Green Hydrogen Global Market Price Model

Methodology and Insights on Global Trade Flows and Market Prices for Green Hydrogen

FTI CONSULTING

The Purpose of the Model Is To Provide (1) a Price Benchmark for H_2 Market Players, (2) a Tool for investors to Quantify ROI, and (3) Identify Main Sensitivities To Price and Flows

OBJECTIVES OF THE MODEL

- Quantification of the green hydrogen price, based on a global equilibrium between supply and demand, integrating transport costs associated with globally-optimal routes

SCOPE OF WORK

- **Geographic:** Global scope with country-level resolution
- **Temporal:** Initial timeframe in 2030, which can be extended to 2050
- **Product definition**: Green hydrogen as defined in the EU's Delegated Acts to the Renewable Energy Directive II (incl. hourly matching of renewables with hydrogen production)

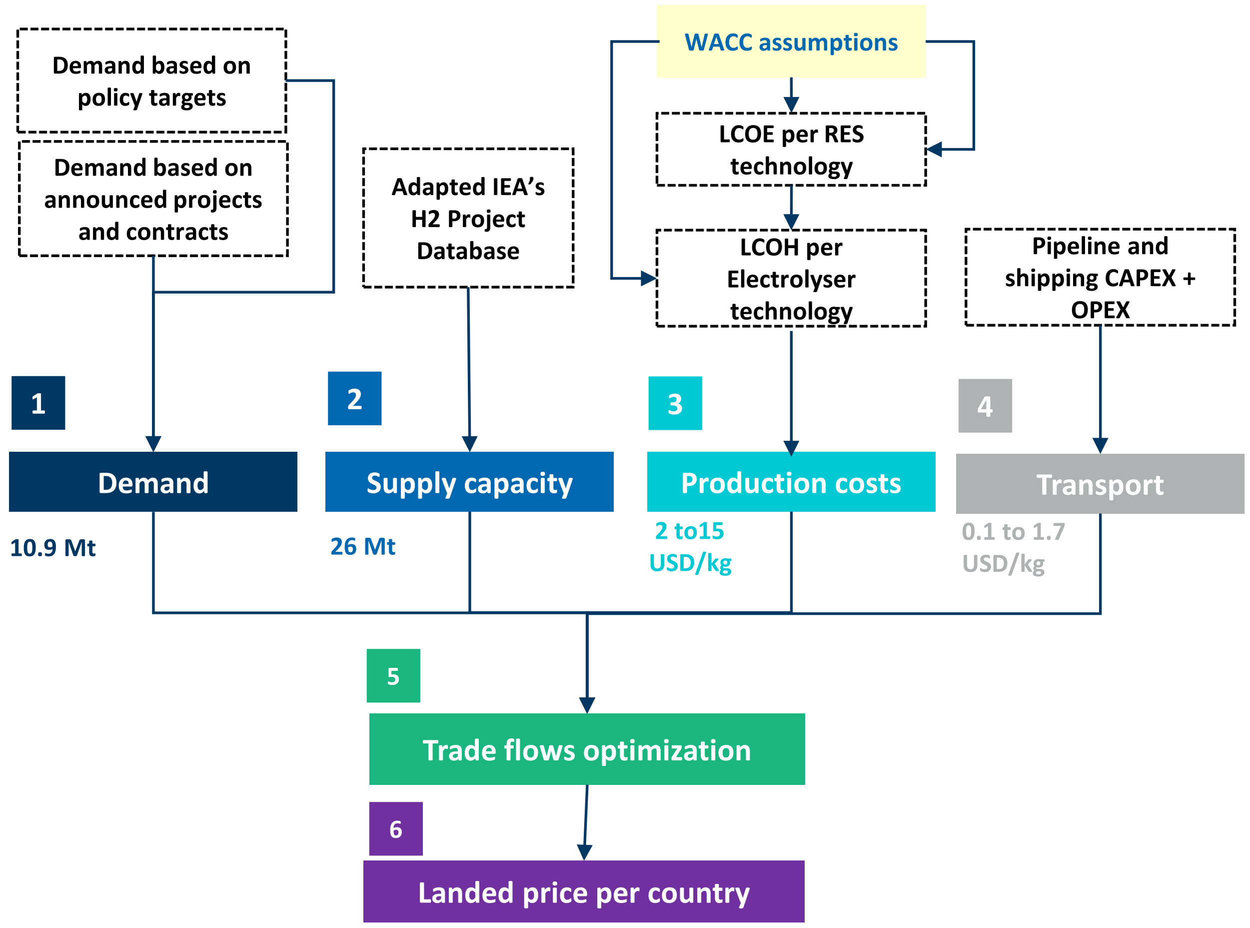
KEY ASSUMPTIONS

- We assume a **demand inelastic to price as a first estimate, as determined by regulatory mandates**.
- Our supply is based on the **probability-weighted global production capacity of green hydrogen** (IEA 2023 Hydrogen Project Database). We assume domestic production in a given country to be consumed as a priority, if demand exists in such a country
- Producers and infrastructure operators in the value chain are assumed to incorporate their **required rate of return into the costs**
- We assume a **uniform clearing price** per country, which is established based on the **inelastic demand and the (highest) long-run marginal cost (LRMC) of required supply in a given country**

PURPOSE & ADDED VALUE FOR GREEN HYDROGEN MARKET PLAYERS

- To provide a **price benchmarking tool for market players** of green hydrogen (i.e. support contracting with quantitative views)
- To serve as a tool for potential investors to **assess competitiveness and potential return on investment** of prospective assets
- To **assess main sensitivities** that change green hydrogen prices or flows in any particular country

Simplified diagram of the green hydrogen price model methodology



Demand based on policy targets

Demand based on announced projects and contracts

Adapted IEA's H2 Project Database

WACC assumptions

LCOE per RES technology

LCOH per Electrolyser technology

Pipeline and shipping CAPEX + OPEX

1 Demand

10.9 Mt

2 Supply capacity

26 Mt

3 Production costs

2 to15 USD/kg

4 Transport

0.1 to 1.7 USD/kg

5 Trade flows optimization

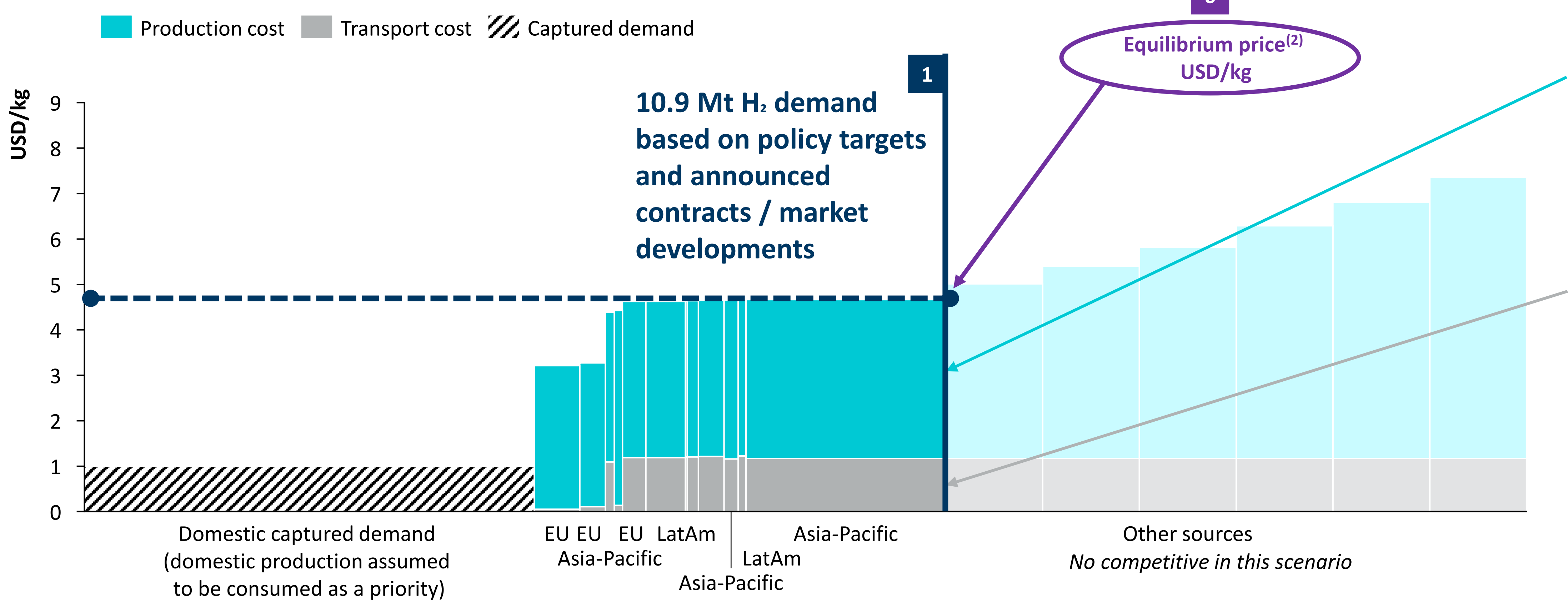
6 Landed price per country

Notes: **(1)** Including countries with no binding demand targets, but with domestic production which will be domestically consumed and therefore considered as demand. **(2)** Includes both shipping and pipeline routes.

A Globally-Traded Green Hydrogen Could Lead to an Average Landed Price of 5.3 USD[1]/kg by 2030, Based on a Global Supply and Demand Equilibrium of Delivered Green H_2

Illustrative

Global demand and supply equilibrium for delivered green hydrogen by 2030(1), *average USD per kg-H_2 and million tonnes H_2*



1

10.9 Mt H_2 demand based on policy targets and announced contracts / market developments

6

Equilibrium price(2) USD/kg

2 **26 Mt of cumulative probability-weighted production capacity**

3

Asset-level assessment of levelized-cost of hydrogen

4

Route-specific transport costs via shipping or pipeline

5

Allocation of routes according to least cost

Notes: (1) USD 2024, inflation based on IMF's WEO 2023 **(2)** Clearing prices are determined per country, including the associated transport costs from different routes taken by the H2 molecules to arrive at the destination country. A global result is reported here for simplicity.

Green Hydrogen Demand Is Expected To Be Mainly Policy Driven by 2030 Due to the EU's and Korea's Ambitious Targets

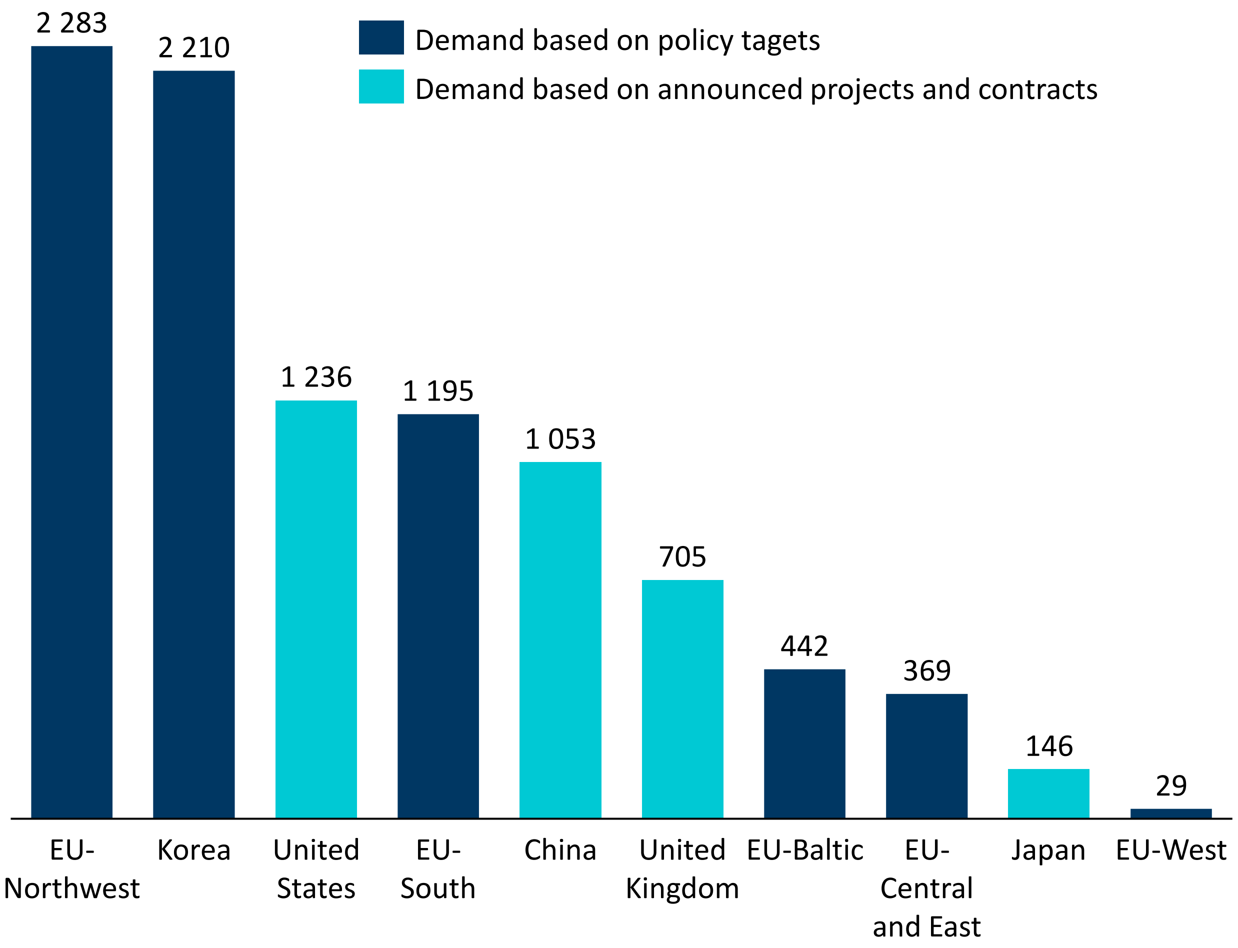
DEMAND BASED ON POLICY TARGETS

- **EU-27** mandates specific green hydrogen or e-fuel consumption targets via the Renewable Energy Directive II, ReFuelEU Aviation and FuelEU Maritime, covering industry (42%) and transport (1% of road, 1.2% of aviation, and 1.2% of shipping)
- **Korea** lays out specific green hydrogen import and production targets as part of its Hydrogen Economy Roadmap

DEMAND BASED ON ANNOUNCED PROJECTS AND CONTRACTS

- **United States'** target of 10 million tonnes of clean hydrogen production by 2030 laid down in its National Clean Hydrogen Strategy and Roadmap allows for blue and green H_2
  - The green H_2 demand is estimated based on captured domestic demand linked to targeted production capacity intended towards the domestic industrial and aviation sectors
  - Green H_2 for export is not planned by the government before 2030
- **China's** Hydrogen Industry Development Plan expects 35 million tonnes of total hydrogen demand by 2030 but without clear distinction between green, grey and blue hydrogen
  - The green H_2 portion is estimated based on captured domestic demand linked to green H_2 production capacity
- **UK**'s green hydrogen demand is based on the average estimated offtake by 2030 based on the government's modelling of the energy needs under the UK Hydrogen Strategy
- **Japan's** Hydrogen Basic Strategy foresees about 3 million tonnes of hydrogen demand but without any specification on the embedded carbon emissions
  - Demand is assessed based on green H_2 contracts and MoUs undertaken by off-takers

Green H_2 demand in selected countries and regions(1) in 2030, *thousand tonnes*



Note: (1) EU Northwest = Germany, France, Netherlands, Sweden, Belgium, Denmark, Luxembourg; EU-South = Italy, Spain, Greece, Romania, Portugal, Malta, Cyprus; EU Central and East = Austria, Slovakia, Hungary, Bulgaria, Czech Republic, Croatia, Slovenia; EU Baltic = Poland, Finland, Lithuania, Latvia, Estonia; EU-West = Ireland

We Leveraged the IEA's H_2 Database To Estimate the Supply; Majority of Projects Are Still in the Conceptual or Feasibility Study Stage Increasing the Uncertainty of the Supply

- Based on the IEA H_2 Projects database 2023, the announced projects in *Concept* or *Feasibility study* stages accounted for 52 Mtpa and 33 Mtpa of future H_2 production capacity, respectively, driven by Europe and South America
- Only **1.9 Mtpa of the projects' cumulative future production capacity is in more advanced stage of development**, including *Final Investment Decision (FID), Construction;* majority of these projects are in Asia, Europe and Middle East
- To account for the uncertainty in the completion of projects in early development stages, we **applied probabilities of completion to set the total supply capacity by 2030** for the model

Probability of completion by 2030 by current status(2)

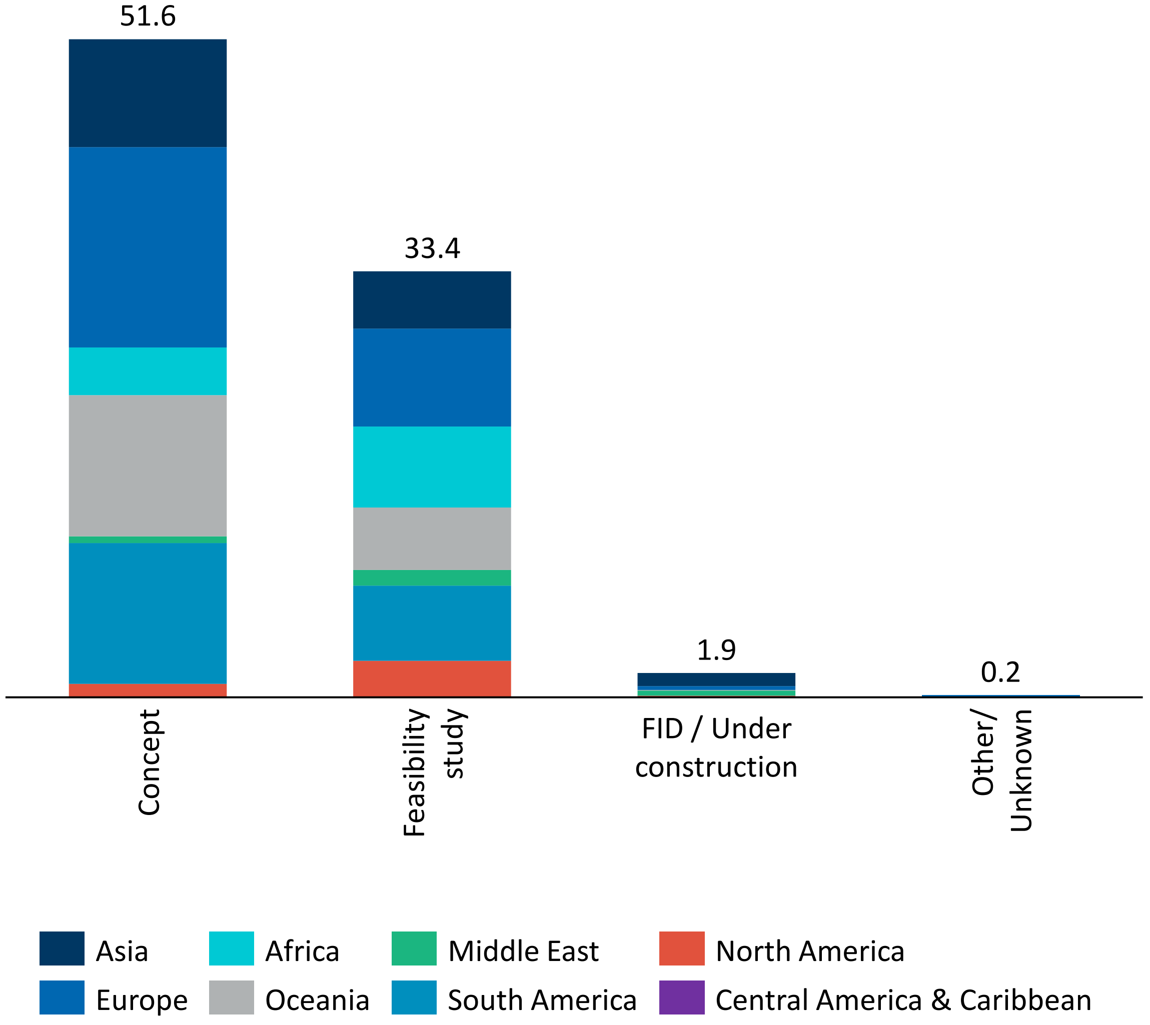
Decommissioned: 0%

Feasibility Study: 40%

Conceptual : 20%

FID/Under Construction: 95%

Supply production capacity by project status(1), *million tonnes per annum*

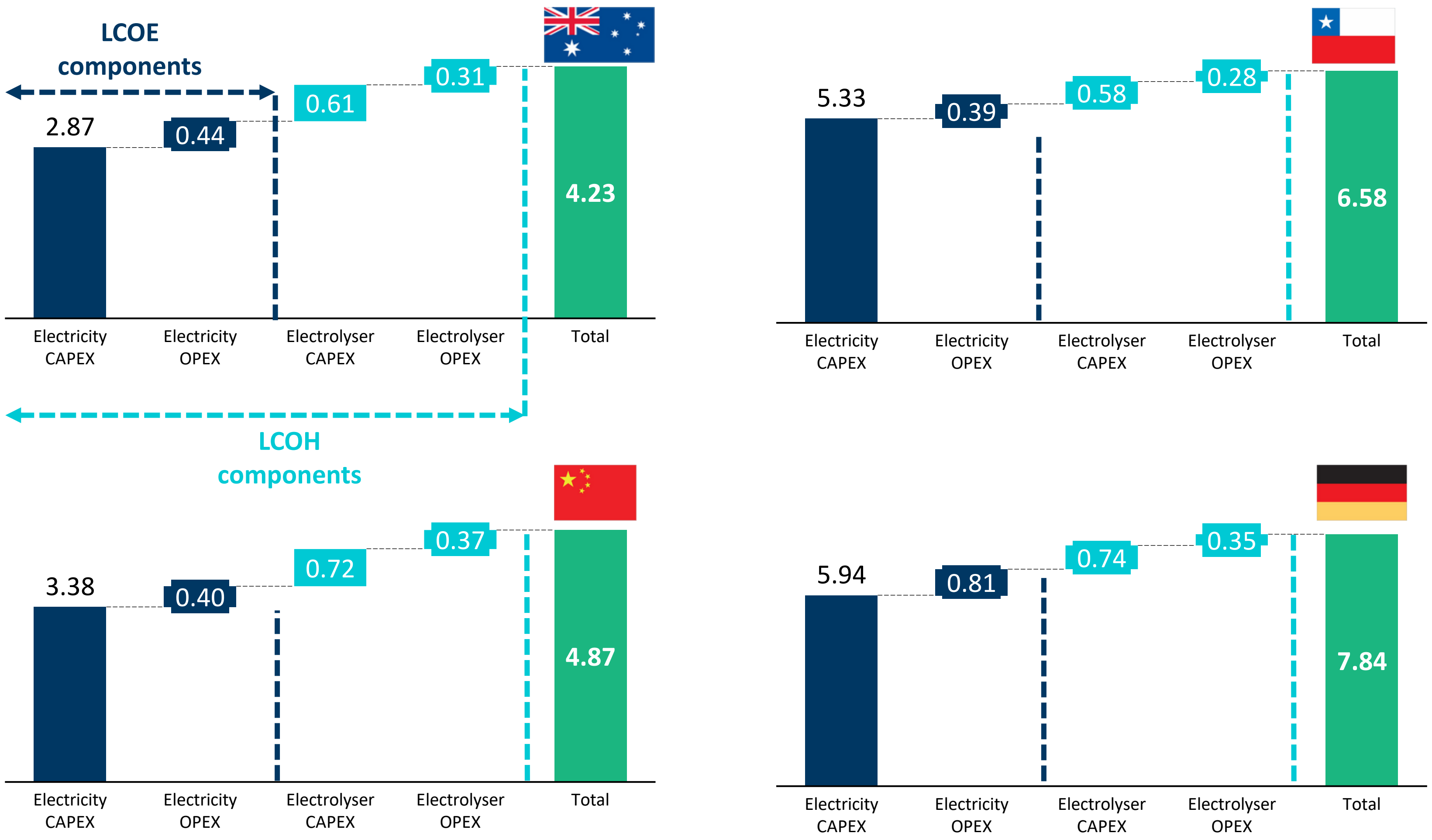


Notes: (1) Based on the IEA Hydrogen Projects Database 2023.
Sources IEA, FTI Consulting analysis

The LCOH Is Largely Driven by the Capital Component in the Cost of Electricity and Is Location-Sensitive, With Significant Reductions Observed in Renewable Rich-Locations

- A global assessment of all the announced green hydrogen projects indicate a wide range of **LCOH from 1.9 USD/kg to 15.4 USD/kg** by 2030
- Due to **hourly matching requirements**, **optimal sizing of electrolysers** in relation to the connected variable renewable supply is considered:
  - The RE asset would need to be slightly oversized to maximise the electrolyser utilisation during periods of **variable electricity output to maintain hourly matching with variable RE**
  - However, oversizing the RE asset increases the capital costs to a point where **reducing the electrolyser output could be more cost-effective**
  - **An optimal oversizing** is therefore needed and is applied in this LCOH calculation(1), calculated **based on the capacity factors** for solar PV and wind for each country
- Project LCOH per country can vary, for example with Germany ranging from 4.2 USD/kg to 9.9 USD/kg
- The largest LCOH component is the **capital component of the electricity source**(2) while the capital component of **electrolysers is generally the second most significant part** of the LCOH by 2030(3)
- Significant reductions of the **CAPEX component of both LCOE and LCOH** can be observed in renewable-rich locations such as in **Australia and Chile,** where high renewable capacity factors lead to higher utilisation rates of electrolysers

Decomposition of components for LCOE and LCOH in different countries(4), *USD/kg-H_2*

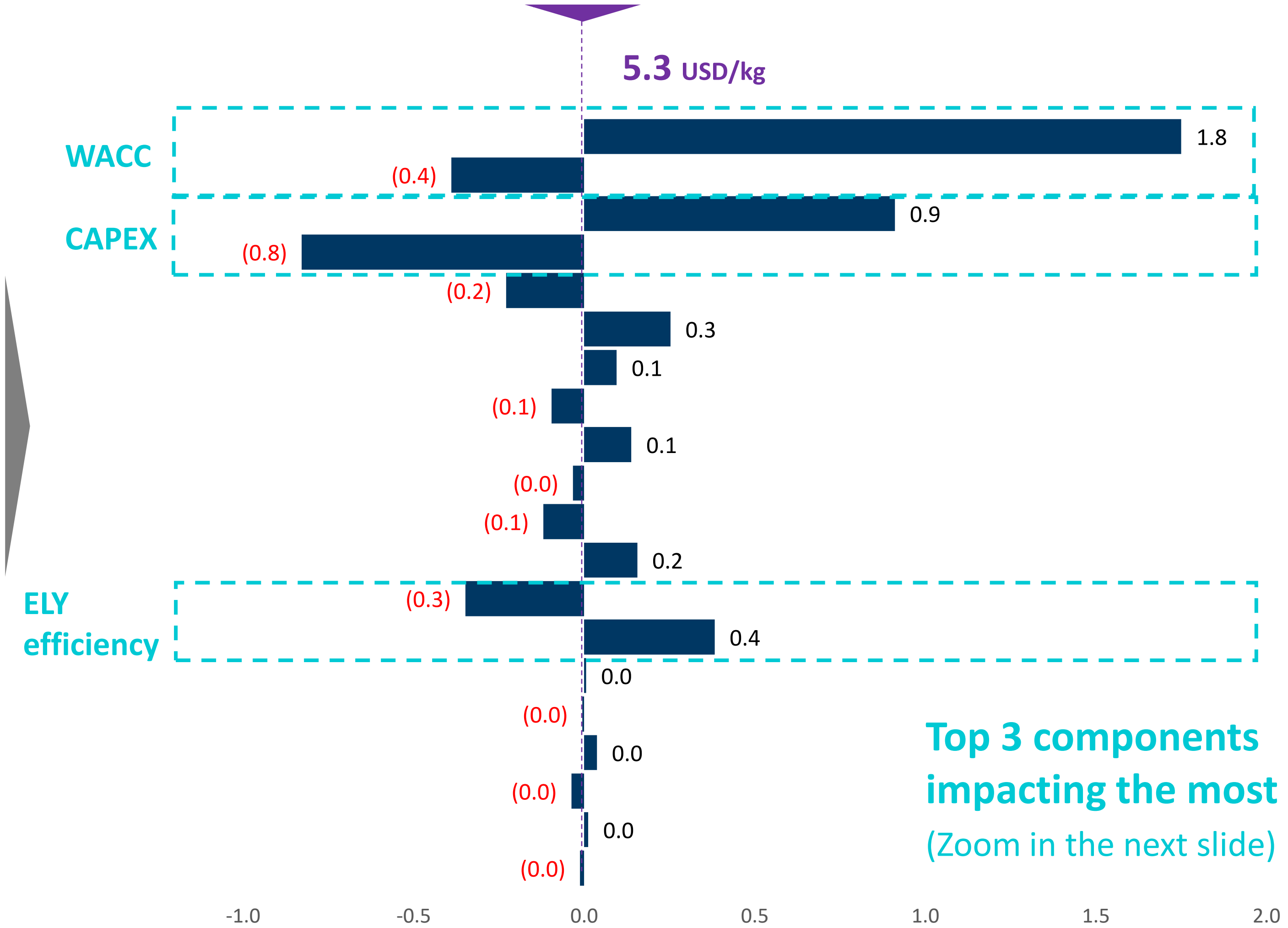


Notes: **(1)** In practice, a green hydrogen producer needs to stack multiple PPAs to achieve a desirable electrolyser output. Therefore, an optimal oversizing corresponds to a factor by which LCOH of each asset is increased to account for the increased costs due to multiple PPAs. **(2)** Renewable electricity sources considered are: Solar PV, onshore wind, offshore wind, and hydropower. **(3)** Considered technologies are: Alkaline, PEM and SOEC. **(4)** LCOE = levelized cost of electricity, LCOH = levelized cost of hydrogen

The LCOH is Largely Impacted by the Cost of Electricity (Capital Part – WACC and Production - CAPEX) and the Efficiency of Electrons-H2 Transformation

Sensitivity analysis on key components of global hydrogen LCOH, ***USD 2024/kg-H_2***

Part of value chain	Key Components	Variation input (%)
Renewable energy source	WACC– high	**Add 4%(1)**
	WACC – Low	**Minus 1%(2)**
	CAPEX - High	**10 %**
	CAPEX - Low	**(10 %)**
	Capacity factor - High	5 %
	Capacity factor - Low	(5 %)
	OPEX - High	20 %
	OPEX - Low	(20 %)
Electrolyser	WACC Electrolysis - High	Add 4 %
	WACC Electrolysis - Low	Minus 1 %
	CAPEX Learning rate (3) - High	Add 5 %
	CAPEX Learning rate - Low	Minus 5 %
	Efficiency - High	**10 %**
	Efficiency - Low	**(10 %)**
	Water price - High	20 %
	Water price - Low	(20 %)
	Opex - High	20 %
	Opex - Low	(20 %)
	Insurance - High	20 %
	Insurance - Low	(20 %)



Top 3 components impacting the most LCOH

(Zoom in the next slide)

Notes: (1) Add on top of the base value. For example, the base WACC is 2% then High WACC is 2 + 4 = 6%; The base WACC assumption is from IRENA's 2022 renewable energy cost report, the upper range of WACC is based on the increase of risk-free rate (from 2020 to 2023). (2) The lower range is based on the lowest WACC used by IRENA, 1.3%, negative WACC is not considered. (3) The base learning rate is retro-calculated by the value of 2020 and 2030 from EU's RFNBO (2020) for different technologies. ELY = Electrolyser

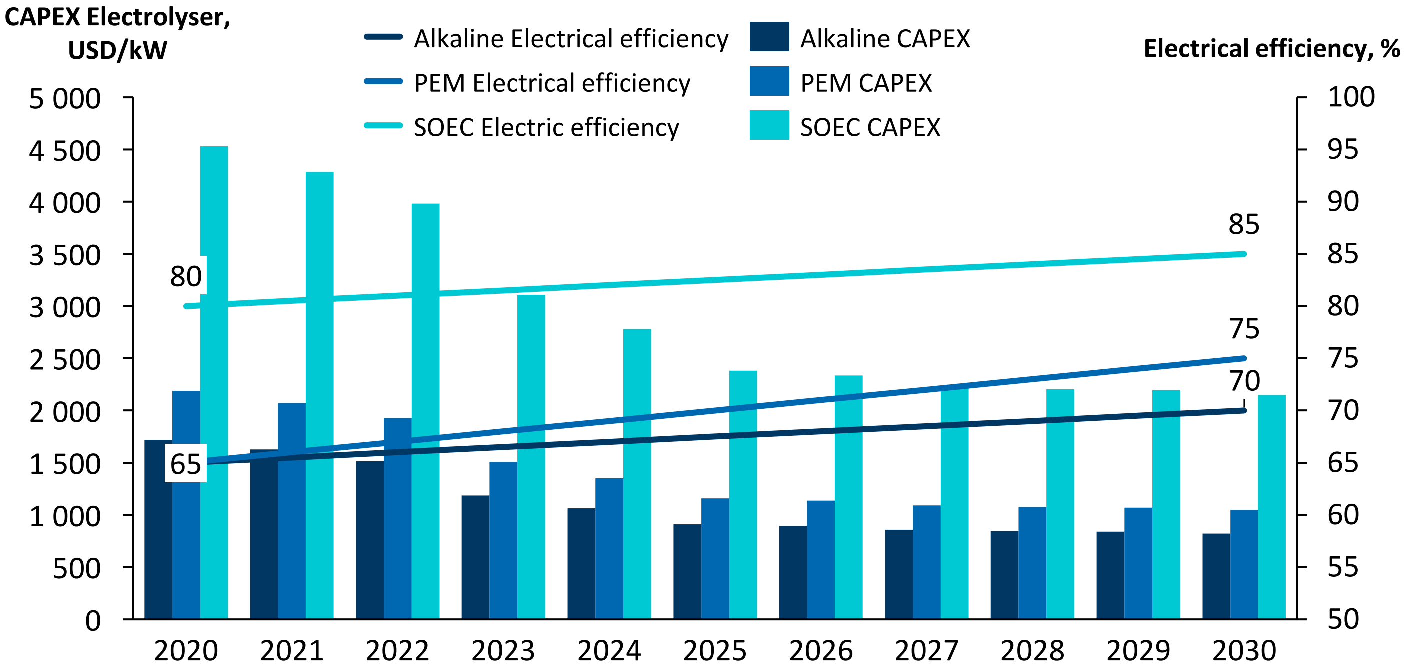
With an Increase of WACC by 4% & RES CAPEX by 10% From the Base, the LCOH Would Almost Double; PEM Might See Higher Efficiency Gain by 2030 vs. ALK With the Same CAPEX drop

LCOH sensitivity analysis, focus on RES capital component (WACC & CAPEX), *USD/kg-H₂*

WACC CAPEX	-1% from base	Base: 2%	+4% on base
-10% from base	4.2	4.5	5.9
Base: 1,755 USD/kW-output 2024	4.9	5.3	7.1
+10% on base	5.8	6.2	8.3

- **The cost of capital**, driven by interest rates, technology, and region factors, is crucial for LCOH
- Renewable electricity assets' **CAPEX** follows closely due to its capital-intensive nature, impacted by material costs, supply chain disruptions and project management
- **The combined impact** of these two factors amplifies the sensitivity of electricity costs

Comparison of the cost and efficiency of different electrolyser technology[1]



- Increasing electrical efficiency (using less electricity to produce the same amount of H2) would lower LCOH, driven by research and development
- While the **current SOEC electrolyser technology is the most efficient**, followed by PEM and SOEC, it in turn implies the highest **Electrolyser CAPEX, which affects competitiveness**
- Based on the available data from IRENA and the European Commission, we observe similar decrease in CAPEX of all three technologies (2020-2030) while the **efficiency gain over the observed period is 10 p.p. for PEM and only 5 p.p. for ALK increasing from 65% to 75% and 70%,** respectively (We do not compare efficiency gain of SOEC as it is in different efficiency increase range (from 80% to 85%))
- As each technology has its pluses and minuses, the above take-away could be considered only with the limits of the data sources and therefore a cost-benefit analysis is essential for individual cases to decide on the most suitable technology

Notes: (1) Based on the data from the IRENA and European Commission's Benchmark REF 2020

Transport Costs for Likely Routes Reach up to 0.7 USD/Kg for Transport Through Pipeline and 1.7 USD/Kg for Shipping, Using Ammonia as a Hydrogen-Carrying Energy Vector

TRANSPORT ROUTES

- About 864 routes have been mapped accounting for the different country-to-country trade that could exist among the 64 countries modelled
- About 753 shipping routes and 111 pipeline routes (mainly in Europe) are modelled and result in different unit costs due to different distances

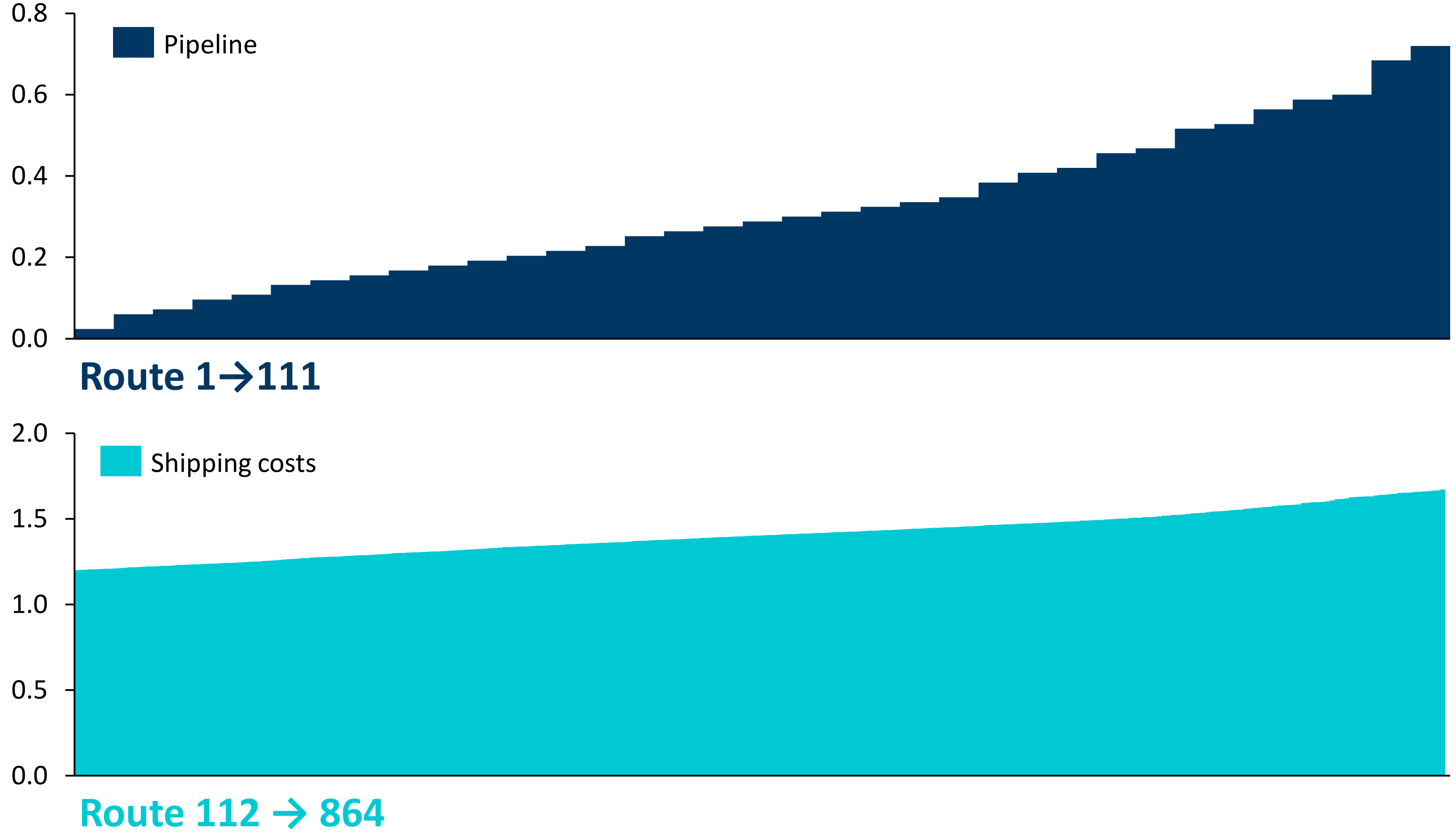
PIPELINE COSTS

- Pipeline costs are based on a unit cost estimate for both **newbuild and retrofitted pipes** (1)
- International pipelines are **currently only expected in Europe**, and interconnections are based on the European Hydrogen Backbone(2)

SHIPPING COSTS

- Shipping costs include the average costs of shipping ammonia **including the costs of converting H_2 to NH_3**(2)
- Shipping routes are based on the **existing and announced ammonia ports** for different countries

Unit transport cost by mode of transport, *USD/kg H_2-transported*

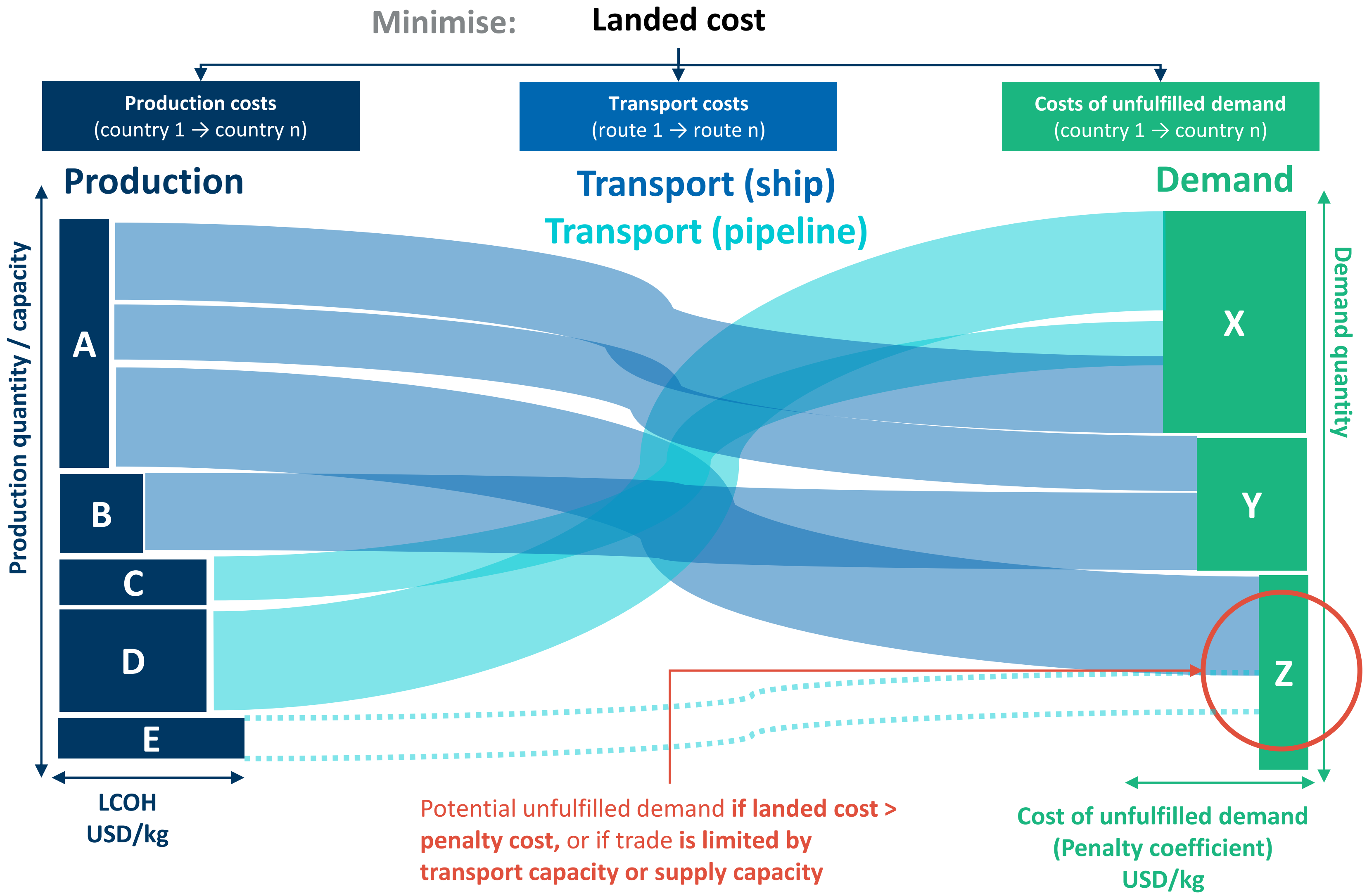


Notes: (1) EHB (2022) European Hydrogen Backbone **(2)** The NH_3 is received as is, and the cost of cracking to obtain H_2 (if H_2 is the final product for a given consumer segment) is assigned as a cost to the consumer and is not included in the price ;

Sources: IEA (2019) Future of Hydrogen; Brandle et al. (2021) Estimating long-term global supply costs for low-carbon hydrogen

The Market Model Combines the Balance of Supply and Demand Alongside an Optimisation of Trade Routes Based on Minimal Landed Cost

- We assume the global trade of hydrogen to be a collection of decisions made by producers and off-takers in such a way that it **minimises the average landed cost of hydrogen**
- For **net exporting countries**, mapping out destinations with the **lowest transport costs** is a sensible strategy as it **increases the possible profit** they obtain for **any clearing price** for a given country
- **The cost of not fulfilling demand is factored in**. This means that:
  - In cases where transport or supply capacity is restricted, the **model adjusts to lower the demand where it is cheapest to do so**; and
  - In cases where the **landed costs prove to be higher than the costs of unfulfilled demand**, then the demand is reduced instead, thereby **reflecting economic decisions to destroy demand as a more preferred economic option**
  - The costs of unfulfilled demand could be based on the **penalty for non-compliance** towards H_2 policy targets**,** **cost of reducing production** due to lack of H_2 supply**,** or the **cost of alternatives** (e.g. fossil-fuel based H_2 with the associated carbon price)



The Minimisation of the Landed Cost To Satisfy Global Demand Is Solved by a Linear Programming Model That Is Guided by a Set of Constraints

- The linear program aims to solve for the minimal cost of serving global demand under a set of **mathematical constraints**
- These constraints represent **real considerations** that guide decision-making in a market:
  - **Physical constraints** ensure that there is **no overproduction or overutilisation** of transport capacity
  - **Trade constraints** ensure that any **routes specified by a contract** is respected even if it is not at minimal cost
  - Model constraints are **supplementary constraints** to ensure that the different variables used in the model are aligned

A Physical constraints **B Trade constraints** **C Model constraints**

A Production volumes estimated by the model does not exceed capacity available for a country for a certain year

Production volumes in kg ≤ **Production capacity**

A Aggregate volumes via ship does not exceed the total shipping supply

Σ **Allocated volumes via ship in kg** X **Route km** ≤ **Global ammonia shipping supply (tonne-km)**

A Volumes via pipeline does not exceed the pipelines' capacities on each route

Allocated volumes via pipeline in kg ≤ **Pipeline capacity (kg/yr or Mt/yr)** **R1 (1)**

B Any future international trade contracts(2) would be prioritised, while the rest are allocated by the model based on the minimum landed cost principle

R1 (1) **Allocated volumes via ship in kg** + **Allocated volumes via pipeline in kg** ≥ **R1 (1) - contracted**

C Production values from different countries should match the volumes transiting to and from the ships and pipelines

Production volumes in kg = **Σ volumes in routes exiting C1 (1)** (**Allocated volumes via ship in kg**, **Allocated volumes via pipe in kg**) - **Σ volumes in routes entering C1 (1)** (**Allocated volumes via ship in kg**, **Allocated volumes via pipe in kg**)

C Demand destruction should be limited to the expected demand for the year (i.e. limiting the final modelled demand to zero) to prevent a negative demand

Destroyed demand ≤ **Expected demand**

Notes: (1) R = any route modelled among the 864 possible routes of trade, C = any country modelled among the 64 countries included, (2) The supply contracts specify a minimum required volume over a certain route. As of Dec 2023, there was no enough public information on bilateral trade contracts to be reflected in the model.

Experts with Impact™

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