Techno-economic dataset for hydrogen storage-based microgrids

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Data Article

Techno-economic dataset for hydrogen storage-based microgrids

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A R T I C L E I N F O

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A B S T R A C T

The challenge of energy storage is a pivotal consideration in renewable energy-based power systems. Hydrogen emerges as a highly promising alternative or complementary solution to electric batteries, showcasing its potential for long-term and high-capacity storage. In this context, energy system modeling and optimization has gained prominence as an indispensable research tool, aiding in the processes of designing, sizing, and managing the day-to-day operations of renewable energy systems integrated with a hydrogen storage unit. However, the gathering of reliable and accurate techno-economic data emerges as time-consuming tasks, and the lack of standardized reference data introduces variability in model results. This variability arises from inconsistent input parameters rather than the physics or complexity of energy systems, leading to potentially erroneous results and misguided policy recommendations. Recognizing the need for comprehensive and transparent datasets, we introduce this open data techno-economic repository. The dataset is meticulously designed to encompass key technologies essential for hydrogen production, compression, storage, and utilization within a power-to-power system. Specifically, techno-economic data are reported for electrolysers, fuel cells, battery energy storage systems, hydrogen compression units, and hydrogen storage vessels. The learning curves and cost functions embedded in this paper, delineating investment costs as a function of production scale up and size, are de-

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rived directly from the raw data, providing a nuanced understanding of the economic landscape.

Specifications Table

Subject	Energy
Specific subject area	Techno-economic data for green hydrogen production, compression, storage, and utilization
Type of data	Table Raw, Processed
Data collection	Literature survey (databases, reports from national and international institutions, peer-reviewed journal articles)
Data source location	Raw data sources are listed in this article and in the data repository
Data accessibility	Repository name: Zenodo Data - Techno-Economic Data for Hydrogen Storage-Based Microgrids Data identification number: 10.5281/zenodo.12784515 Direct URL to data: https://zenodo.org/records/12784516

1. Value of the Data

- The dataset encompasses the power-to-power hydrogen-based systems designed for the integration of microgrids and renewable energy communities.
- This dataset serves as a valuable resource for modelling hydrogen-based systems, especially for techno-economic assessments in stationary applications.
- All recordings adhere to a standardized format with consistent units and currencies. This uniformity allows for swift comparison across various sources and ensures a dependable method for validating both model inputs and outputs.
- Generalized cost functions have been derived to establish a benchmark for similar studies in the modelling of hydrogen-based systems, encouraging the adoption of open data principles.

2. Background

This dataset is developed to support energy system modeling of hydrogen-based renewable energy systems, aiding in the design, management and optimization of energy systems that integrating hydrogen technologies, such as microgrids, energy communities, and positive energy districts.

It assists in modeling hydrogen production, storage, and utilization, as well as complete power-to-power solutions.

The repository provides comprehensive coverage of techno-economic data of key hydrogen technologies, including electrolyzer, hydrogen compression, storage and power fuel cells. It also includes battery energy storage systems (BESS), which are often required to better optimize the management of surplus renewable generation. The database offers detailed data for energy modeling, covering investment and operational costs, energy efficiency, technology lifetime, and operating parameters, collected through extensive literature review and normalized into standard units.

By presenting investment cost functions derived from size-based raw data, the dataset enhances transparency and supports scientific reproducibility. This initiative aims to advance knowledge and encourage collaboration towards sustainable and efficient energy solutions. Additionally, this dataset offers insights into capital expenditures, cost trends, and scaling behaviors, making it a valuable resource for modeling and analyzing the techno-economic aspects of power-to-power technologies. It serves as a foundation for researchers, policymakers, and industry stakeholders to advance the development and deployment of these crucial technologies in the transition to a sustainable energy future.

3. Data Description

This paper details the dataset available in the linked repository [1], which encompasses the techno-economic parameters of equipment used in power-to-power plants. This includes water electrolysis for green hydrogen production, compression units, storage tanks, fuel cells and battery energy storage systems. The data was gathered through a literature review covering publications from 2014 to May 2024. The search was conducted in English using three online bibliographic sources to ensure comprehensive coverage of relevant materials: Scopus (https://www.scopus.com/), Google Scholar (https://scholar.google.com/) and the Google search engine (https://www.google.com/). For each technology assessed, we selected documents that provided at least one estimate of uninstalled capital costs (CAPEX). These selected documents were then thoroughly analyzed through full-text review to extract the necessary data. Additionally, during this process, we identified and included further relevant materials referenced in the collected documents. Finally, we reviewed all entries in the database to ensure the absence of obvious duplicate reports or errors.

This dataset contains 20 sheets within a single Excel file. The first two sheets, named "Constants" and "References", respectively, summarize the constant values used in the data elaboration (such as inflation rate, hydrogen, lower heating value (LHV), higher heating value (HHV) and density, and currency conversion factors) and the references of the collected data, categorized into peer-reviewed journal articles and report/other online sources and databases. Additionally, there are nine sheets, each ending with the suffix "_raw", that compile the collected data as reported in the referenced literature for the analysed technologies:

1. PEMEC_raw: Proton Exchange Membrane Electrolyser (PEMEC).
2. AEL_raw: Alkaline Electrolyser (AEL).
3. other_EL_raw: this sheet includes Solid Oxide Electrolyzer Cell (SOEC) and Anion Exchange Membrane Electrolyser (AEM). These technologies are less mature and have less data available in literature.
4. PEMFC_raw: Proton Exchange Membrane Fuel Cells (PEMFC).
5. SOFC_raw: Solid Oxide Fuel Cells (SOFC).
6. other_FC_raw: this sheet includes Phosphoric Acid Fuel Cells (PAFC), Molten-Carbonate Fuel Cells (MCFC), and Alkaline Fuel Cells (AFC). These technologies are less mature and have less data available in literature.
7. compressor_raw: hydrogen compression units.
8. H2_tank_raw: hydrogen storage tanks.
9. Li_BESS_raw: Lithium-ion Battery Energy Storage Systems (BESS).

Table 1 outlines the main references from which were sourced the technological and economic data.

The dataset includes key technical and economic parameters essential for modelling and analysing the techno-economic aspects of power-to-power technologies, offering detailed insights into capital expenditures, conversion efficiencies and technologies lifetime. An overview of the collected data is provided in Table 2.

The other nine sheets in the Excel file display the processed data. Specifically, for each raw data sheet, there is a corresponding "_actualized" sheet where the data has been processed to ensure consistency and comparability across different studies and sources. This includes adjusting for inflation to reflect 2024 values based on the average annual inflation rate for the European Union [94], converting costs from various currencies to euros [95], and standardizing units of measurement. Moreover, learning curves have been derived to illustrate the expected

Table 1
List of sources for technical and economic data per technology and number of values collected for each technology.

Technology	References	Number of datapoints
PEMEC	[2–40]	114
AEL	[3–5,7–9,12–21,23–26,32,33,35–38,41–43]	110
Other electrolyser technologies	[9,12,23,33,35–37,44–52]	38
PEMFC	[19,27,30,32,40,53–59]	124
SOFC	[19,56,57,59–63]	41
Other fuel cell technologies	[19,60,63–72]	24
Compressor	[14,19,28–31,38,40,68,72–84]	70
H_2 tank	[14,19,26,31,33,34,38,42,43,53,75,76,78,79,81,82,85,86]	71
Li BESS	[26,30,34,40,44,63,87–93]	258

Table 2
Technical and economic parameters of raw data included in the dataset across technologies.

Parameter	Code	Unit	Description
References	reference	–	Bibliographic reference or source for which the data was extracted
Reference years	report_year estimation_year	–	Year of the report and year of data estimation
Specific technology	technology	–	Technology to which the reported data pertains
Nominal size	nominal_power nominal_capacity nominal_gravimetric_capacity nominal_volumetric_capacity	kW kWh kg/h kg m^3	Nominal capacity metrics representative of the technology size
Pressure	maximum_working_pressure minimum_pressure_in maximum_pressure_out	bar	Pressure levels representative of the operating conditions of the technology
Efficiency	efficiecy_HHV efficiency_LHV specific_consumption ther- mal_efficiency_cogeneration_LHV total_cogeneration_efficiency compression_efficiency charge_efficiency discharge_efficiency round_trip_efficiency	% kWh/kg	Efficiency metrics relevant to the reported technology
Capital Expenditure	CAPEX CAPEX_input CAPEX_output_LHV CAPEX_output_HHV CAPEX _H2_power CAPEX_power CAPEX_H2_flow_rate CAPEX_equipment CAPEX_gravimetric CAPEX_volumetric CAPEX_energy	currency/kW currency/(kg/h) cur- rency/equipment currency/kg currency/m^3 currency/kWh	Capital expenditure metrics related to the technology
Operational Expenditure	OPEX_percent_CAPEX OPEX_LHV OPEX_HHV OPEX_kW	%CAPEX currency/(kWh/yr)	Operating expenses metrics representative of the technology
Cost for equipment replacement	replacement_costs	%CAPEX	Costs associated with equipment replacement
Reported currency	currency	€ US$ A$ £	Currency denomination for costs

(*continued on next page*)

Table 2 (*continued*)

Parameter	Code	Unit	Description
Lifetime	lifetime_hours lifetime_years lifetime_cycles	h yr cycles	Lifetime metrics of the technology
System availability	availability	%	Annual availability of the technology
Other parameters	Cogeneration projected_poduction_capacity vessel_class energy_to_power_ratio depth_of_discharge self_discharge	Y/N units/yr - h %	Other characteristics of the reported technologies

reduction in costs as technologies mature and production scales up. The final result of capital expenditure is expressed in euros per unit of size, actualized and projected to 2024 values.

Finally, the cost functions, based on available size data, provide insights into how costs are anticipated to decrease with increasing system sizes

4. Experimental Design, Materials and Methods

Raw data were processed to standardize data and ensure comparability across different sources. A summary of the data reported in the "_actualized" sheets is presented in Table 3.

When a range is proposed in the raw data, it is substituted by the mean value of the bounds in the processed data. The average inflation rate was calculated by the mean value of the inflation factors between the report year and the reference year (2024).

Table 3
Processed data included in the dataset across technologies.

Parameter	Code	Unit	Description
Reference years	estimation_year	–	Year of the data estimation
Inflation rate	avg_inflation_rate	%	Average inflation rate between report year and reference year (2024)
Nominal size	nominal_power nominal_capacity	kW kg kWh	Standardization of the nominal size units
Efficiency	efficiency round_trip_efficiency	$\%_{LHV}$ %	Standardization of the efficiency units
Capital Expenditure	CAPEX	currency/kW currency/kWh	Standardization of CAPEX units
Operational Expenditure	OPEX	%CAPEX	Standardization of OPEX units
CAPEX actualization	CAPEX_actualized	Currency_{2024}/kW	Actualization of the CAPEX at 2024
CAPEX currency conversion	CAPEX_EUR	$€_{2024}$/kW	Conversion of the original currency into euros
CAPEX projection to 2024	CAPEX_EUR_learning_curve	$€_{2024}$/kW	Projection of the CAPEX_EUR to the reference year 2024
CAPEX based on cost functions	CAPEX_EUR_cost_function	$€_{2024}$/kW	Estimation of the CAPEX based on the system size
Pressure	working_pressure_status minimum_pressure_in maximum_pressure_out	Pressurized/Atmospheric bar	Status of the system's operating pressure

The average learning curve index was derived by fitting the actualized CAPEX data, expressed in euros, as a function of the data estimation year ($Y_{estimation}$). The fitting coefficients $CAPEX_{ref}$ and exp were obtained by minimizing the root mean square error (RMSE) between the $CAPEX_{EUR}$ data and the values estimated by the learning curve function defined in Eq. (1). Then, the average yearly learning index ($I_{learning}$) for each year (Y) relative to 2024 was computed using equation Eq. (2). This index is subsequently used in Eq. (3) to compute the CAPEX projections for 2024 ($CAPEX_{EUR\ learning\ curve}$).

$$CAPEX_{learning\ curve} = CAPEX_{ref} \cdot \left(\frac{Y_{estimation}}{2024}\right)^{-exp} \tag{1}$$

$$I_{learning} = \frac{\frac{CAPEX_{learning\ curve,\ Y}}{CAPEX_{learning\ curve,\ 2024}} - 1}{2024 - Y} \tag{2}$$

$$CAPEX_{EUR\ learning\ curve} = CAPEX_{EUR}\left[1 + I_{learning} \cdot (2024 - Y_{estimation})\right] \tag{3}$$

The CAPEX as a function of size ($CAPEX_{cost\ function}$) was calculated by fitting the CAPEX projected to 2024 as a function of the standardized nominal size (S_{st}). The fitting coefficients C_{ref}, S_{ref} and exp were estimated by minimizing the RMSE between the $CAPEX_{learning\ curve}$ data and the values estimated by the cost function defined in the following equation (Eq. (4)).

$$CAPEX_{cost\ function} = \frac{C_{ref}S_{ref}\left(\frac{S_{st}}{S_{ref}}\right)^{exp}}{S_{st}} \tag{4}$$

Table 4 provides learning curve indices, fitting coefficients of the cost functions along with their performance metrics for the reported technologies.

Table 4
learning curve indices and cost function coefficients.

Technology	Learning curve index [%]	Performance metrics learning curve	Cost function coefficients	Performance metrics cost function
PEMEC	−5.6 %	RMSE: 770 R^2: 0.19	C_{ref}: 1300 S_{ref}: 897 exp: 0.9	RMSE: 383 R^2: 0.31
AEL	−4.5 %	RMSE: 575 R^2: 0.10	C_{ref}: 1039 S_{ref}: 890 exp: 0.9	RMSE: 300 R^2: 0.34
PEMFC	0 %	RMSE: 2833	C_{ref}: 2911 S_{ref}: 1137 exp: 0.92	RMSE: 2713 R^2: 0.08
SOFC	0 %	RMSE: 3652	C_{ref}: 719 S_{ref}: 948 exp: 0.58	RMSE: 1918 R^2: 0.72
Compressor	−5.9 %	RMSE: 5586 R^2: 0.07	C_{ref}: 1769 S_{ref}: 2154 exp: 0.77	RMSE: 2568 R^2: 0.41
H_2 tank	−7.1 %	RMSE: 983 R^2: 0.07	C_{ref}: 467 S_{ref}: 2028 exp: 0.83	RMSE: 473 R^2: 0.22
Li BESS	−5.4 %	RMSE: 196 R^2: 0.30	C_{ref1}: 452 S_{ref1}: 17 exp_1: 0.97 C_{ref2}: 99 * S_{ref2}: 106 exp_2: 0.7	RMSE: 112 R^2: 0.45

* Note: For Li BESS, refer to Eq. (21) for details on the cost function coefficients.

4.1. Electrolysers

For electolyser technologies, the following calculations were conducted:

1. Standardizing nominal size into input power capacity expressed in kW ($S_{EL,st}$) according to Eq. (5).
2. Reporting efficiency metrics as a percentage relative to the hydrogen lower heating value ($\eta_{LHV,st}$) according to Eq. (6).
3. Expressing CAPEX as currency per unit of input power ($CAPEX_{st}$), as per Eq. (7).
4. Adjusting CAPEX data to euros 2024 by applying the inflation rate ($CAPEX_{actualized,\ 2024}$) and currency-to-euros conversion factors ($CAPEX_{EUR}$) based on Eqs. (8) and (9).
5. Expressing OPEX as a percentage of CAPEX, with the conversion detailed in Eq. (10).
6. Setting the system's operating pressure status to "Atmospheric" if the maximum operating pressure of the electrolyser is 1 bar, and "Pressurized" otherwise (Eq. (11)).

$$\begin{cases} S_{EL,st} = S_{EL} \; if \; S_{EL} = \; kW \\ S_{EL,st} = \frac{S_{EL} \cdot LHV}{\eta_{LHV,st}} \; if \; S_{EL} = \frac{kg}{h} \end{cases} \tag{5}$$

$$\begin{cases} \eta_{LHV,st} = \; \eta \; if \; \eta = \%_{LHV} \\ \eta_{LHV,st} = \eta \cdot \frac{LHV}{HHV} \; if \; \eta = \%_{HHV} \\ \eta_{LHV,st} = \frac{LHV}{\eta} \; if \; \eta = \frac{kWh}{kg} \end{cases} \tag{6}$$

$$\begin{cases} CAPEX_{st} = CAPEX \; if \; CAPEX = \frac{currency}{kW_{input}} \\ CAPEX_{st} = CAPEX \cdot \eta_{LHV,st} \; if \; CAPEX = \frac{currency}{kW_{output,LHV}} \\ CAPEX_{st} = CAPEX \cdot \eta_{LHV,st} \cdot \frac{HHV}{LHV} \; if \; CAPEX = \frac{currency}{kW_{output,HHV}} \end{cases} \tag{7}$$

$$CAPEX_{actualized,\ 2024} = CAPEX_{st} \cdot (1+i)^{(2024-Y_{report})} \tag{8}$$

$$\begin{cases} CAPEX_{EUR} = CAPEX \; if \; currency = € \\ CAPEX_{EUR} = CAPEX \cdot 0.92 \; if \; currency = US\$ \\ CAPEX_{EUR} = CAPEX \cdot 0.61 \; if \; currency = A\$ \\ CAPEX_{EUR} = CAPEX \cdot 1.17 \; if \; currency = £ \end{cases} \tag{9}$$

$$\begin{cases} OPEX_{st} = OPEX \; if \; OPEX = \%CAPEX \\ OPEX_{st} = OPEX \cdot \frac{\eta_{LHV,st}}{CAPEX_{st}} \; if \; OPEX = \frac{currency}{kWh_{LHV} \cdot yr} \\ OPEX_{st} = OPEX \cdot \frac{\eta_{LHV,st} \cdot \frac{HHV}{LHV}}{CAPEX_{st}} \; if \; OPEX = \frac{currency}{kWh_{HHV} \cdot yr} \end{cases} \tag{10}$$

$$\begin{cases} Pressure\ Status = \text{Atmospheric} \; if \; Pressure = 1 \\ Pressure\ Status = \text{Pressurized} \; if \; Pressure > 1 \end{cases} \tag{11}$$

Where P_{EL} is the nominal power of the electrolyser, LHV and HHV are the hydrogen lower and higher heating values respectively, η is the electrolyser efficiency, and Y_{report} is the data publication year.

Fig. 1 illustrates trends and variations over time in capital costs across PEM and AEL electrolysers, showcasing the decrease in capital costs with cumulative production or development.

Fig. 2 displays the relationship between capital cost and nominal power, along with cost function estimates for PEM and AEL electrolysers.

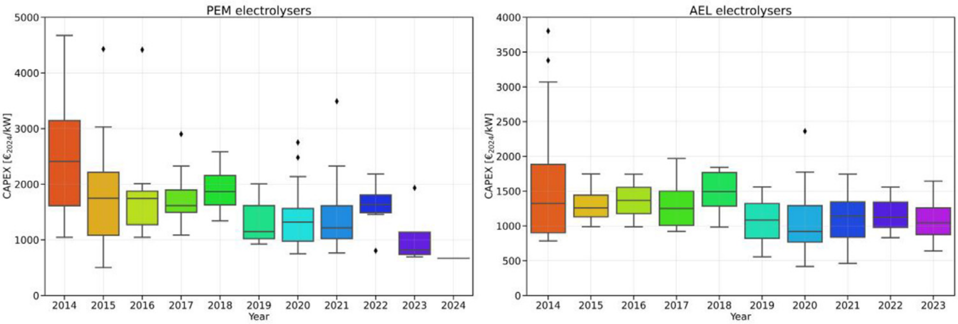

Fig. 1. Capital cost range over time for PEM (*left*) and AEL (*right*) electrolysers.

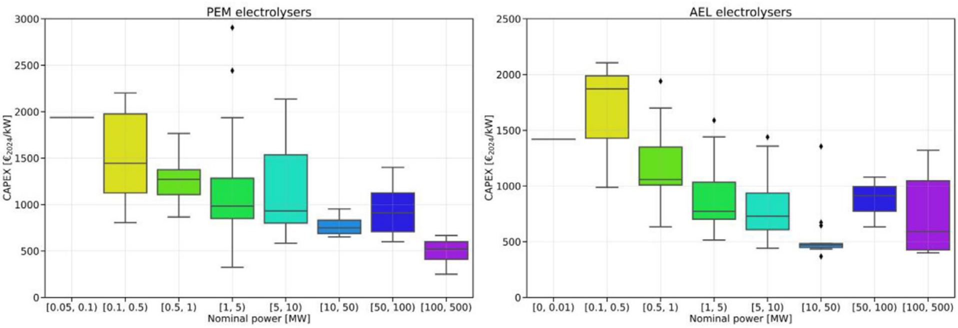

Fig. 2. Capital cost as a function of nominal power range for PEM (*left*) and AEL (*right*) electrolysers.

4.2. Fuel cells

The data processing for fuel cell technologies follows a similar approach as described for electrolysers:

1. Standardizing nominal size into output power capacity expressed in kW ($S_{FC,st}$) according to Eq. (12).
2. Reporting efficiency metrics as a percentage relative to the hydrogen lower heating value ($\eta_{LHV,st}$) according to Eq. (13).
3. CAPEX values are all expressed as currency per unit of output power ($CAPEX_{st}$), and OPEX data are reported as a percentage of CAPEX. Thus, no additional processing is required for these parameters.
4. Adjusting CAPEX data to euros 2024 by applying the inflation rate ($CAPEX_{actualized,\ 2024}$) and the currency-to-euros conversion factors ($CAPEX_{EUR}$) based on Eqs. (8) and (9).

$$\begin{cases} S_{FC,st} = S_{FC}\ if\ S_{FC} = \ kW \\ S_{FC,st} = S_{FC} \cdot LHV \cdot \eta_{LHV,st}\ if\ S_{FC} = \frac{kg}{h} \end{cases} \tag{12}$$

$$\begin{cases} \eta_{LHV,st} = \ \eta\ if\ \eta = \%_{LHV} \\ \eta_{LHV,st} = \eta \cdot \frac{LHV}{HHV}\ if\ \eta = \%_{HHV} \end{cases} \tag{13}$$

Figs. 3 and 4 depict trends in capital costs over time and nominal size for PEMFC and SOFC fuel cells.

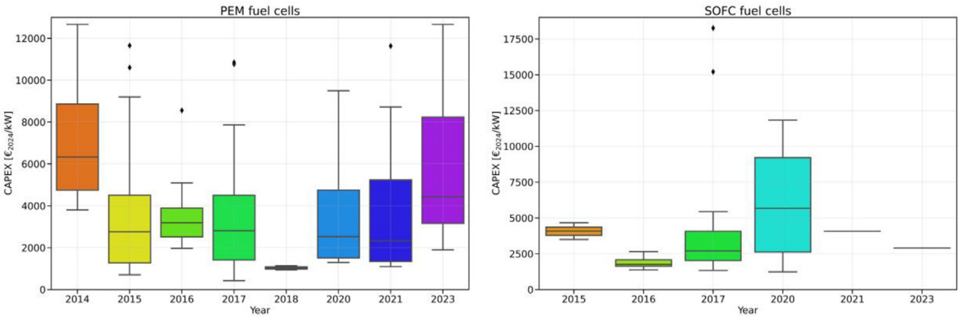

Fig. 3. Capital cost range over time for PEMFC (*left*) and SOFC (*right*) fuel cells.

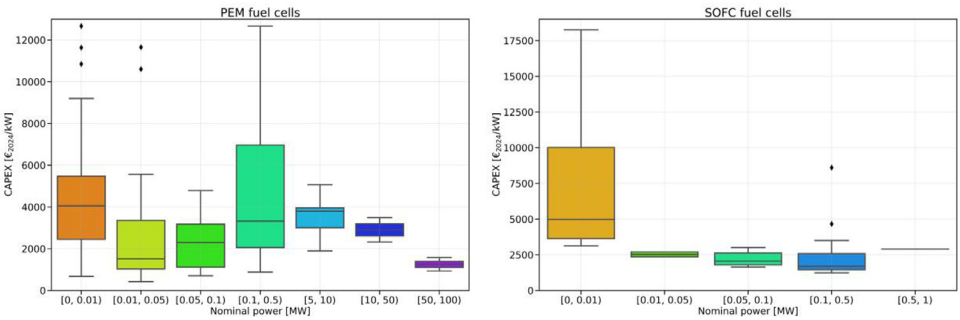

Fig. 4. Capital cost as a function of nominal power range for PEMFC (*left*) and SOFC (*right*) fuel cells.

4.3. Hydrogen compression units

The raw data pertaining to hydrogen compression units were processed through the following steps:

1. Standardizing nominal size into electrical input power expressed in kW ($S_{compr,st}$) according to Eq. (14).
2. Expressing CAPEX as currency per unit of input power ($CAPEX_{st}$), as per Eq. (15).
3. Adjusting CAPEX data to euros 2024 by applying the inflation rate ($CAPEX_{actualized,\ 2024}$) and currency-to-euros conversion factors ($CAPEX_{EUR}$) based on Eqs. (8) and (9).
4. Setting the minimum inlet pressure (P_{in}) at 1 and the maximum outlet pressure equal to "N/A" if raw data are not available in the reference report .

$$S_{compr,st} = S_{compr}\ if\ S_{compr} = kW$$
$$S_{compr,st} = S_{compr} \cdot \frac{Z \cdot T \cdot R}{M_{H_2} \cdot \eta_{st}} \cdot \frac{N \cdot \gamma}{\gamma - 1}\left[\left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{N\gamma}} - 1\right]\ if\ S_{compr} = \frac{kg}{h}$$
$$N = \frac{ceil\left(\frac{P_{out}}{P_{in}}\right)}{\beta_{max}} \tag{14}$$

$$\begin{cases} CAPEX_{st} = CAPEX\ if\ CAPEX = \frac{currency}{kW_{input}} \\ CAPEX_{st} = \frac{CAPEX \cdot S_{compr,\ kg/h}}{S_{compr,\ st}}\ if\ CAPEX = \frac{currency}{kg/h} \\ CAPEX_{st} = \frac{CAPEX}{S_{compr,st}}\ if\ CAPEX = \frac{currency}{compression\ unit} \end{cases} \tag{15}$$

Where Z is the hydrogen compressibility factor, T is the temperature at the inlet of the compressor, R is the ideal gas constant, M_{H_2} is the molecular mass of hydrogen, η_{st} is the compression efficiency, N the number of compressor stages, γ the diatomic constant factor, and β_{max} is the maximum compression ratio set equal to 8.

The trends in capital costs over time and nominal size for the hydrogen compression units is shown in Fig. 5.

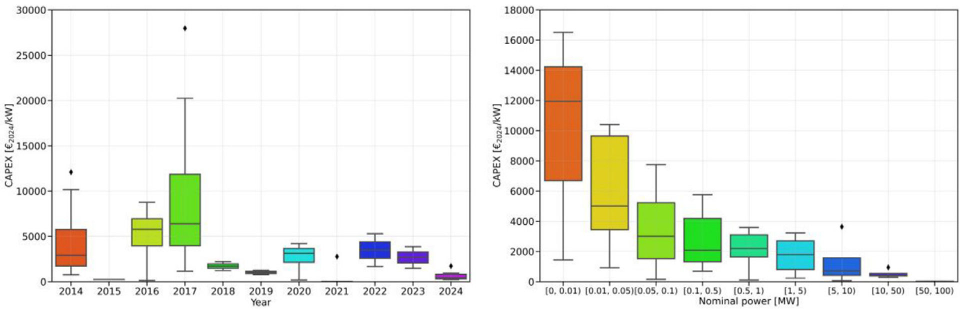

Fig. 5. Capital cost range over time (*left*) and capital cost as a function of nominal power range (*right*) for hydrogen compression units.

4.4. Hydrogen storage tank

The following steps were taken to process the raw data for hydrogen storage:

1. Standardizing nominal size into gravimetric capacity in kg ($S_{H_2tank,st}$) according to Eq. (16).
2. Expressing CAPEX as currency per unit of storage capacity ($CAPEX_{st}$), as per Eq. (17).
3. Adjusting CAPEX data to euros 2024 by applying the inflation rate ($CAPEX_{actualized,\ 2024}$) and currency-to-euros conversion factors ($CAPEX_{EUR}$) based on Eqs. (8) and (9).

$$\begin{cases} S_{H_2tank,st} = S_{H_2tank} \ if \ S_{H_2tank} = \ kg \\ S_{H_2tank,st} = S_{H_2tank} \cdot \rho_{H2} \ if \ S_{H_2tank} = m^3 \\ S_{H_2tank,st} = \frac{S_{H_2tank}}{LHV} \ if \ S_{H_2tank} = kWh \end{cases} \tag{16}$$

$$\begin{cases} CAPEX_{st} = CAPEX \ if \ CAPEX = \frac{currency}{kg} \\ CAPEX_{st} = \frac{CAPEX}{\rho_{H_2}} \ if \ CAPEX = \frac{currency}{m^3} \\ CAPEX_{st} = \frac{CAPEX}{LHV} \ if \ CAPEX = \frac{currency}{kWh_{H_2}} \\ CAPEX_{st} = \frac{CAPEX}{S_{H_2tank,st}} \ if \ CAPEX = \frac{currency}{tank} \end{cases} \tag{17}$$

Where ρ_{H2} is the hydrogen density.

Fig. 6 illustrates the trend of capital costs for hydrogen storage tanks over time and nominal size.

4.5. Battery energy storage systems

The following steps were taken to process the raw data for Li-ion battery energy storage systems:

1. Standardizing nominal size into energy storage capacity in kWh ($S_{BESS,st}$) according to Eq. (18).
2. Setting energy-to-power ratio ($h_{ch/dh}$) to 1 is this information is not given.

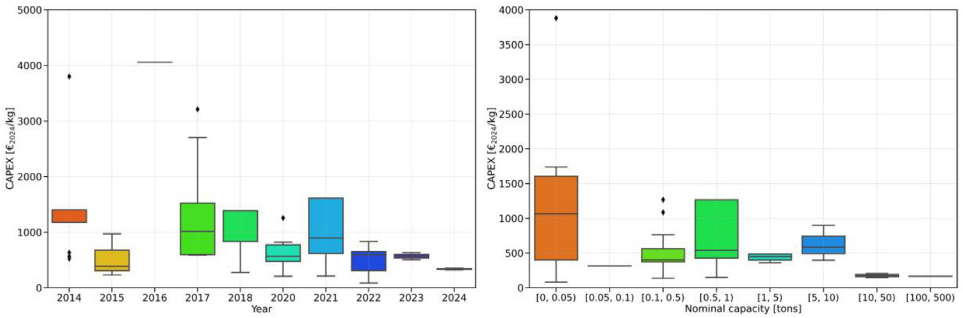

Fig. 6. Capital cost range over time (*left*) and capital cost as a function of nominal power range (*right*) for hydrogen storage.

3. Expressing CAPEX as currency per unit of storage capacity ($CAPEX_{st}$), as per Eq. (19).
4. Adjusting CAPEX data to euros 2024 by applying the inflation rate ($CAPEX_{actualized,\ 2024}$) and currency-to-euros conversion factors ($CAPEX_{EUR}$) based on Eqs. (8) and (9).
5. Standardizing round-trip-efficiency, according to Eq. (20).

$$\begin{cases} S_{BESS,st} = S_{BESS}\ if\ S_{BESS} = \ kWh \\ S_{BESS,st} = S_{BESS} \cdot h_{ch,dh}\ if\ S_{BESS} = \mathrm{kW} \end{cases} \tag{18}$$

$$\begin{cases} CAPEX_{st} = CAPEX\ if\ CAPEX = \frac{currency}{kWh} \\ CAPEX_{st} = \frac{CAPEX}{h_{ch,dh}}\ if\ CAPEX = \frac{currency}{kW} \end{cases} \tag{19}$$

$$\begin{cases} \eta_{R-T} = \eta\ if\ \eta = \eta_{ch} \cdot \eta_{dh} \\ \eta_{R-T} = \eta^2\ if\ \eta = \eta_{ch} \end{cases} \tag{20}$$

The cost function equation, as detailed in Eq. (21), considers both the energy storage capacity (S_{energy}) and nominal power (S_{power}).

$$CAPEX_{cost\ \ function} = \frac{C_{ref_1} S_{ref_1} \left(\frac{S_{energy}}{S_{ref_1}}\right)^{exp_1}}{S_{energy}} + \frac{C_{ref_2} S_{ref_2} \left(\frac{S_{power}}{S_{ref_2}}\right)^{exp_2}}{S_{power}} \tag{21}$$

Fig. 7 depicts the trend in capital costs for battery energy storage systems over time and across different nominal sizes.

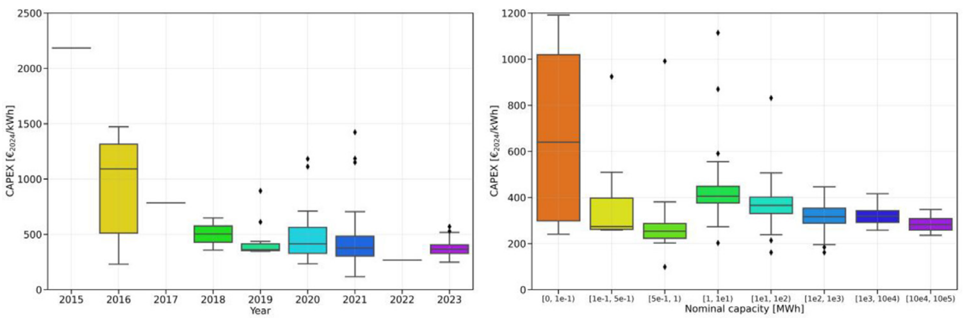

Fig. 7. Capital cost range over time (*left*) and capital cost as a function of nominal power range (*right*) for BESS.

Limitations

A review of relevant literature on investment costs for power-to-gas appliances has revealed significant variability in cost estimations, influenced by factors such as technology, system size, and year of installation. Additionally, comparing available data is challenging due to the frequent omissions of critical information, such as system size, included peripherals (e.g., gas conditioning), and capacity reference (electric input, lower heating value (LHV) output, higher heating value (HHV) output).

Ethics Statement

The authors declare that they did not conduct human or animal studies. The authors declare that they did not collect social media data and did not need permission to use the primary data.

Data Availability

Techno-Economic Data for Hydrogen Storage-Based Microgrids (Reference data) (Zenodo)

CRediT Author Statement

Elena Rozzi: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization; **Francesco D. Minuto:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration; **Andrea Lanzini:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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This manuscript reflects only the authors’ views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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