ISE, 2021; Reksten et al., 2022; IEA, 2023b)

4.3 Hydrogen conversion

We assume that the specific investment cost degression over time for conversion processes is mainly due to scale effects. The typical scale of plants is expected to increase over time due to the market ramp-up for synthetic fuels. We estimate the scale effects on the investment costs by the seven-tenth rule:

$$IC_{\text{plant A}} = IC_{\text{plant B}} \left(\frac{C_{\text{plant A}}}{C_{\text{plant B}}} \right)^{0.7} \tag{32}$$

, where IC are the investment costs and C is the plant capacity (Couper et al., 2007). Figure 9 shows the specific investment costs depending on the plant capacity of hydrogen conversion plants in relation to values found in the literature. We assume that the typical plant capacity increases from 50 MW_{product} in 2025 to 250 MW_{product} in 2050 in the baseline scenario and from 100 MW_{product} to 1,000 MW_{product} in the optimistic scenario. A capacity of 1,000 MW_{product} corresponds to 10 % of an average refineries' capacity in the present (McKinsey, 2021) and is chosen based on the authors' assessment that the global production of synthetic fuels is unlikely to reach the scale of present-day fossil fuel production. The resulting specific investment cost curves over time for the *baseline* and *optimistic* scenario can be found in Figure 10.

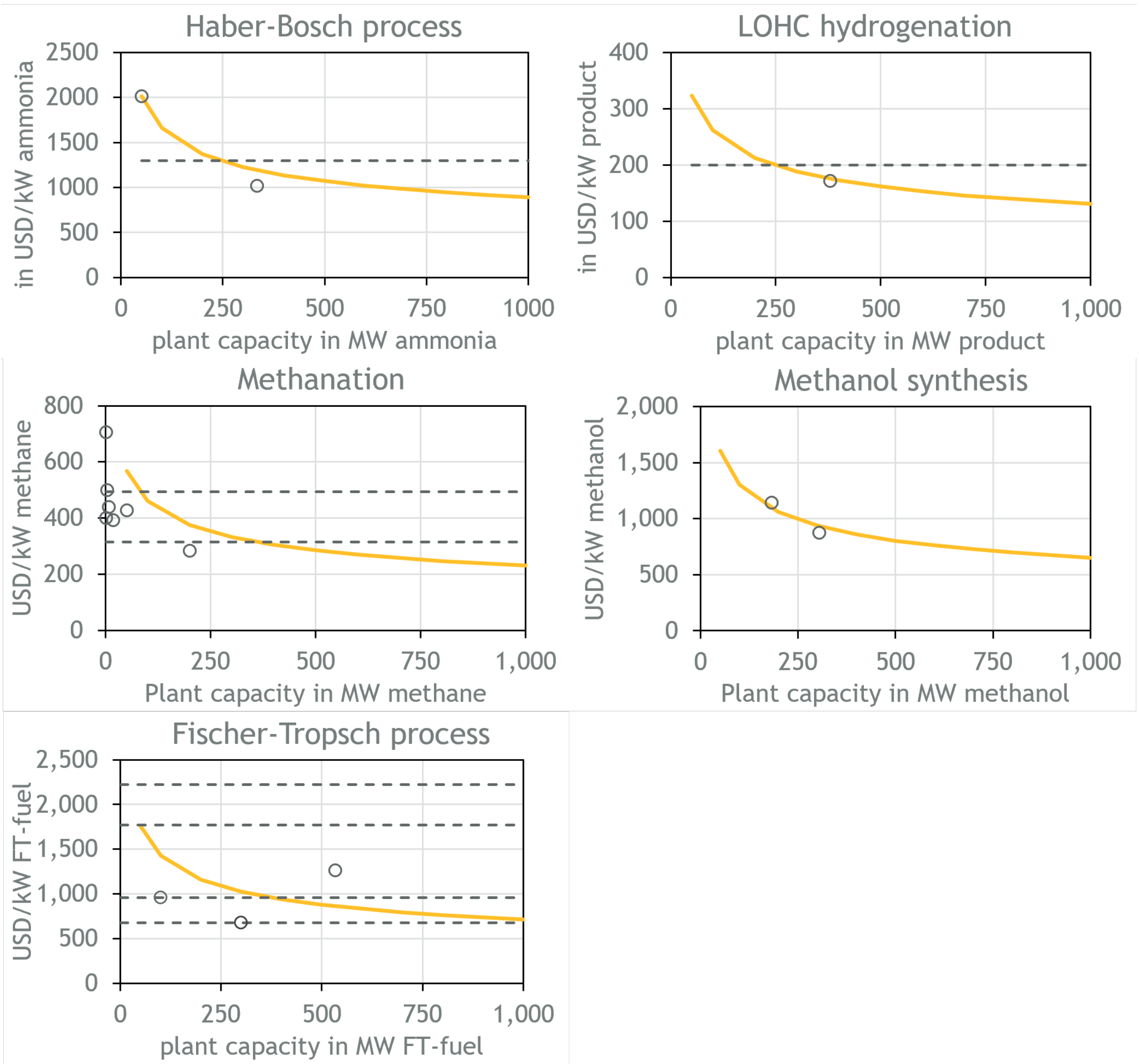

Figure 9: Specific investment costs of conversion processes depending on the plant capacity in relation to literature values. Golden lines represent our assumption. Dashed lines represent values from sources which did not provide a plant capacity. The data is taken from Moritz et al. (2020); IEA (2023); Ortiz Cebolla et al. (2022); Brynolf et al. (2018); EWI (2021); Götz et al. (2016); Gorre et al. (2019); Lehner et al. (2014); Grond & Holstein (2014); Hannula & Kurkela (2013); Pérez-Fortes et al. (2016); Kreutz et al. (2020).

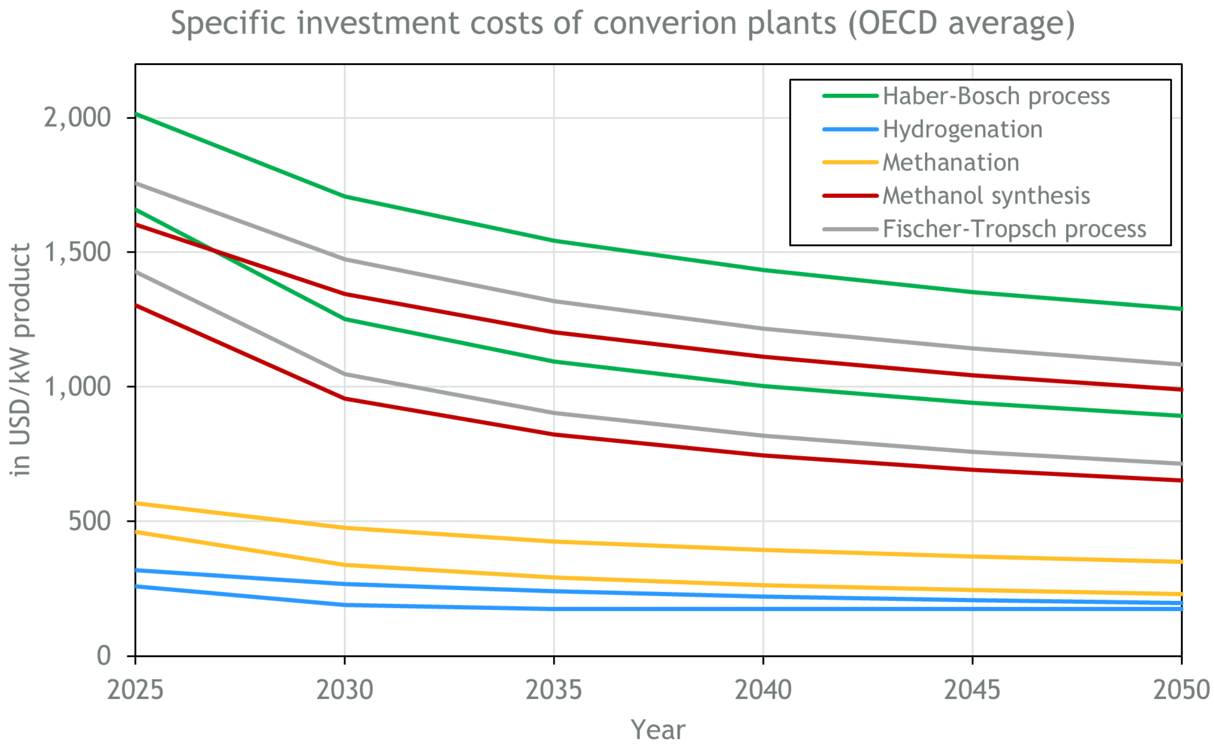

Figure 10: Specific investment costs of conversion processes over time. The upper lines of each colour refer to the baseline scenario, and the lower lines refer to the optimistic scenario. The costs refer to countries with the average labour costs of the OECD. Investment costs differ in countries with different labour costs.

The investment costs found in the literature are from authors based in OECD countries. Therefore, we assume that the reported investment costs are valid for OECD countries. The investment costs of a plant consist, among others, of equipment and construction costs. A large fraction of the construction costs are labor costs. According to Peters et al. (1991), labor costs typically account for 40 % of fixed capital investment costs in chemical plants. Based on this share and country-specific labor costs of industrial workers, we calculate country-specific investment costs by:

$$IC = IC_{OECD}\left((1-0.4)+0.4\frac{W}{\overline{W_{OECD}}}\right) \tag{33}$$

, where IC are investment costs and W are hourly wages of industrial workers with $\overline{W_{OECD}}$ representing the average wages across OECD countries. Country-specific wages are taken from Schröder (2019). For countries, we could not find data on wages, we synthetically generate data using a regression of the hourly wages over a country's GDP per capita and assuming that the wages cannot get higher or lower than in the data provided by Schröder (2019). Figure 11 shows the original data on hourly wages, the synthetically generated data points, and the regression.

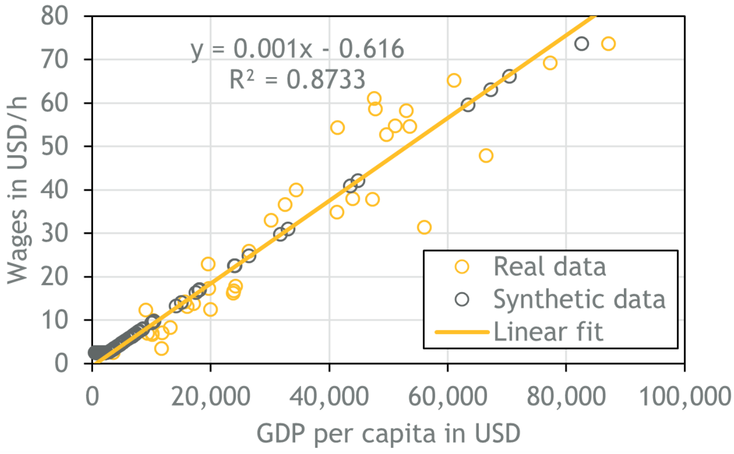

Figure 11: Hourly wages of industrial workers, depending on a country's GDP per capita. Golden markers represent data from Schröder (2019). The golden line is a linear regression through this data. Grey markers are synthetically generated data points based on the regression.

4.4 Direct air capturing

We use CO_2 Direct Air Capturing (DAC) as the carbon source for the hydrogen derivates methane, methanol, and FT-fuel. We use a solid DAC plant which requires heat at a medium temperature level slightly above 80-100°C, where the CO_2 is released during desorption (IEA, International Energy Agency, 2022). As the hydrogen derivate conversion processes release heat at higher temperature levels, we couple the DAC plant with the conversion plants to utilize waste heat. Only waste heat above the required temperature level that can not be utilized in the conversion processes itself can be utilized for the DAC process. The remaining heat is provided by an electric heat pump whose capacity is defined by the coupled conversion process. We calculate the DAC investment costs based on the levelized CO_2 capturing cost-breakdown shown in IEA, International Energy Agency (2022). For the cost development, we do not assume economies of scale effects but a learning rate of 15%. We calculate investment costs for the heat pump based on Pieper et al. (2018) and do not assume further cost reductions as we do not assume economies of scale effects for large-scale heat pumps after a certain threshold. The resulting investment costs for the integrated DAC plant including the heat pump for the baseline and optimistic scenario are shown in Figure 12.

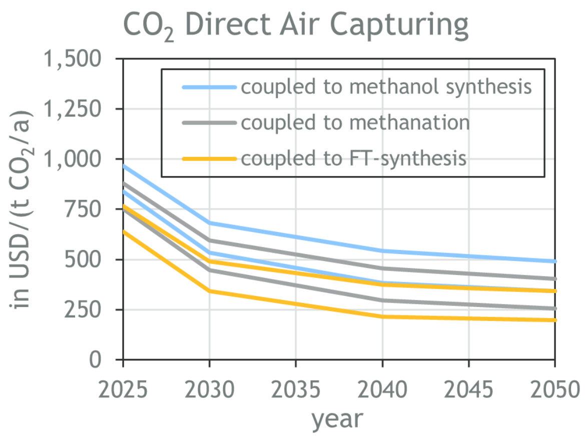

Figure 12: Investment costs of CO_2 Direct Air Capturing with integrated heat pump in the baseline and optimistic scenario (based on IEA, International Energy Agency (2022); Kreutz et al. (2020); Brynolf et al. (2018); Hannula & Kurkela (2013); Pieper et al. (2018))

The sorption material has to be changed regularly and is therefore not included in the investment costs leading to high operational costs. We assume annual fixed operational and maintenance costs of 36% of the investment costs based on IEA, International Energy Agency (2022). The required electricity for the ventilation and the heat pump is provided by the renewable heat sources built by the optimization model (see section 3). Moreover, we assume that 20% of the investment costs are country-specific labor costs and therefore adjust the investment costs for all origin countries according to their labor costs level.

4.5 Transport

This subsection covers the data and assumptions of the transport cost calculations, which include pipelines, regasification, liquefaction, and reconversion plants. In the case of hydrogen transportation via ammonia or LOHC shipping, conversion costs are also allocated to transportation costs. However, the input data of all conversion costs are already described in section 4.3.

4.5.1 Pipeline

We model pipeline transportation for hydrogen and all analyzed derivates. In the case of hydrogen pipeline transportation, we have three investment cost scenarios.*High cost new* has the highest costs and represents transport costs in newly constructed 700 mm pipelines. *Low cost new* has medium costs and represents transport costs in newly constructed 950 mm pipelines. *Retrofitted* has the lowest costs and represents transport costs in retrofitted natural gas pipelines. A hydrogen compressor for recompression is added for all three hydrogen pipelines. Investment costs for the pipeline and compressor are based on IEA (2023b). Fixed operational and maintenance costs are uniform and based on Brändle et al. (2021).

Investment costs for methane pipelines and pipelines for liquid fuels are based on Global Energy Monitor (2021). LOHC, methanol, and FT-Fuel are transported in liquid pipelines and the investment costs are adjusted to their volumetric energy density, respectively. In the case of LOHC, pipeline costs are doubled due to the toluene return. Ammonia pipeline transportation takes place at the gaseous state and investment costs are taken from the reference case shown in Galimova et al. (2023).

4.5.2 Regasification and Liquefaction

Analyzing data from Global Energy Monitor (2022), we find that investment costs for LNG regasification and liquefaction terminals do not show significant scale effects.[4] Hence, we assume constant specific investment costs, independent of the capacity (see Figure 13). The low scale effects might be due to the modular structure of LNG terminals. For instance, liquefaction terminals are often scaled up by building several parallel liquefaction trains instead of one large one. Data from collected by IRENA (2022) shows that hydrogen liquefaction shows scale effects for smaller-scale terminals. Almost no data is available for larger terminals. In analogy to LNG terminals, we assume constant specific investment costs for terminals larger than 300 MW H_2. Most sources in the literature do not specify capacity-related costs for hydrogen regasification terminals. Hence, we assume constant specific investment costs in analogy to methane regasification.

[4] A regression analysis of the absolute investment costs over the capacity shows that a linear function without intercept provides the fit with the lowest root mean squared error.

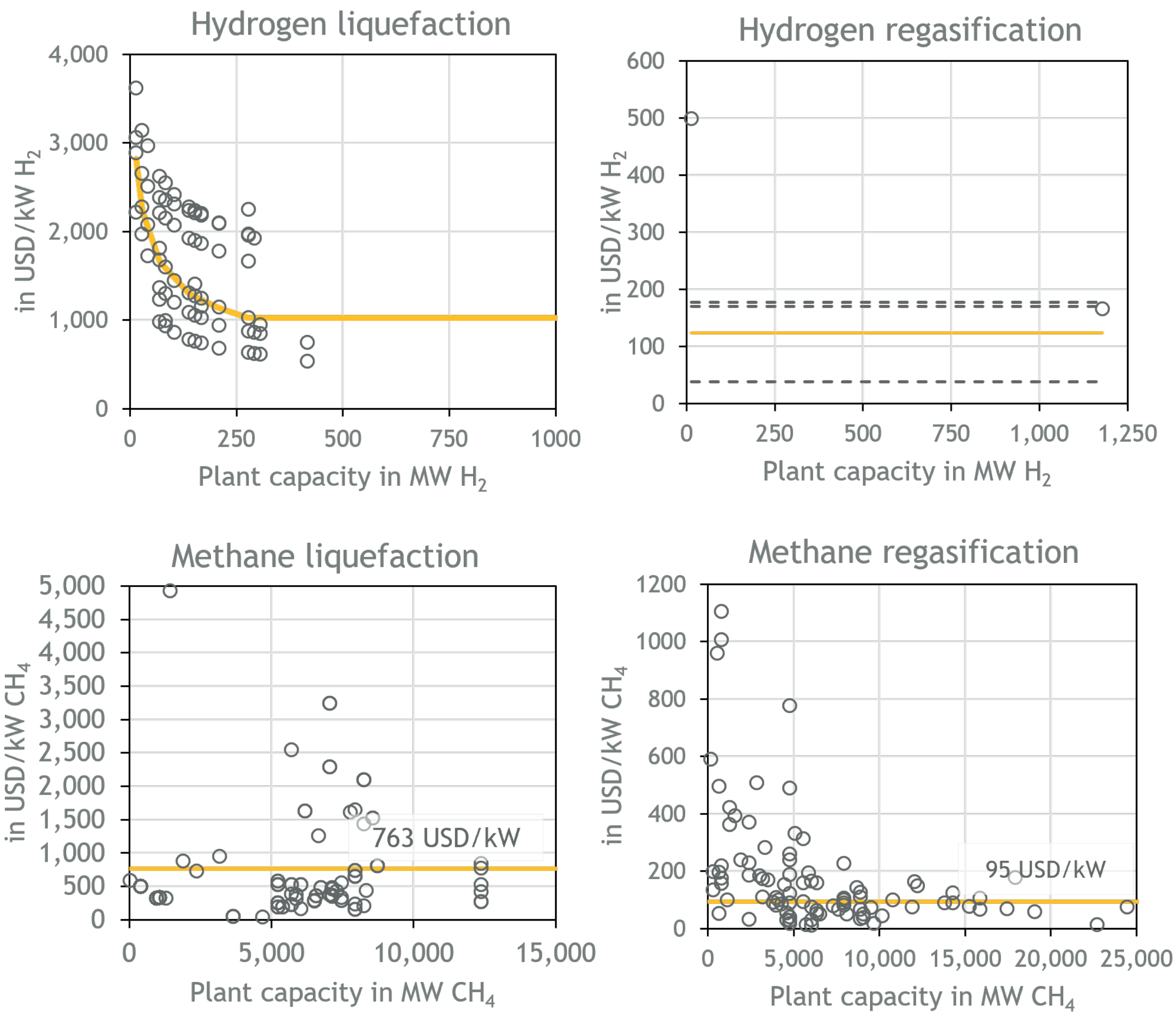

Figure 13: Investment costs of hydrogen and methane liquefaction and regasification depending on the terminal capacity. The data for hydrogen is taken from IRENA (2022), the data for methane is taken from Global Energy Monitor (2022).

4.5.3 Reconversion

We model reconversion to hydrogen in the case of ammonia shipping and LOHC shipping. In the case of ammonia shipping, ammonia cracking is required to retrieve hydrogen as the end product. In the case of LOHC shipping, a dehydrogenation process is required. As for conversion processes, we assume investment cost degressions due to economies of scale. We use the same path for capacity expansion as for conversion processes. Investment costs from the literature and our cost assumptions are shown in Figure 14.

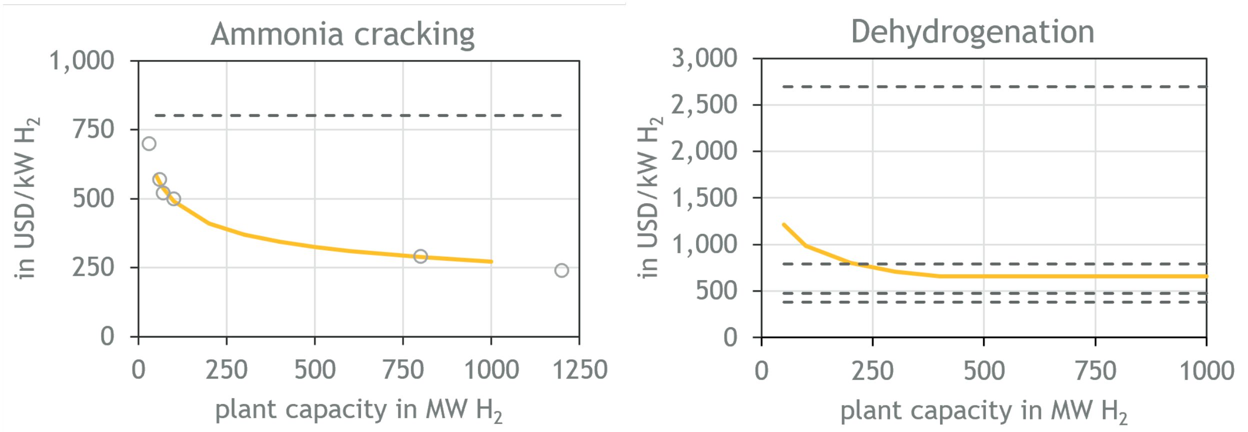

Figure 14: Specific investment costs of conversion processes depending on the plant capacity in relation to literature values. Golden lines represent our assumption. Dashed lines represent values from sources which did not provide a plant capacity. The data is taken from IEA (2023b); Cesaro et al. (2020); Ortiz Cebolla et al. (2022); IRENA (2022)

We assume 40% labor costs and adjust the investment costs to the labor cost level in the destination countries. Both processes are endothermic and therefore require heat for which we utilize hydrogen in a combustion process. We assume a heat demand of 0.22 kW_{th}/kW_{H2} for ammonia cracking and 0.34 kW_{th}/kW_{H2} for dehydrogenation based on **?**.

4.6 Further techno-economic parameters

Assumptions and sources for techno-economic parameters like mass and energy balances, efficiencies, fixed operations and maintenance costs, utilization or economic lifetime can be found in the Sheets *Techno-economics conversion*, *Techno-economics tarnsport*, *Techno-economics RES* and *Techno-economic storages*. Country-specific parameters like grid electricity prices, historical electricity consumption, or WACC can be found in the *Country-specific parameter* sheet. RES-potentials can be found in the *RES-potential* sheet.

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