Agora Energiewende

Agora Industry

DOCUMENTATION

EU map of hydrogen production costs

Version 1.0 — June 2024

Please cite as:

Agora Industry, Agora Energiewende (2024): EU map of hydrogen production costs – documentation.

Documentation
EU map of hydrogen production costs

Authors
Darlene D’Mello
Yu-Chi Chang
Leandro Janke

Acknowledgements
Agora Industry and Agora Energiewende would like to gratefully acknowledge the time and effort devoted by Elisabeth Zeyen (TU Berlin). We also thank our colleagues from the Hydrogen Team (Matthias Deutsch, Fabian Barrera, Emir Çolak, Caroline Paul, Mathias Koch, Veerle Dossche, and Zaffar Hussain), Industry Team (Helen Burmeister), Energy Data and Modelling Team (Thorsten Lenck, Saeed Sayadi, Samarth Kumar, and Long Nguyen), and Communication Team (Anja Werner, Alexandra Steinhardt, Frank Jordan, and Mathias Fengler) of Agora Industry and Agora Energiewende.

The views expressed in this report are those of the authors and should not be attributed to any of the aforementioned.

Content

List of abbreviations

Term	Explanation
BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
ELTS	Electrolysers
FLH	Full Load Hours
GEN	Generation
GIS	Geographic Information System
HVDC	High Voltage Direct Current
LCOE	Levelised Cost of Energy
LCOH	Levelised Cost of Hydrogen
NUTS	Nomenclature of Territorial Units for statistics
OPEX	Operational Expenditure
RES	Renewable Sources (wind and photovoltaic in this study)
WACC	Weighted Average Cost of Capital

1 Introduction

This documentation is intended to provide guidance on how the levelised cost of energy (LCOE) and the levelised cost of hydrogen (LCOH) are modelled in the EU map of hydrogen production costs, a digital tool developed in-house by Agora Industry and Agora Energiewende.

The tool displays modelling results that focus on the techno-economic aspects of renewable energy and hydrogen generation for a selected number of regions in Europe. Other publications from Agora Energiewende, Agora Industry (**Umlaut & Agora Industry (2023)**), and third parties provide additional information to help contextualise hydrogen production in the European energy policy landscape.

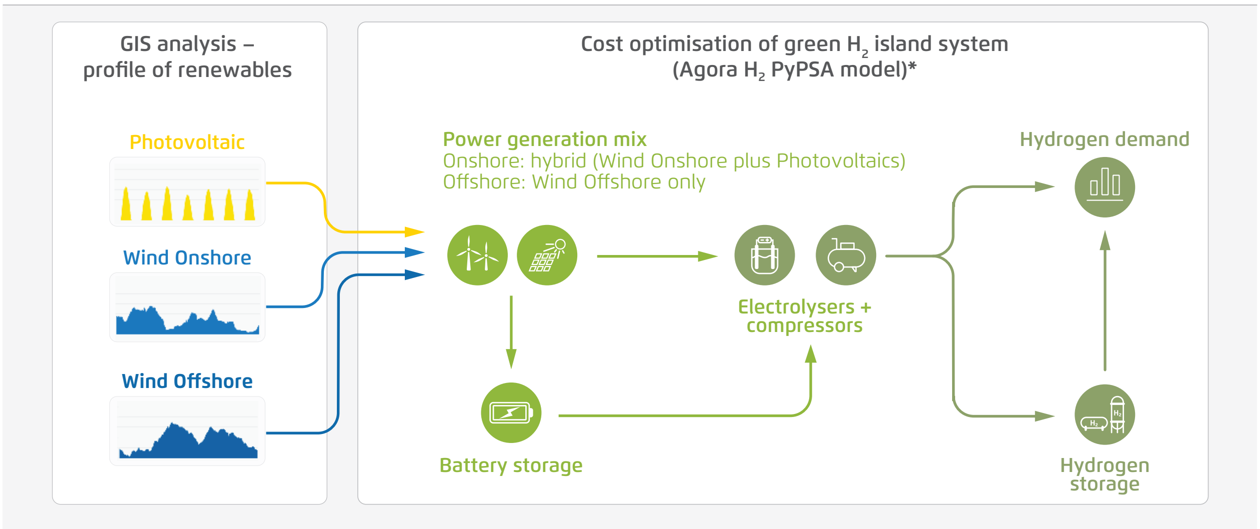
The tool is intended to provide insights for a broad range of stakeholders on how regions rich in renewable energy resources can benefit; either by producing cost-competitive hydrogen for exports or by attracting energy-intensive industries to produce low-carbon products.

2 Methods

2.1 System description

The main components of the model and the interconnections between them are described in a simplified process diagram in Figure 1.

Process flow diagram → Fig. 1



Agora Industry (2024) based on Agora Atlite and Agora H_2 PyPSA model. *The system in the cost optimisation is an island system and is not connected to the power grid.

An island system without a renewable energy connection to the grid is assumed for the model. Three renewable energy sources (RES) are considered: photovoltaic, onshore wind, and offshore wind. For onshore regions, the model assumes a hybrid generation system of onshore wind and photovoltaic. Offshore wind is an isolated generation system which generates electricity solely for offshore regions. The offshore wind turbines are assumed to be seabed fixed near the coast (refer to Annex A for further information). Generated electricity is transported with high-voltage direct current (HVDC) cables to onshore electrolysers and hydrogen storage sites. Compressors are installed next to the electrolysers to pressurise hydrogen to the required pressure, which can then supply the hydrogen demand or be fed into hydrogen storage. The input data and parameters are explained in the following section.

2.2 Input data

As the Agora H_2 PyPSA model is run on an hourly basis, it requires high-temporal resolution weather data in the form of hourly capacity factors of onshore wind, offshore wind, and photovoltaic generation. It also requires techno-economic assumptions for the different technologies assessed.

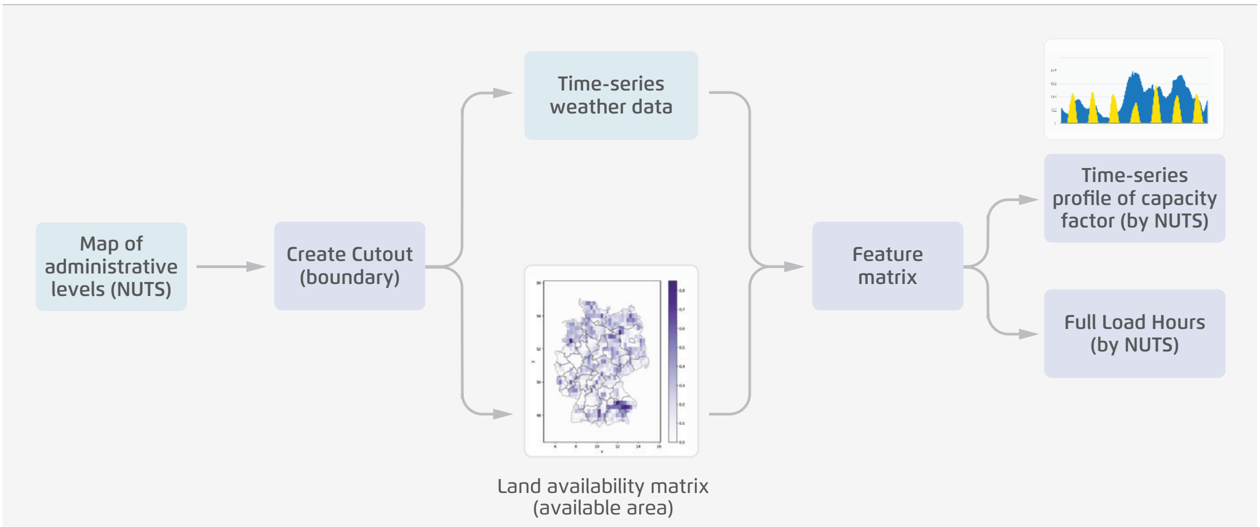
2.2.1 Weather-energy-system data conversion

To evaluate the capacity factors of different RES, the hourly weather pattern is considered and further converted into energy system data. The weather year is defined as 2021, and the hourly weather pattern data is extracted from ERA5, Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (**Hersbach, H. et al. (2023)**). The Agora Atlite model is developed based on Atlite, an open-source Python-based package, and is used to transform meteorological information into time-series input (**Hofmann et al., (2021)**).

A simplified workflow is described in Figure 2, using Germany as an example. The boundary of a country, administrative level, or Nomenclature of Territorial Units for Statistics (NUTS) region, as well as the available area, are evaluated first with geographic information system (GIS) analysis to obtain the land availability matrix. Land availability factor is calculated with a resolution of 0.3 ° x 0.3 ° of longitude and latitude.

The land availability matrix is further converted into weighted hourly capacity factors based on the weather data of the different locations, as well as NUTS and land cover information presented in Annex A. A time-series profile of capacity factors and an annual full load hours (FLH) list is generated from the model. These two outputs are aggregated from point-level in the matrix into NUTS level. Other technical parameters related to the performance of wind turbines and photovoltaic panels are also presented in Annex A.

Availability matrix → Fig. 2



Agora Industry (2024) based on Agora-Atlie model.

2.2.2 Techno-economic parameters

In this energy system model, two technological scenarios are considered for optimisation: 2023 and 2030. Both scenarios are assumed to be greenfield installations with no legacy installations from the past. Uniform capital expenditure (CAPEX) and operational expenditure (OPEX) was assumed for all regions in 2023 and 2030, due to limited publicly available information on country-specific values. However, country-specific WACC was considered, by assuming country equity risk premiums as discount rates (**Hypat (2021)**)
The adjustment of cost of capital in Europe was considered with values in 2023 (**Damodaran (2024)**).

For renewable energy generation technologies, average CAPEX and OPEX values from a range of sources were considered, and a summary of these cost assumptions is presented in Annex A. Similarly, average hydrogen generation and storage costs were considered and are presented in Annex B. In addition to overnight costs at the start of the project, a re-investment for replacing the electrolyser stack is considered at year 10.

All cost-related sources were further converted into annualised assumptions based on the lifetime and replacement time of each technology. These sources were carefully selected to reflect the most updated values, and whenever applicable, they were adjusted for inflation. All values are indicated in $EUR_{2023.}$

2.2.3 Economic assessment

To convert all cost related values into annualised costs, the total investment cost is multiplied by the annuity factor, the formula for which is presented in **eq. 1.** The annuity factor is a function of the discount rate r (unit in fraction), and the asset lifetime T (unit in year):

$$a(r,T) = \frac{r}{1-(1-r)^{-T}} \quad \text{[e.q. 1]}$$

The LCOE (unit in EUR_{2023} /MWh) is further calculated based on the annualised CAPEX (unit in in EUR_{2023}) and OPEX (unit in in EUR_{2023}) of RES and battery storage system (BESS) divided by the annual generation of RES (unit in MWh). The electricity production cost (unit in EUR_{2023}/MWh) is the LCOE including the cost of curtailment, as a reflection of the real cost related to power generation.

$$\text{LCOE} = \frac{\text{CAPEX}_{a_{\text{RES}}} + \text{CAPEX}_{a_{\text{BESS}}} + \text{OPEX}_{\text{RES}} + \text{OPEX}_{\text{BESS}}}{\sum_{t=1}^{8760} \text{Generation}_{\text{RES}}} \quad \text{[e.q. 2]}$$

$$\text{Production Cost}_{\text{electricity}} = \text{LCOE with Curtailment Cost} \quad \text{[e.q. 3]}$$

The LCOH is calculated with the electricity production cost and the cost of the hydrogen production network. The cost of the hydrogen production network is the annualised CAPEX (unit in in EUR_{2023}) and OPEX (unit in EUR_{2023}) of the electrolyser (ELTS) (including cost of compressor) and hydrogen storage divided by the annual generation of electrolyser (unit in MWh).

$$\text{LCOH} = \text{Production Cost}_{\text{electricity}} + \frac{\text{CAPEX}_{a_{\text{ELTS}}} + \text{CAPEX}_{a_{h_2\,\text{storage}}} + \text{OPEX}_{\text{ELTS}} + \text{OPEX}_{h_2\,\text{storage}}}{\sum_{t=1}^{8760} \text{Generation}_{\text{ELTS}}} \quad \text{[e.q. 4]}$$

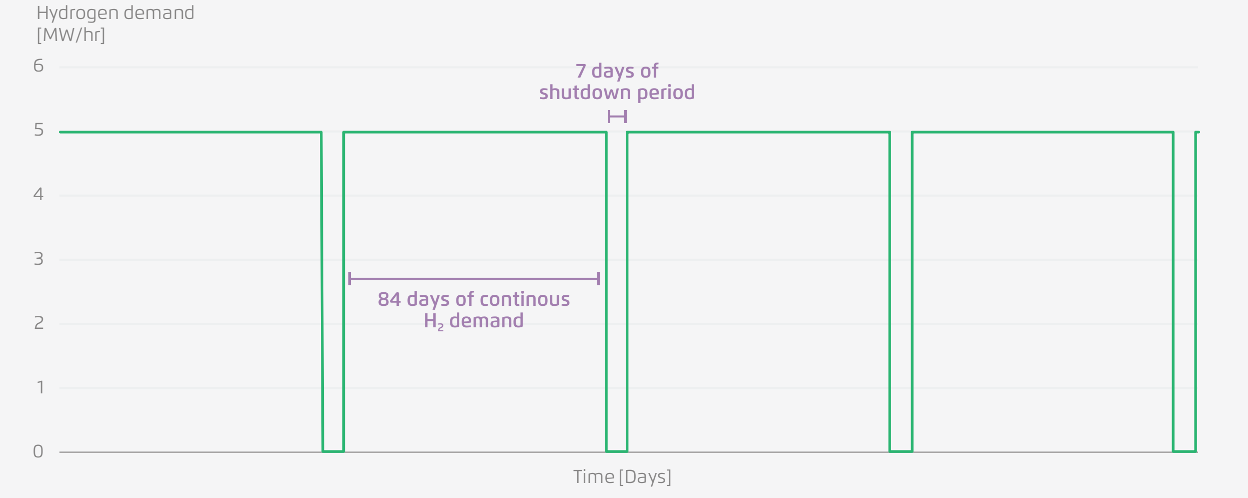
2.3 Hydrogen demand profile

Considering the major hydrogen demand from industrial applications, the hydrogen load curve is assumed to be a cyclic pattern consisting of an 84-day continuous operation period with a demand of 5 MW/hour, with a 7-day shutdown period for maintenance.

2.4 Optimisation procedure (Agora H_2 PyPSA)

Hourly hydrogen demand profile

→ Fig. 3



Agora Industry (2024) based on Agora H_2 PyPSA model

Python for power system analysis (PyPSA) is an open-source modelling framework for energy system modelling (**Brown, T.; Hörsch, J.; Schlachtberger, D. (2018)**). The flexible and modular framework can be used to represent the energy system in a wide range of different temporal, geographic and sectoral representations. It is being used by academia, research institutes, private companies, and utilities. Fundamentally, PyPSA is a bottom-up cost optimisation model. The framework takes various techno-economic parameters as inputs including fuel costs, CAPEX, OPEX, power plants capacities, and interconnection capacities. The framework carries out a complete year cost optimisation under given technical constraints, such as energy balance (energy demand must be met at all hours) (**GIZ, CASE & Agora (2022)**).

Based on the PyPSA modelling framework, the Agora H_2 PyPSA model was developed to assess the LCOE and LCOH in the cost-optimised scenario for different European countries.

3 Results interpretation

For an appropriate interpretation of the results, it is important to understand the scope and limitations of the modeling exercise. As the aim of the study was to solely assess production costs for different regions in Europe, the definition of available area was separated into onshore and offshore regions. In the onshore regions, land use constraints were not considered and hence occupied areas such as buildings, national parks, and transportation units were not excluded. In the offshore regions, since the offshore wind turbines are assumed to be near-coast installations with DC lines connected to onshore electrolysers, areas with distance to the coastline larger than 50 km were excluded from the exclusive economic zones, as well as areas with water depth deeper than 50 m. A more comprehensive assessment of exclusion areas would be necessary in case renewables and hydrogen production potentials for every nodal region were part of the scope of the analysis.

Another aspect to be highlighted is that hydrogen production was modelled to reflect two different system operations: (a) driven solely by renewable energy with a variable hourly hydrogen output, and (b) driven by a nearly constant hourly demand to reflect the off-take of an industrial consumer. For the former case, only renewable energy and electrolyser capacities are optimised for the lowest possible hydrogen production cost without a specific demand. The latter case relies on the option of battery and/or hydrogen storage to enhance the balance between variable renewable energy generation and the nearly constant hydrogen demand.

Furthermore, in our assessment based on island systems, batteries did not play a major role in lowering the cost of hydrogen production, likely due to the characteristics of the scenarios modelled. The storage does not consider transportation cost, which is not a focus in this model. The least-cost optimisation approach prefers to store energy in the form of hydrogen in rock caverns (low-cost hydrogen storage scenario) which has 141 times cheaper specific CAPEX compared to batteries, or underground pipelines (high-cost hydrogen storage scenario) which has 16 times cheaper specific CAPEX compared to batteries (in 2030). If grid constraints such as hybrid systems allowing generation of hydrogen or electricity to the grid are considered, batteries could potentially play a more prominent role, particularly if the electricity is commercialised at peak prices in the spot market.

There are multiple options for storing hydrogen underground, including salt caverns, lined rock caverns, and depleted oil and gas fields. The choice of each hydrogen storage type will depend on locally available resources, such as suitable geological formations. Due to the limited availability of open-source GIS databases regarding the precise location of every suitable geological formation for hydrogen storage in Europe, the model excluded the assessment of individual nodal regions in terms of locally available resources for storing hydrogen. To reflect the cost difference among underground hydrogen storage options, a sensitivity analysis was performed based on low-cost underground hydrogen storage (i.e., lined rock cavern) and high-cost underground hydrogen storage (i.e., pipelines). As a low-cost option, lined rock caverns were chosen since they are more evenly distributed across European countries than salt caverns or depleted oil and gas fields. As a high-cost option, underground pipelines were chosen since they can be built in any geography, resembling the way hydrogen is stored in many existing refineries.

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Annex A – Spatial and techno-economic assumptions used for renewable energy

Spatial definitions and description used for calculation of hourly capacity factor → Table 1

Name	Definition	Description	Source
Administrative levels	Names of different sub-regions	Official names of different geographical regions used for statistics.	**Global Administrative Areas (2023)**
Exclusive Economic Zone	Offshore area used for wind energy assessment.	Areas with distance to the coastline larger than 50 km are excluded.	**Flanders Marine Institute (2023)**
Water depth	Offshore water depth used for wind energy assessment.	Areas with water depth deeper than 50m are excluded.	**GEBCO (2023)**

Technical parameters related to the performance of wind turbines and photovoltaic used for calculation of hourly capacity factor → Table 2

Technology	Parameter	Unit	Value
Onshore wind	Power density	MW/km²	4
	Correction factor	-	0.88
Offshore wind	Power density	MW/km²	2
	Correction factor	-	0.88
Photovoltaic	Power density	MW/km²	1.7
	Correction factor	-	0.85
	Orientation	-	Latitude optimal angle

Photovoltaic refers to fixed axis with latitude optimal angle and includes degradation of 0.5% per year.
All values are based on Brown, T.; Hörsch, J.; Schlachtberger, D. (2018).

Techno-economic assumptions used for renewable energy generation → Table 3

Technology	Parameter	Unit	2023	2030	Source
Onshore wind	CAPEX	EUR/kW_{el}	1 420	1 190	**NREL (2023), IEA (2023), BNEF (2022), IRENA (2022)**
	OPEX	EUR/kW_{el} – year	28	27	
	Lifetime	Years	25	25	
Offshore wind	CAPEX	EUR/kW_{el}	3 450	2 400	
	OPEX	EUR/kW_{el} – year	102	74	
	Lifetime	Years	25	25	
Photovoltaic	CAPEX	EUR/kW_{el}	970	670	
	OPEX	EUR/kW_{el} – year	16	11	
	Lifetime	Years	20	20	

For offshore wind, an additional CAPEX of 50 000 EUR/MW for a HVDC cable to the coast is also considered (50 km length).

Annex B – Techno-economic assumptions used for energy storage

Techno-economic assumptions used for energy storage → Table 4

Technology	Parameter	Unit	2023	2030	Source
Battery	CAPEX	EUR/kW_{el}	439	206	Fasihi, M. et al. (2021)
	OPEX	EUR/kW_{el} – year	6	4	Fasihi, M. et al. (2021)
	Lifetime	Years	20	20	Fasihi, M. et al. (2021)
Lined rock H_2 cavern	CAPEX	EUR/MW_{el}	1 960	1 460	Fasihi, M. et al. (2021), Guidehouse (2021), Argonne (2020), BNEF (2019)
	OPEX	EUR/MW_{el} – year	78	30	Fasihi, M. et al. (2021), Guidehouse (2021), Argonne (2020), BNEF (2019)
	Lifetime	Years	30	58	Fasihi, M. et al. (2021)
Underground H_2 pipeline	CAPEX	EUR/MW_{el}	17 650	13 180	Fasihi, M. et al. (2021), Argonne (2020)
	OPEX	EUR/MW_{el} – year	353	264	Fasihi, M. et al. (2021), Argonne (2020)
	Lifetime	Years	30	30	Fasihi, M. et al. (2021)

Li-ion battery includes the interface. Underground H2 pipeline storage is operated at 100 bar, and includes compressor costs.

Techno-economic assumptions used for hydrogen production Table 5

Technology	Parameter	Unit	2023	2030	Source
Electrolyser	CAPEX	EUR/kW_{el}	1 500	600	IEA (2023), BNEF (2023)
	OPEX	EUR/kW_{el} – year	30	12	IEA (2023), BNEF (2023)
	Stack replacement	fraction of CAPEX	0.29	0.26	IRENA (2020)
	Power consumption	kWh/kgH_2	52	48	IEA (2021)
	Water Consumption	kgH_2O/ kgH_2	21.00	21.00	IRENA (2020)
	Water Cost	EUR/m^3	2.20	2.20	Caldera, U.; Breyer, C. (2020)
	Stack lifetime	Years	10	10	IRENA (2020)
	H_2 plant lifetime	Years	20	20	IEA (2023), BNEF (2023)

Refers to low-temperature pressurised electrolyser operated at 30 bar; CAPEX includes balance of plant and engineering, procurement and construction; all values in EUR_{2023}. Stack replacement was calculated based on a maximum 60 000 operational hours and an average 6 000 full-load hours of operation per year.

Equity risk premium for European countries in 2023

Table 6

Country	Value	Country	Value	Country	Value
Andorra	7.38%	Greece	8.26%	Poland	5.84%
Austria	5.18%	Hungary	7.38%	Portugal	6.35%
Belgium	5.48%	Iceland	5.84%	Romania	7.81%
Bulgaria	6.94%	Ireland	5.48%	Slovakia	5.84%
Croatia	7.38%	Italy	7.81%	Slovenia	6.35%
Cyprus	7.38%	Latvia	6.35%	Spain	6.94%
Czech Republic	5.48%	Liechtenstein	4.60%	Sweden	4.60%
Denmark	4.60%	Lithuania	5.84%	Switzerland	4.60%
Estonia	5.63%	Luxembourg	4.60%	United Kingdom	4.60%
Finland	5.18%	Malta	5.84%	–	–
France	5.32%	Netherlands	4.60%	–	–
Germany	4.60%	Norway	4.60%	–	–

All values based on Damodaran (2024)

Imprint

About Agora
Agora Industry develops scientifically sound and politically feasible concepts for successful pathways to a climate-neutral industry – in Germany, Europe and internationally. The organisation which is part of the Agora Think Tanks works independently of economic and partisan interests. Its only commitment is to climate action.

Agora Industry
Agora Think Tanks gGmbH
Anna-Louisa-Karsch-Straße 2
10178 Berlin | Germany
P +49 (0) 30 7001435-000
www.agora-industry.org
info@agora-industrie.org

Agora Energiewende
Agora Think Tanks gGmbH
Anna-Louisa-Karsch-Straße 2
10178 Berlin | Germany
P +49 (0) 30 7001435-000
www.agora-energiewende.org
info@agora-energiewende.de