DOCUMENTATION

Brazil map of hydrogen production costs

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Documentation
Brazil map of hydrogen production costs

Authors
Darlene D'Mello
Yu-Chi Chang
Leandro Janke

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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

Abbreviation	Meaning
BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
ELTS	Electrolyser
FLH	Full Load Hours
GEN	Generation
GIS	Geographic Information System
LCOE	Levelised Cost of Energy
LCOH	Levelised Cost of Hydrogen
OPEX	Operational Expenditure
RES	Renewable Sources (wind and photovoltaic in this study)
USD	United States Dollar
WACC	Weighted Average Cost of Capital

1 Introduction

This documentation is intended to provide guidance on how the levelised cost of hydrogen (LCOH) is modelled in the Brazil map of hydrogen production costs, a digital tool developed in-house by Agora Industry and Agora Energiewende. This map has been developed in the framework of the report *12 Insights on Hydrogen – Brazil Edition*.

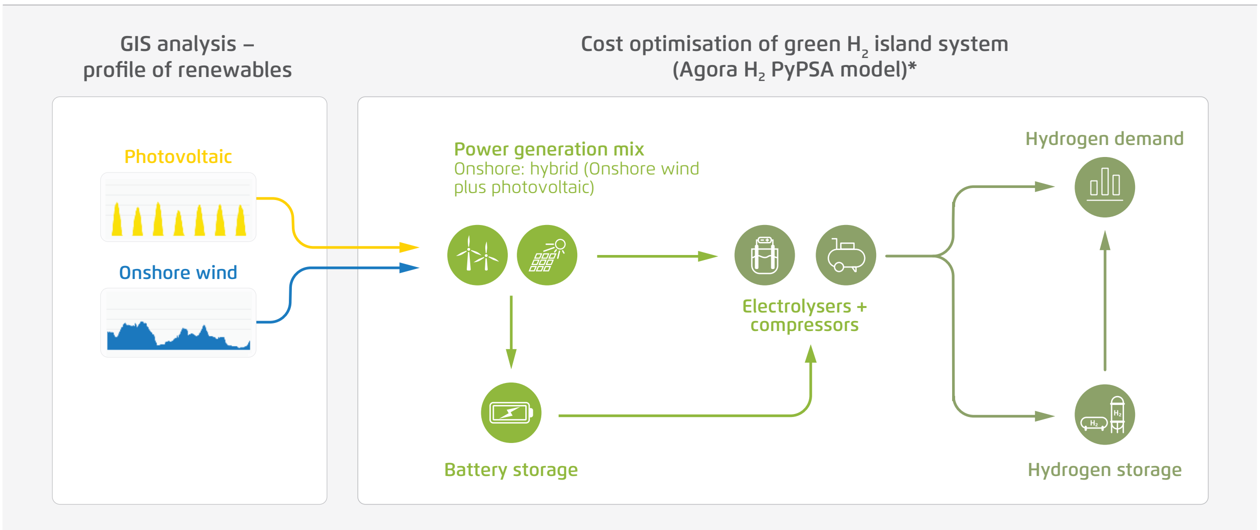
Further insights into LCOH calculation are outlined in Umlaut & Agora Industry (2023).

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. Two renewable energy sources (RES) are considered: photovoltaic and onshore wind. The model assumes a hybrid generation system of onshore wind and photovoltaic. 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 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 2019, 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)**).

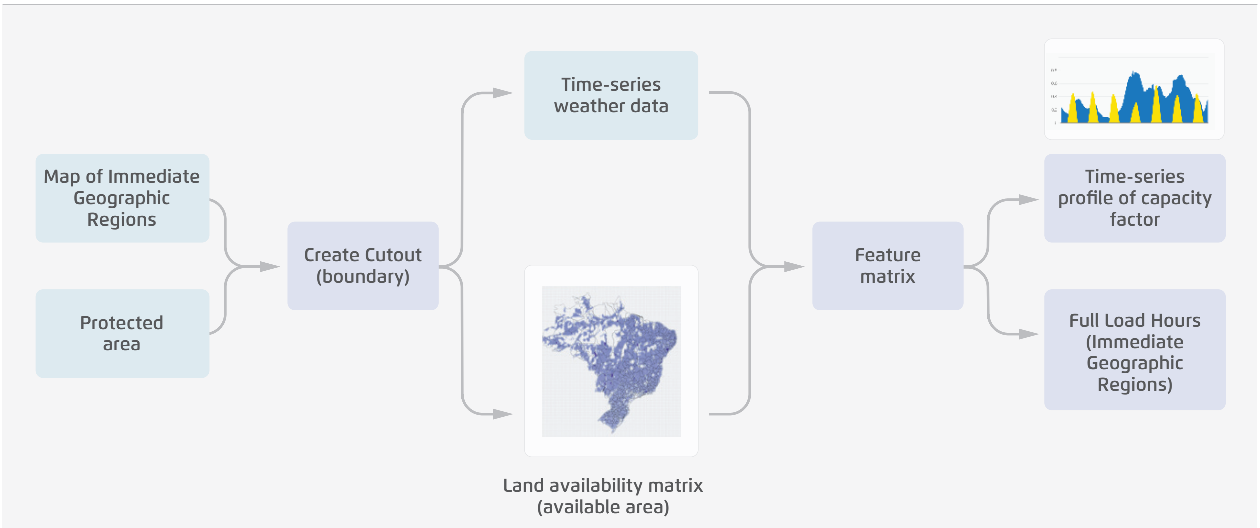
A simplified workflow is described in Figure 2. The boundaries of the Immediate Geographic Regions of Brazil, as well as the available area, are evaluated with geographic information system (GIS) analysis to obtain the land availability matrix. The land availability factor is calculated with a resolution 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 separate locations, as well as the 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 the Immediate Geographic Regions level. Other technical parameters related to the performance of wind turbines and photovoltaic panels are also presented in Annex A.

2.2.2 Techno-economic parameters

In this energy system model, the 2030 technological scenario is considered for optimisation. The scenario is assumed to be a greenfield installation with no legacy installations from the past. The WACC is considered by assuming Brazil's country equity risk premium as the discount rate (**Hypat (2021)**). The adjustment of cost of capital in Brazil is considered with a discount rate of 9.57% in 2023 (**Damodaran (2023)**).

Availability matrix → Fig. 2



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

For renewable energy generation technologies, country-specific CAPEX and OPEX values (**EPE, MME (2021)**) are considered, and a summary of these cost assumptions is presented in Annex A. Similarly, average hydrogen generation and storage costs are 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 are further converted into annualised assumptions based on the lifetime and replacement time of each technology. These sources are carefully selected to reflect the most updated values, and whenever applicable, they are adjusted for inflation. All values are indicated in USD_{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 $a(r,T)$, 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 USD_{2023} /MWh) is further calculated based on the annualised CAPEX (unit in USD_{2023}) and OPEX (unit in USD_{2023}) of RES and battery storage system (BESS) divided by the annual generation of RES (unit in MWh). The electricity production cost (unit in USD_{2023} /MWh) is the LCOE including the cost of curtailment, as a reflection of the real cost related to power generation.

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

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

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 USD_{2023}), OPEX (unit in USD_{2023}) of the electrolyser (ELTS) (including cost of compressor), and hydrogen storage divided by the annual generation of electrolyser (unit in MWh).

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

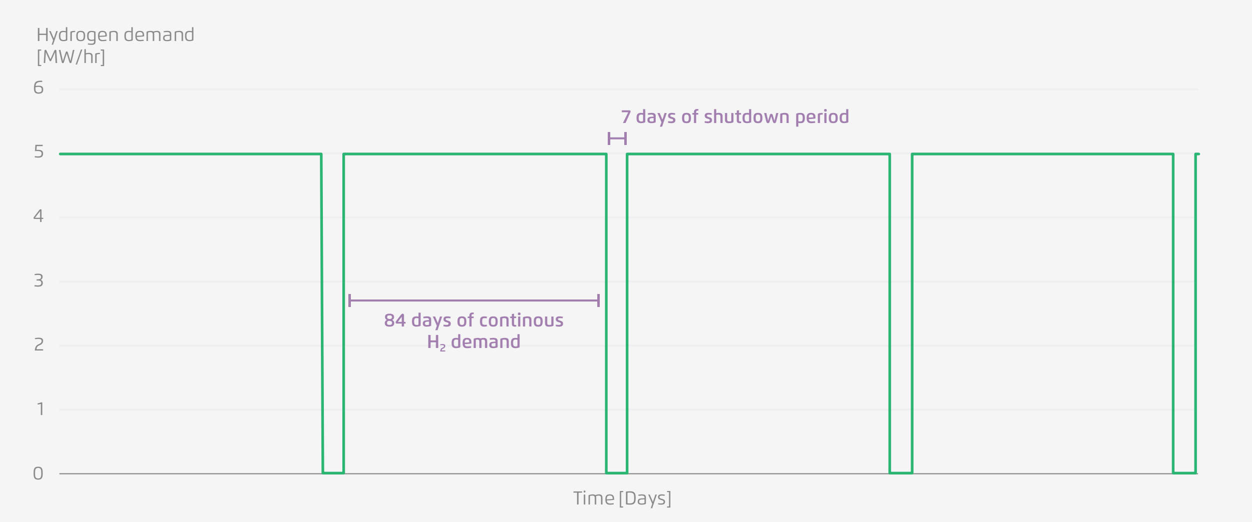
2.3 Hydrogen demand profile

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 Python for Power System Analysis (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 conducts 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 LCOH in the cost-optimised scenario for Brazil.

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 solely to assess production costs for different regions in Brazil, the only land use constraints considered were protected areas (**Protected Planet (2023)**) and occupied areas such as buildings and transportation units were not excluded.

Another aspect to be highlighted is that hydrogen production was modelled to reflect a system operation driven by a nearly constant hourly demand to reflect the offtake of an industrial consumer. This 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 significant role in lowering the cost of hydrogen production, due to the characteristics of the scenarios modelled. The storage did not consider any transportation cost, which was not a focus in this model. The least-cost optimisation approach prefers to store energy in the form of hydrogen in rock caverns which has 141 times cheaper specific CAPEX compared to batteries.

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 Brazil, the model excluded the assessment of individual nodal regions in terms of locally available resources for storing hydrogen. As a low-cost option, lined rock caverns were chosen since they are more evenly distributed across Brazil than salt caverns or depleted oil and gas fields.

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

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

Name	Definition	Description	Source
Immediate Geographic Regions	Names of different sub-regions	Official names of different geographical regions used for statistics.	**Instituto Brasileiro de Geografia e Estatística (2017)**
Protected Areas	Total Protected Areas	Terrestrial and Inland Waters Protected Areas	**Protected Planet (2023)**

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

Technology	Parameter	Unit	Value
Immediate Geographic Regions	Power Density	MW/km_2	4
	Correction Factor		0.88
	Power Density	MW/km_2	1.7
Protected Areas	Correction Factor		0.85
	Orientation		Latitude optimal angle

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

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

Technology	Parameter	Unit	2030	Source
Onshore wind	CAPEX	USD/kW_{el}	770	**EPE, MME (2021)**
	OPEX	USD/kW_{el} – year	22	
	Lifetime	Years	25	
Photovoltaic	CAPEX	USD/kW_{el}	720	
	OPEX	USD/kW_{el} – year	12	
	Lifetime	Years	20	

5 Annex B – Techno-economic assumptions used for energy storage

Techno-economic assumptions used for energy storage → Table 4

Technology	Parameter	Unit	2030	Source
Battery	CAPEX	USD/kW_{el}	223	Fasihi, M. et al. (2021)
	OPEX	USD/kW_{el}– year	5	Fasihi, M. et al. (2021)
	Lifetime	Years	20	Fasihi, M. et al. (2021)
Lined rock H_2 cavern	CAPEX	USD/MW_{el}	1 577	Fasihi, M. et al. (2021), Guidehouse (2021), Argonne (2020), BNEF (2019)
	OPEX	USD/MW_{el}– year	33	Fasihi, M. et al. (2021), Guidehouse (2021), Argonne (2020), BNEF (2019)
	Lifetime	Years	58	Fasihi, M. et al. (2021)

Li-ion battery includes the interface. Underground H_2 pipeline storage is operated at 100 bar, and includes compressor costs.

Techno-economic assumptions used for hydrogen production. → Table 5

Technology	Parameter	Unit	2030	Source
Electrolyser	CAPEX	USD/kW_{el}	648	IEA (2023), BNEF (2023)
	OPEX	USD/kW_{el} – year	12	IEA (2023), BNEF (2023)
	Stack replacement	fraction of CAPEX	0.26	IRENA (2020)
	Power consumption	kWh/kgH_2	48	IEA (2021)
	Water Consumption**	kgH_2O/kgH_2	21.00	IRENA (2020)
	Water Cost	USD/m^3	2.37	Caldera, U.; Breyer, C. (2020)
	Stack lifetime***	Years	10	IRENA (2020)
	H_2 plant lifetime	Years	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 USD_{2023}. ** Water cost is assumed based on desalinated water. *** Stack replacement is calculated based on a maximum 60 000 operational hours and an average 6 000 full-load hours of operation per year.

References

Argonne (2020): *System Level Analysis of Hydrogen Storage Options.* URL: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/st001_ahluwalia_2020_o.pdf

BNEF (2019): *Hydrogen: the economics of storage – storing clean molecules at scale.*

BNEF (2023): *Hydrogen levelised cost update: cost of capital and inflation takes hold.*

Brown, T.; Hörsch, J.; Schlachtberger, D. (2018): *PyPSA: Python for Power System Analysis.* URL: https://doi.org/10.5334/jors.188

Caldera, U.; Breyer, C. (2020): *Strengthening the global water supply through a decarbonised global desalination sector and improved irrigation systems.* URL: https://doi.org/10.1016/j.energy.2020.117507

Damodaran (2023): *Country Default Spreads and Risk Premiums.* URL: https://pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/ctryprem.html

EPE, MME (2021): *Plano Decenal de Expansão de Energia 2030.* URL: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-490/PDE%202030_RevisaoPosCP_rv2.pdf

Fasihi, M.; Weiss, R.; Savolainen, J.; Breyer, C. (2021): *Global potential of green ammonia based on hybrid PV-wind power plants.* URL: https://doi.org/10.1016/j.apenergy.2020.116170

GIZ, CASE & Agora (2022): *Towards a collective vision of Thai energy transition: National long-term scenarios and socioeconomic implications.* URL: https://www.agora-energiewende.org/publications/towards-a-collective-vision-of-thai-energy-transition

Guidehouse (2021): *Picturing the value of underground gas storage to the European hydrogen system.* URL: https://www.gie.eu/wp-content/uploads/filr/3517/Picturing%20the%20value%20of%20gas%20storage%20to%20the%20European%20hydrogen%20system_FINAL_140621.pdf

Hersbach, H., et al. (2023): *ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS).* URL: https://doi.org/10.24381/cds.adbb2d47

Hofmann et al., (2021).: *atlite: A Lightweight Python Package for Calculating Renewable Power Potentials and Time Series.* URL: https://doi.org/10.21105/joss.03294

Hypat (2021): *Import von Wasserstoff und Wasserstoffderivaten: von Kosten zu Preise.* URL: https://www.hypat.de/hypat-wAssets/docs/new/publikationen/HyPAT_Working-Paper_01-2021.pdf

IEA (2021): *Global Hydrogen Review 2021: Assumptions.* URL: https://iea.blob.core.windows.net/assets/2ceb17b8-474f-4154-aab5-4d898f735c17/IEAGHRassumptions_final.pdf

IEA (2023): *Global Hydrogen Review 2023.* URL: https://www.iea.org/reports/global-hydrogen-review-2023

Instituto Brasileiro de Geografia e Estatística (2017): *Regional Divisions of Brazil.* URL: https://www.ibge.gov.br/en/geosciences/territorial-organization/regional-division/21536-regional-divisions-of-brazil.html?=&t=acesso-ao-produto

IRENA (2020): *Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5 °C climate goal. Abu Dhabi.* URL: https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

Protected Planet (2023): *Brazil Protected Areas (WDPA).* URL: https://www.protectedplanet.net/country/BRA

Umlaut & Agora Industry (2023): *Levelised cost of hydrogen calculation tool. Version 1.0.* URL: https://www.agora-energiewende.org/data-tools/levelised-cost-of-hydrogen-calculator

Imprint

About Agora Industry and Agora Energiewende
Agora Industry and Agora Energiewende develop scientifically sound and politically feasible strategies for a successful pathway to climate neutrality – in Germany, Europe and internationally. The organisations which are part of the Agora Think Tanks work independently of economic and partisan interests. Their 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