Data in Brief 60 (2025) 111666

Contents lists available at ScienceDirect

Data in Brief

journal homepage: www.elsevier.com/locate/dib

Data Article

Life cycle inventory dataset for energy production and storage technologies: Standardized metrics for environmental modeling

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A R T I C L E I N F O

Article history:
Received 28 March 2025
Revised 2 May 2025
Accepted 8 May 2025
Available online 14 May 2025

Dataset link: Life Cycle Assessment Data for Energy Production and Storage Technologies (Original data)

Keywords:
Environmental impact
Carbon footprint
Midpoint impact
LCA
Renewable energy
Energy storage
Energy communities

A B S T R A C T

The presented dataset provides the results of a comprehensive inventory of Life Cycle Assessments (LCA) for multiple energy production and storage technologies. Unlike conventional LCA studies, which often provide case-specific data that are difficult to apply in the analysis and design of energy systems, this work delivers standardized values, expressed per unit of installed capacity (kW), and, where relevant, per unit of operational energy output (kWh). These normalized metrics are essential for the integration of environmental considerations into energy system modeling and optimization. The dataset is the result of a comprehensive review of peer-reviewed studies, institutional reports, industrial data, and existing LCA databases. Robust average values were derived by consolidating information from multiple sources, thereby addressing a key gap in the literature whereby heterogeneous and fragmented data can make their practical application problematic. Minimum and maximum estimates are also reported to characterize the variability across technologies and datasets, providing a more comprehensive understanding of the underlying uncertainty. Unlike existing LCA databases, which are often paywalls, and can have highly detailed but less accessible data, this method provides aggregated and user-friendly parameters that are ready for di-

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https://doi.org/10.1016/j.dib.2025.111666

rect use. The inventory covers such technologies as photovoltaic systems, energy storage solutions, hydrogen production, internal combustion engines, boilers, heat pumps, and organic Rankine cycles, as well as energy carriers, including natural gas, electricity, hydrogen, and biomass. Environmental impacts are reported across multiple midpoint categories, such as the global warming potential, mineral and metal depletion, land and water use, particulate matter, acidification, eutrophication, ecotoxicity, ionizing radiation, human toxicity, and the ozone depletion potential. The dataset, which was drawn up according to International Reference Life Cycle Data System (ILCD), ReCiPe Life Cycle Impact Assessment Method (ReCiPe), and Intergovernmental Panel on Climate Change Global Warming Potential (IPCC GWP) guidelines, ensures consistency and comparability across technologies. Moreover, the dataset, which is provided as an open-access Excel Workbook, is readily applicable to environmental assessments, optimization studies, and energy planning in energy communities and smart grids, to support informed decisions for sustainable energy transitions.

Specifications Table

Subject	Earth & Environmental Sciences
Specific subject area	Life Cycle Assessment of energy technologies through the evaluation of environmental impacts using midpoint indicators to obtain sustainable energy planning.
Type of data	Table Raw, Filtered, Processed
Data collection	Literature survey (databases, reports from national and international institutions, peer-reviewed journal articles)
Data source location	The raw data sources are listed in this article and in the data repository
Data accessibility	Repository name: Zenodo Data - Life Cycle Assessment Data for Energy Production and Storage Technologies Data identification number: 10.5281/zenodo.15095980 Direct URL to data: https://zenodo.org/records/15324175
Related research article	None

1. Value of the Data

- The dataset offers detailed and harmonized life cycle assessment data across a wide range of energy technologies and carriers. This makes it invaluable for comparisons of the environmental impacts of various energy systems and to support the development of sustainable energy production and storage solutions.
- The dataset mainly reports information on LCA emissions per unit of installed technology capacity (kW), with some additional operational-phase data (kWh) provided, whenever relevant, e.g. for CO_2 emissions. This approach allows a more accurate sizing and optimization of systems during the design phase and makes it easier to obtain a clear evaluation of the environmental performance across their life cycles.
- This data can also be used to model and assess integrated energy systems, such as smart grids or renewable energy communities (RECs), which combine different energy production

and storage technologies. Researchers can use the obtained LCA values to optimize the environmental performance of complex systems.
- The dataset complies with internationally recognized LCA methodologies, including ILCD, ReCiPe, and IPCC GWP. This ensures consistency and comparability across different studies, thus making the dataset a valuable resource for sustainability assessments and cross-study comparisons.
- The open-access nature of the dataset allows researchers, policymakers, and industry experts to introduce it into their own studies. Its versatility makes it suitable for use over a wide range of applications, ranging from environmental impact assessments to energy policy analysis and strategic energy planning.

2. Background

This dataset was developed in response to the growing need for accurate and consistent environmental LCA data across a wide range of energy production, storage, and conversion technologies. As the energy sector is shifting toward more sustainable systems, having reliable data is crucial to model and optimize integrated energy systems, including photovoltaic systems, hydrogen production, energy storage solutions, and biomass technologies. Indeed, the dataset can be used to support the design, management, and optimization of energy systems, such as microgrids, energy communities, and smart grids.

It compiles detailed LCA data across various environmental impact categories, such as CO_2 emissions, land use, resource depletion, and water use, thereby ensuring comprehensive coverage of the key sustainability concerns. The data were collected through an extensive review of highly quoted LCA studies, reports from reputable national and international institutions, and other established sources to provide a reliable foundation for technology comparisons.

The dataset, in which the data are normalized to standard units, facilitates consistent comparisons and evaluations of the environmental performance of different technologies, thereby enabling an accurate sizing and optimization of systems. Thus, the dataset contributes to advancing knowledge of sustainable energy transitions, as it offers valuable insights for researchers, policymakers, and professional figures in industry to support informed decisions in the design and implementation of energy systems with a minimal environmental impact.

3. Data Description

This paper presents a detailed overview of the dataset that is available in the linked repository [1], which compiles LCA parameters for equipment utilized in the generation, conversion, and storage of energy. The dataset encompasses a diverse range of energy technologies, including photovoltaic systems, hydrogen production, energy storage solutions, biomass technologies, internal combustion engines, boilers, heat pumps, and organic Rankine cycles. The structure of the developed database is summarized in Fig. 1, which shows a categorization of the energy technologies, and the set of life cycle assessment indicators included for each system block.

This dataset is organized in a single Excel file which comprises 16 distinct sheets. The initial sheets, named “Metadata” and “References”, provide the essential context and documentation:

- The Metadata sheet outlines the key attributes of the dataset.
- The References sheet categorizes the sources of the collected data, distinguishing between peer-reviewed journal articles and reports, online databases, and other reference materials.

The remaining sheets contain the processed and harmonized LCA data, and they ensure consistency of the measurement units across various energy technologies. These sheets are structured as follows:

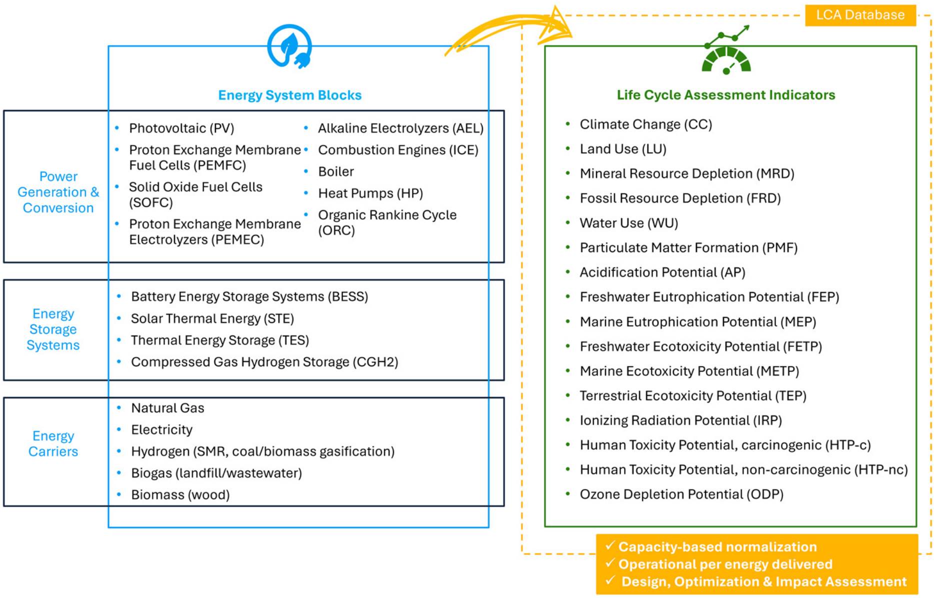

Fig. 1. Schematic of the database structure, showing the energy system components (generation, storage, and energy carriers) and the associated environmental impact indicators.

- PV: LCA inventory for Distributed Photovoltaic (PV) systems, which are further classified into Mono-crystalline Silicon (Mono-Si), Poly-crystalline Silicon (Poly-Si), Copper Indium Gallium Selenide (CIS/CIGS), and Cadmium Telluride (CdTe) technologies.
- BESS: LCA data for Battery Energy Storage Systems (BESS).
- STE: LCA data for Solar Thermal Energy (STE) technologies.
- TES: LCA inventory for Thermal Energy Storage (TES) systems.
- PEMFC: LCA dataset for Proton Exchange Membrane Fuel Cells (PEMFC).
- SOFC: LCA data for Solid Oxide Fuel Cells (SOFC).
- PEMEC: LCA assessment for Proton Exchange Membrane Electrolyzers (PEMEC).
- AEL: LCA data for Alkaline Electrolyzers (AEL).
- CGH2: LCA inventory for Compressed Gas Hydrogen Storage (CGH2).
- ICE: LCA dataset for Internal Combustion Engines (ICE).
- Boiler: LCA inventory for Boiler systems.
- HP: LCA dataset for Heat Pumps (HP).
- ORC: LCA data for Organic Rankine Cycle (ORC) systems.
- Energy Carriers: LCA dataset for various energy carriers, including natural gas, electricity, hydrogen from steam methane reforming (SMR), coal gasification, biomass gasification, biogas, and biomass.

In addition, the repository includes a second Excel file that summarizes the impact results, reporting the average, minimum, and maximum values for each technology and each environmental impact category.

Table 1 presents the primary references from which the technological and environmental data were sourced. The number of datapoints depends on the number of available data reported in the literature.

The dataset incorporates several key environmental parameters that offer comprehensive insights into the environmental impacts associated with the technologies of multiple impact categories, including climate change, resource depletion, land use, water consumption, emissions of particulate matter, acidifying and eutrophying substances, ecotoxicity, ionizing radiation, human

Table 1
List of sources for the LCA data and number of values collected across technologies. The references include peer-reviewed studies and reports covering midpoint environmental indicators across 200 entries from 79 sources.

Technology		References	Number of datapoints
PV		[2–11]	33
BESS		[12–19]	20
STE		[9,10,20,21]	13
TES		[12,20]	5
PEMFC		[22–27]	8
SOFC		[27–34]	18
PEMEC		[33–37]	8
AEL		[33–36,38]	6
CGH2		[39–42]	17
ICE		[43–46]	10
Boiler		[27,45,47,47–52]	8
HP		[47–50,52,53]	12
ORC		[34,54–57]	10
Energy carriers	Natural gas	[58–60]	3
	Electricity	[61–64]	6
	H_2 (SMR)	[42,65–68]	5
	H_2 (Coal gasification)	[68,69]	2
	H_2 (Biomass gasification)	[68,70–72]	4
	Biogas (landfill or wastewater)	[29,73–77]	8
	Biomass (wood)	[78–80]	4
TOTAL		79 references	200

toxicity, and ozone layer depletion. The dataset provides harmonized LCA indicators that are normalized per unit of installed technology capacity, operational CO_2 emissions per unit of energy delivered, and the environmental impact of energy carriers per unit of fuel energy content, thus enabling consistent comparisons across different technologies and facilitating accurate system-level assessments. An overview of the LCA data structure and the corresponding parameters is presented in Table 2.

In addition to the comprehensive dataset that is available in the repository, a summary of the key LCA indicators is presented hereafter to provide a detailed overview of the environmental performance of the selected technologies. This summary focuses on five representative and widely recognized midpoint impact categories:

- Climate Change (manufacturing and operational phases)
- Land Use
- Mineral and Metal Depletion
- Water Use.

These categories were selected due to their prevalence in energy-related, LCA studies, and to their relevance for stakeholders who have to assess the environmental implications of power generation, conversion, and storage technologies.

The minimum, average, and maximum values of each technology are reported to capture the variability observed in the literature and to offer a clear understanding of the range of environmental impacts. The summary tables facilitate an intuitive comparison of the technologies and energy carriers, and they highlight the key trade-offs and performance differences.

Tables 3–5 present the aggregated results, expressed per unit of installed capacity (e.g., $kg_{CO2,eq}$/kW) or per unit of energy delivered or processed (e.g., $kg_{CO2,eq}$/MWh), with the latter applying to both energy carriers and the operational phase of technologies.

Table 2
Life cycle assessment parameters included in the dataset across various technologies. The table summarizes LCA parameters including general metadata, additional technical specifications, and normalized environmental impact indicators. For each parameter, the name, dataset code (i.e., variable identifier), unit of measurement, and description are provided, offering a concise overview of the dataset structure.

Parameter	Code	Unit	Description
Reference number	reference_number	–	Bibliographic reference or source for which the data was extracted
Reference years	report_year	–	Year of publication of the report
Specific technology	technology	–	Technology to which the reported data pertains
Nominal size	size_kWel, size_kWth	kW	Nominal capacity metrics representative of the technology size
	size_kWh	kWh	
	size_m3	m^3	
Additional technology specifications	mounting	Roof or ground	Installation type of solar panels/collectors: rooftop installation or ground-mounted system
	number_of_cycles	–	Battery lifespan, expressed as the total number of charge-discharge cycles.
	feedstock	–	Type of fuel that powers the technology
	refrigerant	–	Type of refrigerant fluid
	carrier	–	Type of energy carrier
Climate change (CC)	CC_kgCO2_per_kW_manufactory	kg_{CO2}/kW	Impact of climate change, in terms of CO_2 emissions per unit of energy or power
	CC_kgCO2_per_kWh_manufactory	kg_{CO2}/kWh	
	CC_gCO2_per_kWh_operational	kg_{CO2}/kWh	
	CC_kgCO2_per_MWh_direct	kg_{CO2}/MWh	
	CC_kgCO2_per_MWh_indirect	kg_{CO2}/MWh	
Land use (LU)	LU_m2a_per_kW	m^2a/kW	Land occupation required for the technology
	LU_m2a_per_kWh	m^2a/kWh	
	LU_kgCO2_per_kW	kg_{CO2}/kW	
	LU_m2a_per_MWh	m^2a/MWh	
Mineral resource depletion (MRD)	MRD_gSb_per_kW	g_{Sb}/kW	Depletion of mineral resources associated with the technology
	MRD_gSb_per_kWh	g_{Sb}/kWh	
	MRD_kgCu_per_kW	kg_{Cu}/kW	
	MRD_kgCu_per_kWh	kg_{Cu}/kWh	
	MRD_kgFe_per_kWh	kg_{Fe}/kWh	
	MRD_gSb_per_MWh	g_{Sb}/MWh	
	MRD_kgCu_per_MWh	kg_{Cu}/MWh	
Fossil resource depletion (FRD)	FRD_MJ_per_kW	MJ/kW	Fossil fuel energy consumption required for the technology
	FRD_MJ_per_kWh	MJ/kWh	
	FRD_MJ_per_MWh	MJ/MWh	
Water use (WU)	WU_m3_per_kW	m^3/kW	Water consumption associated with the technology
	WU_m3_per_kWh	m^3/kWh	
	WU_m3_per_MWh	m^3/MWh	
Particulate matter formation (PMF)	PMF_10e-6disease_per_kW	10^{-6} disease/kW	Particulate matter emissions associated with the technology
	PMF_kgPM2.5_per_kW	$kg_{PM2.5}/kW$	
	PMF_kgPM2.5_per_kWh	$kg_{PM2.5}/kWh$	
	PMF_kgPM2.5_per_MWh	$kg_{PM2.5}/MWh$	
Acidification potential (AP)	AP_molH+_per_kW	mol_{H+}/kW	Potential acidification emissions from the technology
	AP_molH+_per_kWh	mol_{H+}/kWh	
	AP_kgSO2_per_kW	kg_{SO2}/kW	
	AP_kgSO2_per_kWh	kg_{SO2}/kWh	
	AP_molH+_per_MWh	mol_{H+}/MWh	
	AP_kgSO2_per_MWh	kg_{SO2}/MWh	
Freshwater eutrophication potential (FEP)	FEP_gP_per_kW	g_P/kW	Impact on freshwater ecosystems due to nutrient enrichment
	FEP_gP_per_kWh	g_P/kWh	
	FEP_gP_per_MWh	g_P/MWh	
Marine eutrophication potential (MEP)	MEP_gN_per_kW	g_N/kW	Impact on marine ecosystems due to nutrient enrichment
	MEP_gN_per_kWh	g_N/kWh	
	MEP_gN_per_MWh	g_N/MWh	

(*continued on next page*)

Table 2 (*continued*)

Parameter	Code	Unit	Description
Freshwater ecotoxicity potential (FETP)	FETP_CTUe_per_kW FETP_CTUe_per_kWh FETP_kgDCB_per_kW FETP_kgDCB_per_kWh FETP_kgDCB_per_MWh	CTUe/kW CTUe/kWh kgDCB/kW kgDCB/kWh kgDCB/MWh	Toxicity potential in freshwater environments
Marine ecotoxicity potential (METP)	METP_kgDCB_per_kW METP_kgDCB_per_MWh	kgDCB/kW kgDCB/MWh	Toxicity potential in marine environments
Terrestrial ecotoxicity potential (TEP)	TETP_kgDCB_per_kW TETP_kgCTUe_per_kW TETP_kgDCB_per_kWh TETP_kgDCB_per_MWh	kgDCB/kW CTUe/kW kgDCB/kWh kgDCB/MWh	Toxicity potential in terrestrial environments
Ionizing radiation potential (IRP)	IRP_kgU235_per_kW IRP_kBqU235_per_kWh IRP_kBqCo60_per_kW IRP_kBqU235_per_MWh IRP_kBqCo60_per_MWh	kg_{U235}/kW kBq_{U235}/kWh kBq_{Co60}/kW kBq_{U235}/MWh kBq_{Co60}/MWh	Ionizing radiation emissions from the technology
Human toxicity potential, carcinogenic (HTP-c)	HTPc_mCTUh_per_kW HTPc_CTUh_per_kWh HTPc_kgDBC_per_kW HTPc_1,4-DB _per_kWh HTPc_CTUh_per_MWh HTPc_kgDBC_per_MWh	mCTUh/kW CTUh/kWh kg_{DBC}/kW $kg_{1,4\text{-}DB}$ /kWh CTUh/MWh kg_{DBC}/MWh	Human toxicity potential pertaining to carcinogenic substances
Human toxicity potential, non-carcinogenic (HTP-nc)	HTPnc_1,4-DB _per_kWh HTPnc_CTUh_per_kWh HTPnc_kgDBC_per_kW HTPnc_CTUh_per_MWh HTPnc_kgDBC_per_MWh	$kg_{1,4\text{-}DB}$ /kWh CTUh/kWh kg_{DBC}/kW CTUh/MWh kg_{DBC}/MWh	Human toxicity potential pertaining to non-carcinogenic substances
Ozone depletion potential (ODP)	ODP_mgCFC11_kW ODP_mgCFC11_kWh ODP_mgCFC11_MWh	mg_{CFC11}/kW mg_{CFC11}/kWh mg_{CFC11}/MWh	Contribution to ozone layer depletion
Notes and assumptions	notes	–	Additional considerations regarding data assumptions and methodology

Table 3
Summary of the LCA indicators for power generation and conversion technologies. The table reports minimum, average, and maximum values for selected midpoint impact categories - Climate Change (manufacturing and operational), Land Use, Mineral and Metal Depletion, and Water Use -normalized per unit of installed capacity or delivered energy, as appropriate.

		Climate Change - Manufacturing $kg_{CO2,eq}$/kW	Climate Change - Operational $g_{CO2,eq}$/kWh	Land Use m^2/kW	Mineral and Metal Depletion g_{Sb}/kW	Water Use m^3/kW
Mono-Si PV	min	1243	0.01	37	41	225
	average	2002	0.01	115	119	592
	max	2412	0.01	215	159	960
Poly-Si PV	min	1101	0.01	37	41	201
	average	1291	0.01	205	126	588
	max	1464	0.01	1200	216	816
CIS/CIGS PV	min	342	0.01	29	50	146
	average	861	0.01	196	84	176
	max	1185	0.01	765	140	212
CdTe PV	min	357	0.01	33	46	69
	average	553	0.01	290	110	135
	max	775	0.01	792	158	212

(*continued on next page*)

Table 3 (*continued*)

		Climate Change - Manufacturing $kg_{CO2,eq}$/kW	Climate Change - Operational $g_{CO2,eq}$/kWh	Land Use m^2/kW	Mineral and Metal Depletion g_{Sb}/kW	Water Use m^3/kW
STE	min	317	–	5	5	1
	average	351	–	15	55	3
	max	371	–	23	66	4
PEMFC	min	24	0.02	3	2	0.5
	average	116	0.53	6	2	9
	max	293	1.65	10	2	22
SOFC	min	185	0.005	–	–	0
	average	565	0.009	–	–	32
	max	794	0.021	–	–	181
PEMEC	min	84	0.095	7	2	2
	average	275	0.406	9	66	3
	max	489	1.019	12	170	4
AEL	min	28	0.006	4	2	1
	average	154	0.006	8	19	3
	max	476	0.006	12	43	4
ICE	min	772	–	3	14	92
	average	772	–	3	14	92
	max	772	–	3	14	92
Boiler	min	280	0.26	1	1	42
	average	520	0.27	24	4	42
	max	760	0.27	47	9	42
HP	min	78	0.09	75	6	233
	average	445	0.10	80	13	889
	max	1028	0.11	85	18	1283
ORC	min	117	0.00	24	8	3
	average	186	0.04	30	74	27
	max	314	0.08	41	139	122

Table 4
Summary of the LCA indicators for energy storage systems. The table reports minimum, average, and maximum values for selected midpoint impact categories - Climate Change (manufacturing and operational), Land Use, Mineral and Metal Depletion, and Water Use -normalized per unit of installed capacity or delivered energy, as appropriate.

		Climate Change - Manufacturing $kg_{CO2,eq}$/kWh	Climate Change - Operational* $g_{CO2,eq}$/kWh	Land Use m^2/kWh	Mineral and Metal Depletion g_{Sb}/kWh	Water Use m^3/kWh
BESS	min	28	39	1	28	0.4
	average	135	60	4	107	1
	max	308	112	7	195	2
TES	min	3	–	0	7	–
	average	4	–	0	28	–
	max	4	–	0	78	–
CGH2	min	14	4	–	0.1	4
	average	27	5	–	0.6	4
	max	54	7	–	1	4

* In this table, kWh refers to the installed storage capacity (i.e., system size) in all the columns, except for the Climate Change Operational column, where kWh indicates the amount of energy delivered during the operational phase.

Table 5
Summary of the LCA indicators for energy carriers. The table reports minimum, average, and maximum values for selected midpoint impact categories - Climate Change (manufacturing and operational), Land Use, Mineral and Metal Depletion, and Water Use - normalized per unit of fuel energy content.

		Climate Change - Indirect $kg_{CO2,eq}$/MWh	Climate Change - Direct $kg_{CO2,eq}$/MWh	Land Use m^2/MWh	Mineral and Metal Depletion g_{Sb}/MWh	Water Use m^3/MWh
Natural Gas	min	30	153	0.00	–	0.04
	average	32	173	0.03	–	0.06
	max	34	198	0.05	–	0.09
Electricity	min	0	248	0.04	3	48
	average	0	420	0.04	4	112
	max	0	680	0.04	7	186
H_2 -SMR	min	0	315	0.2	0.04	12
	average	0	425	0.3	0.04	104
	max	0	701	0.4	0.04	173
H_2 - Coal Gasification	min	0	726	7	0.05	393
	average	0	885	7	0.26	393
	max	0	1044	7	0.46	393
H_2 - Biomass Gasification	min	0	43	1	0.02	148
	average	0	97	134	0.02	148
	max	0	168	267	0.02	148
Biogas	min	45	3	102	0.13	56
	average	50	103	102	0.13	168
	max	54	214	102	0.13	254
Biomass (wood)	min	12	28	0.6	0.05	25
	average	15	94	0.6	0.05	28
	max	18	169	0.6	0.05	32

4. Experimental Design, Materials and Methods

The dataset was developed through a systematic data collection process, on the basis of an extensive literature review. Three major online bibliographic sources were consulted to ensure comprehensive coverage of the relevant scientific and technical literature: Scopus (https://www.scopus.com/), Google Scholar (https://scholar.google.com/), and Google Search (https://www.google.com/). The search was conducted in English, and it was focused on retrieving documents that reported LCA midpoint indicators for energy production, conversion, and storage technologies.

Each selected document underwent a full-text review to extract the relevant data, while any additional studies cited within these documents were also analyzed and included, whenever appropriate. A thorough validation step was conducted, after the data extraction, to eliminate duplicates, to cross-check the obtained values, and to ensure the internal consistency of the dataset.

Documents were selected for each technology on the basis of the availability of at least one LCA midpoint indicator, along with additional key parameters, such as nominal capacity, energy or power output, and operational lifetime. These parameters were necessary to convert the environmental impacts - typically expressed per unit of energy delivered (e.g., kg_{CO2}/kWh) - into values normalized per unit of installed technology capacity (e.g., kg_{CO2}/kW).

This conversion was systematically applied to all the environmental indicators, which were normalized per unit of installed capacity. The only exception was Operational Climate Change, for which we maintained the per unit of energy delivered (kg_{CO2}/kWh) to reflect their specific relevance to the use-phase and to ensure alignment with standard LCA reporting practices. The distinction between the manufacturing and operational phases was only made for CO_2 emissions, as CO_2 is the most significant contributor during the operational phase, and such a disaggregation was deemed feasible, considering the available data, which were either directly reported in some studies or derived from energy consumption. This separation was not performed for any of the other impact categories, due to the lack of consistent data in the literature, where operational-phase contributions are rarely quantified independently. The normalization was performed by calculating the total lifetime energy output (i.e., the product of annual energy delivered and the lifetime of the system) and dividing the original LCA values by the nominal capacity of the technology, as expressed in Eq. (1).

$$\text{Impact}_{\text{normalized}} = \frac{\text{Impact}_{\text{per kWh delivered}} \cdot \text{Annual energy output} \cdot \text{Lifetime}}{\text{Nominal capacity}} \tag{1}$$

Where $\text{Impact}_{\text{per kWh delivered}}$ is the LCA indicator that was originally reported per unit of energy delivered, Annual energy output is the energy delivered by the system in one year, Lifetime is the expected operational life of the technology in years, and Nominal capacity is the rated capacity of the system, expressed in kW for generation technologies or in kWh for storage systems.

For illustrative purposes, consider a PV system with an annual energy yield of 2925 kWh, a service life of 30 years, an installed capacity of 3 kW_p, and a life cycle climate change impact of 42.5 g_{CO2}/kWh delivered. The normalized impact per unit of installed capacity (expressed in kg_{CO2}/kW) is calculated according to Eq. (2).

$$\text{Impact}_{\text{normalized}} = \frac{42.5\left[\frac{g_{CO_2}}{kWh}\right] \cdot 2925\ [kWh] \cdot 30\ [yr]}{3\ [kW_p] \cdot 1000\left[\frac{g}{kg}\right]} = 1243\left[\frac{kg_{CO_2}}{kW_p}\right] \tag{2}$$

In this calculation, the numerator represents the total CO_2 emissions over the system's lifetime energy output, while the denominator includes the installed capacity and the conversion factor to kilograms.

No conversion to installed capacity was performed for energy carriers, such as natural gas, electricity, hydrogen or biomass. Indeed. their LCA emissions were retained in their original form, i.e., expressed as emissions per unit of fuel energy content (MWh of carrier energy).

Fig. 2 schematically illustrates how the different components of the energy system are categorized and how their environmental impacts are expressed. The figure differentiates between design variables whose impacts are quantified per unit of installed capacity (as defined in Eq. (1)), operational variables whose impacts are expressed per unit of energy processed (generation, conversion, storage), and energy carriers, for which the impacts are retained in their energy-based units. In the figure, light blue arrows refer to operational impacts, dark blue arrows indicate energy carrier impacts (in this case, the carbon intensity of electricity drawn from the grid), and devices highlighted in red represent the technologies to which manufacturing-related

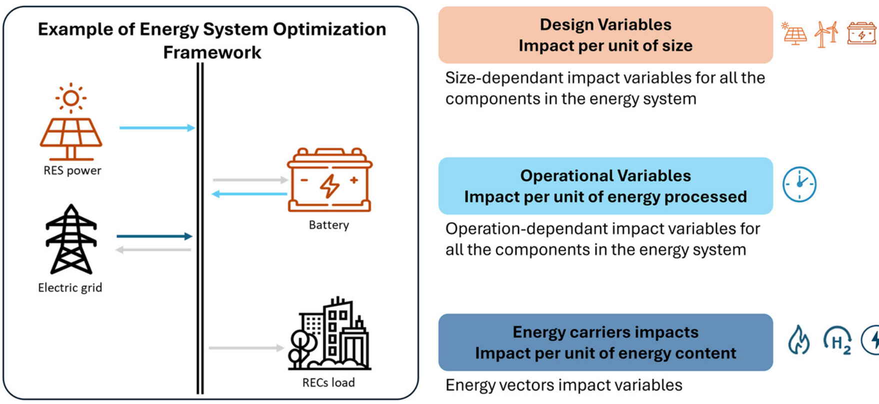

Fig. 2. Schematic representation of the categorization of energy system components and the corresponding units used for environmental impact attribution. Design variables are expressed per unit of installed capacity, operational variables are expressed per unit of energy processed, and energy carrier impacts are reported per unit of energy content.

impacts are attributed. Together, these differentiated contributions define the overall environmental performance of the energy system and enable a consistent integration of heterogeneous components within a unified optimization framework.

All the data harmonizations and conversions were implemented in Microsoft Excel using standardized formulas to ensure reproducibility and transparency. The dataset was structured in tabular format, with one sheet dedicated to each technology and energy carrier.

Fig. 3 presents the comparative life cycle assessment results across a range of midpoint impact categories for the analyzed hydrogen production, energy conversion, and storage technologies. The figure aggregates environmental performance indicators across 17 impact categories, distinguishing between power generation and conversion technologies, storage systems, and energy carriers. Results are expressed using normalized units consistent with the functional role of each technology, as previously defined. To support transparency and reproducibility, the dataset underlying Fig. 3 comprising summary statistics including mean, minimum, and maximum values for each impact category is made available in the associated data repository [1].

The comparative assessment reveals distinct environmental performance patterns among the technologies. In the manufacturing phase, the HP, boiler, ICE, and PV systems exhibit comparatively relevant contributions to climate change potential, primarily due to energy- and material-intensive production processes. Heat pumps, and to a lesser extent, boilers, are characterized by substantial uncertainty ranges, as shown by wide error bars, which reflect the variability in reported data and sensitivity to assumptions regarding material composition, component lifetime, and system boundaries.

In contrast, operational climate change impacts remain relatively low for most technologies, with the exception of BESS, whose operational emissions are significantly affected by maintenance cycles and component replacements. Among energy carriers, NG and biogas exhibit the highest operational (direct) emissions, driven by direct CO_2 release during combustion, whereas the impact of electricity largely depends on the indirect emissions associated with the national energy mix.

With respect to land use, the most significant impacts are associated with biomass-based energy carriers, including both hydrogen from biomass gasification and biogas, mainly due to the cultivation and harvesting of biomass feedstocks. Here, high variability points to substantial differences in land intensity across crop types and agricultural practices.

In terms of mineral resource depletion, PV and BESS again rank among the most critical, highlighting their dependence on rare and strategic raw materials such as silicon, lithium, and cobalt. ORC systems, solar thermal collectors, and electrochemical devices (fuel cells and electrolyzers) also show moderate but relevant contributions to this category, reflecting the embedded impact of complex material supply chains.

The fossil resource depletion indicator shows pronounced values for HP and Boiler, likely due to upstream inputs such as thermal insulation materials, refrigerants, and other fossil-derived components. Other technologies display more consistent and lower values, suggesting a reduced reliance on fossil-based manufacturing inputs.

Impacts related to water use, ozone depletion, and marine eutrophication are largely dominated by HP technologies, consistent with their dependency on refrigerants and water-intensive processes. In contrast, acidification and freshwater eutrophication potentials are mainly driven by ICE systems, which contribute via upstream fuel production and direct emissions of sulfur- and nitrogen-containing compounds.

As for ionizing radiation impacts, elevated values are observed for technologies that depend on grid electricity, such as HP and ORC, reflecting the influence of nuclear power in the electricity mix and its significant contribution to upstream emissions. This underscores the importance of background energy systems in shaping the life cycle performance of electrically powered technologies.

Finally, human and ecotoxicity potentials, either carcinogenic or non-carcinogenic, are highest for Boiler, ORC, and electrochemical technologies (fuel cells, electrolyzers, and BESS), due to their reliance on complex supply chains involving mining, chemical treatment, and material processing.

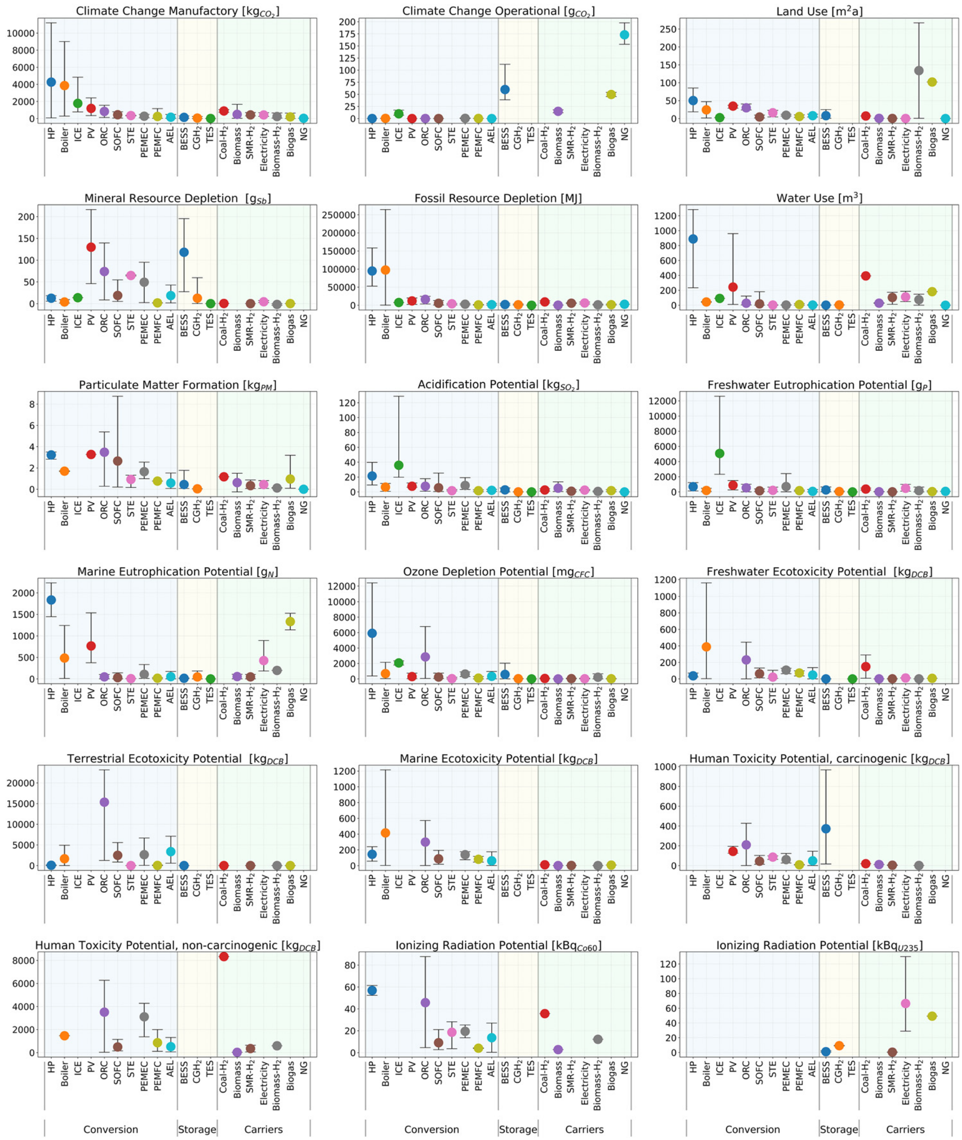

Fig. 3. Comparative life cycle assessment results for energy conversion technologies, energy storage systems, and energy carriers across 17 midpoint environmental impact categories. Technologies are grouped as Conversion (normalized per unit of power capacity, e.g., kg_{CO2}/kW), Storage (per unit of energy capacity, e.g., kg_{CO2}/kWh), and Carriers (per unit of energy content, e.g., kg_{CO2}/MWh). For Climate Change Operational category, both Conversion and Storage technologies are expressed per unit of energy delivered (e.g., kg_{CO2}/kWh). For energy carriers, manufacturing CO_2 emissions correspond to indirect emissions (e.g., coal gasification for hydrogen production), while operational CO_2 emissions represent direct emissions (e.g., natural gas combustion). Error bars indicate the range between minimum and maximum values reported in the literature, reflecting data variability and uncertainty.

Limitations

The dataset presents a wide range of variability of the collected values, particularly for certain indicators, such as land use, mineral depletion, and water use, as highlighted in Fig. 3. This variability reflects the heterogeneity of the technologies, of the regional contexts, and of the methodological choices found in the literature. In many cases, studies assess integrated systems including multiple components, thus making it challenging to disaggregate the LCA indicators and allocate impacts to individual technologies. Additionally, not all the sources clearly specified the adopted functional unit, or the assumptions related to the size, energy output, and/or lifetime of the system.

This issue is particularly critical for technologies such as heat pumps and cogeneration units, where it is often unclear whether thermal output is included in the system boundary and in the energy accounting.

Despite these limitations, the dataset provides a harmonized and transparent structure that facilitates the consistent use and comparison of available data. All impact values have been normalized according to technology function, enabling integration into broader modelling frameworks or decision-support tools. The dataset includes both conventional and widely adopted technologies, as well as selected emerging options with relatively high technology readiness levels (TRL), with a specific focus on energy communities in urban contexts. Future work may expand this dataset to include lower-TRL technologies, as well as options from other sectors, such as transportation and industry, thereby offering a more comprehensive perspective on long-term energy transition scenarios.

In addition, opportunities exist to leverage data science approaches, such as artificial intelligence and automated literature mining, for the periodic updating and expansion of the dataset, especially to capture innovation trends in new storage materials, power-to-X systems, and hybrid energy solutions. Continued efforts in standardizing functional units and reporting practices across the literature will also be essential to reduce uncertainty and improve the robustness of future assessments.

Ethics Statement

The authors declare that no human or animal studies were conducted in the course of this research. Additionally, no social media data were collected or analyzed. All the primary data used in this study were derived exclusively from publicly available, third-party literature and databases. The authors confirm that the data sources comply with open-access policies and licensing standards, and that appropriate permissions and terms of use were verified prior to their inclusion in the analysis. Where applicable, citations and acknowledgements have been provided, in accordance with the original data providers' guidelines.

Data Availability

Life Cycle Assessment Data for Energy Production and Storage Technologies (Original data) (Zenodo).

CRediT Author Statement

Elena Rozzi: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing – original draft; **Paolo Marocco:** Conceptualization, Methodology, Supervision, Writing – review & editing; **Marta Gandiglio:** Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing.

Acknowledgements

This research has been funded by the EU – Next Generation EU, Mission 4, Component 1, CUP E53D23004020006, project entitled "Smart Energy in Cities and Communities for 2050" (Prot. 2022ZM87LR).

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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