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Data Article

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

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ABSTRACT

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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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.

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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:

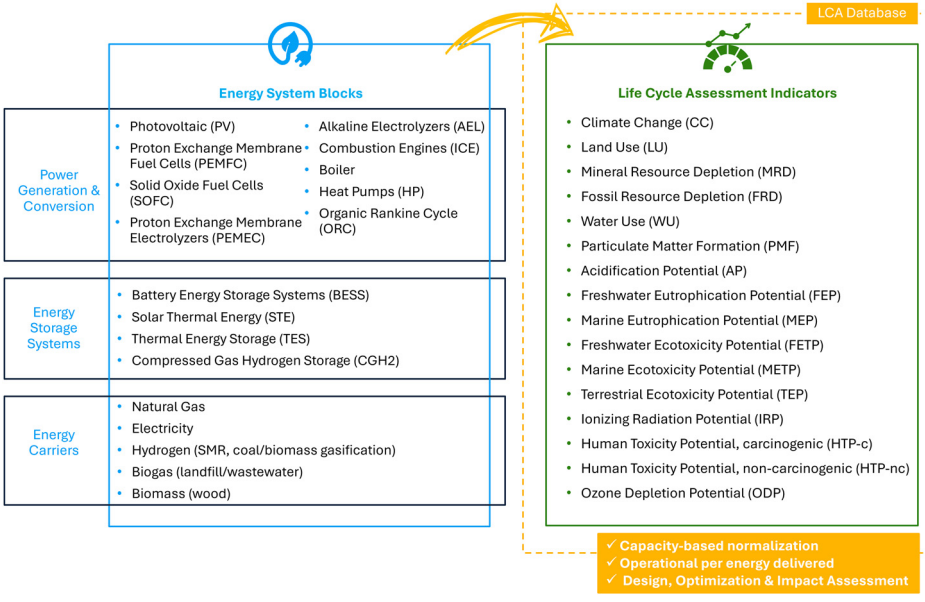

Fig. 1. Schematic of the database structure, showing the energy system components (generation, storage, and energy carriers) and the associated environmental impact indicators.

- 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
	size_kWh	kWh	representative of the technology
	size_m3	m^3	size
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
	CC_kgCO2_per_kWh_manufactory	kg_{CO2}/kWh	terms of CO_2 emissions per unit
	CC_gCO2_per_kWh_operational	kg_{CO2}/kWh	of energy or power
	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
	LU_m2a_per_kWh	m^2a/kWh	technology
	LU_kgCO2_per_kW	kg_{CO2}/kW	
	LU_m2a_per_MWh	m^2a/MWh	
Mineral resource depletion	MRD_gSb_per_kW	g_{Sb}/kW	Depletion of mineral resources
(MRD)	MRD_gSb_per_kWh	g_{Sb}/kWh	associated with the technology
	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_MJ_per_kW	MJ/kW	Fossil fuel energy consumption
(FRD)	FRD_MJ_per_kWh	MJ/kWh	required for the technology
	FRD_MJ_per_MWh	MJ/MWh	
Water use (WU)	WU_m3_per_kW	m^3/kW	Water consumption associated
	WU_m3_per_kWh	m^3/kWh	with the technology
	WU_m3_per_MWh	m^3/MWh	
Particulate matter formation	PMF_10e-6disease_per_kW	10^{-6} disease/kW	Particulate matter emissions
(PMF)	PMF_kgPM2.5_per_kW	$kg_{PM2.5}$/kW	associated with the technology
	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
	AP_molH+_per_kWh	mol_{H+}/kWh	from the technology
	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	FEP_gP_per_kW	g_P/kW	Impact on freshwater ecosystems
potential (FEP)	FEP_gP_per_kWh	g_P/kWh	due to nutrient enrichment
	FEP_gP_per_MWh	g_P/MWh	
Marine eutrophication	MEP_gN_per_kW	g_N/kW	Impact on marine ecosystems
potential (MEP)	MEP_gN_per_kWh	g_N/kWh	due to nutrient enrichment
	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	CTUe/kW	Toxicity potential in freshwater environments
	FETP_CTUe_per_kWh	CTUe/kWh	
	FETP_kgDCB_per_kW	kgDCB/kW	
	FETP_kgDCB_per_kWh	kgDCB/kWh	
	FETP_kgDCB_per_MWh	kgDCB/MWh	
Marine ecotoxicity potential (METP)	METP_kgDCB_per_kW	kgDCB/kW	Toxicity potential in marine environments
	METP_kgDCB_per_MWh	kgDCB/MWh	
Terrestrial ecotoxicity potential (TEP)	TETP_kgDCB_per_kW	kgDCB/kW	Toxicity potential in terrestrial environments
	TETP_kgCTUe_per_kW	CTUe/kW	
	TETP_kgDCB_per_kWh	kgDCB/kWh	
	TETP_kgDCB_per_MWh	kgDCB/MWh	
Ionizing radiation potential (IRP)	IRP_kgU235_per_kW	kg_{U235}/kW	Ionizing radiation emissions from the technology
	IRP_kBqU235_per_kWh	kBq_{U235}/kWh	
	IRP_kBqCo60_per_kW	kBq_{Co60}/kW	
	IRP_kBqU235_per_MWh	kBq_{U235}/MWh	
	IRP_kBqCo60_per_MWh	kBq_{Co60}/MWh	
Human toxicity potential, carcinogenic (HTP-c)	HTPc_mCTUh_per_kW	mCTUh/kW	Human toxicity potential pertaining to carcinogenic substances
	HTPc_CTUh_per_kWh	CTUh/kWh	
	HTPc_kgDBC_per_kW	kg_{DBC}/kW	
	HTPc_1,4-DB _per_kWh	$kg_{1,4\text{-}DB}$ /kWh	
	HTPc_CTUh_per_MWh	CTUh/MWh	
	HTPc_kgDBC_per_MWh	kg_{DBC}/MWh	
Human toxicity potential, non-carcinogenic (HTP-nc)	HTPnc_1,4-DB _per_kWh	$kg_{1,4\text{-}DB}$ /kWh	Human toxicity potential pertaining to non-carcinogenic substances
	HTPnc_CTUh_per_kWh	CTUh/kWh	
	HTPnc_kgDBC_per_kW	kg_{DBC}/kW	
	HTPnc_CTUh_per_MWh	CTUh/MWh	
	HTPnc_kgDBC_per_MWh	kg_{DBC}/MWh	
Ozone depletion potential (ODP)	ODP_mgCFC11_kW	mg_{CFC11}/kW	Contribution to ozone layer depletion
	ODP_mgCFC11_kWh	mg_{CFC11}/kWh	
	ODP_mgCFC11_MWh	mg_{CFC11}/MWh	
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	min	0	726	7	0.05	393
Gasification	average	0	885	7	0.26	393
	max	0	1044	7	0.46	393
H_2 - Biomass	min	0	43	1	0.02	148
Gasification	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 per-

formed 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).

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

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).

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

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

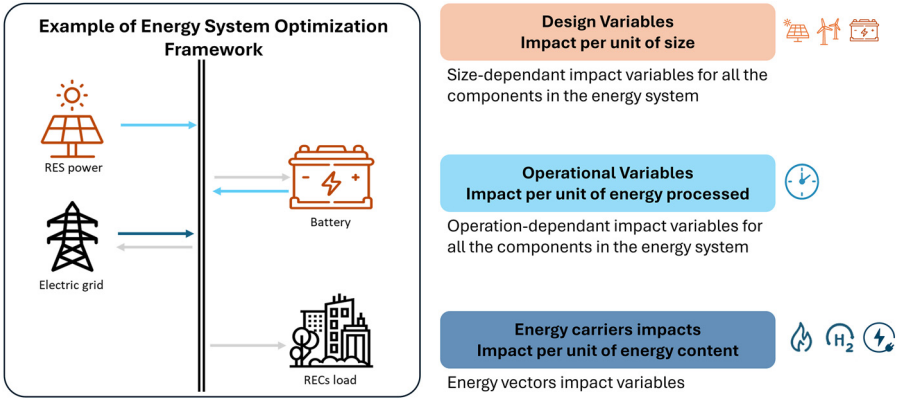

Fig. 2. Schematic representation of the categorization of energy system components and the corresponding units used for environmental impact attribution. Design variables are expressed per unit of installed capacity, operational variables are expressed per unit of energy processed, and energy carrier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

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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

References

[1] E. Rozzi, P. Marocco, M. Gandiglio, Life cycle assessment data for energy production and storage technologies, (2025). https://zenodo.org/records/15324175.
[2] R. Frischknecht, L. Krebs, Environmental life cycle assessment of electricity from PV systems, 2021. https://iea-pvps.org/wp-content/uploads/2021/11/IEA-PVPS-Task12-LCA-PV-electricity-_-Fact-Sheet.pdf.
[3] UNECE, Life cycle assessment of electricity generation options, 2021. https://unece.org/sites/default/files/2021-11/LCA_final.pdf.
[4] M. Bošnjaković, R. Santa, Z. Crnac, T. Bošnjaković, Environmental impact of PV power systems, Sustainability 15 (2023) 11888, doi:10.3390/su151511888.
[5] X.X. Ehsan Alam, Life cycle assessment of photovoltaic electricity production by mono–crystalline solar systems: a case study in Canada, (2023). https://link.springer.com/article/10.1007/s11356-022-24077-3.
[6] D. Polverini, N. Espinosa, U. Eynard, E. Leccisi, F. Ardente, F. Mathieux, Assessing the carbon footprint of photovoltaic modules through the EU Ecodesign Directive, Sol. Energy 257 (2023) 1–9, doi:10.1016/j.solener.2023.04.001.
[7] R. Frischknecht, L. Krebs, Resource use footprints of residential PV systems, 2022. https://iea-pvps.org/wp-content/uploads/2022/03/Report_IEA_PVPS_T12-22-2022-ResourceUseFootprintsResidentialPV-v1.2.pdf (accessed March 14, 2025).
[8] P. Stolz, R. Frischknecht, G. Heath, K. Komoto, J. Macknick, P. Sinha, A. Wade, Water footprint of European rooftop photovoltaic electricity based on regionalised life cycle inventories, IEA PVPS Task. 12 (2017) https://iea-pvps.org/wp-content/uploads/2020/01/Water_Footprint_of_European_Rooftop_Photovoltaic_Electricity_based_in_Re-giornalised_Life_Cycle_Inventories_by_Task_12.pdf. accessed March 14, 2025.
[9] A.-G. Lupu, V.M. Homutescu, D.-T. Bălănescu, A. Popescu, Hybrid PV-TE-T modules: life cycle analysis and end of life assessment, IOP Conf. Ser.: Mater. Sci. Eng 997 (2020) 012149, doi:10.1088/1757-899X/997/1/012149.
[10] M. Milousi, M. Souliotis, G. Arampatzis, S. Papaefthimiou, Evaluating the environmental performance of solar energy systems through a combined life cycle assessment and cost analysis, Sustainability 11 (2019) 2539, doi:10.3390/su11092539.
[11] E.R. Sanseverino, M. Cellura, L.Q. Luu, M.A. Cusenza, N. Nguyen Quang, N.H. Nguyen, Life-cycle land-use requirement for PV in Vietnam, Energies 14 (2021) 861, doi:10.3390/en14040861.
[12] B.R. David, S. Spencer, J. Miller, S. Almahmoud, H. Jouhara, Comparative environmental life cycle assessment of conventional energy storage system and innovative thermal energy storage system, Int. J. Thermofluids 12 (2021) 100116, doi:10.1016/j.ijft.2021.100116.
[13] Q. Wang, W. Liu, X. Yuan, H. Tang, Y. Tang, M. Wang, J. Zuo, Z. Song, J. Sun, Environmental impact analysis and process optimization of batteries based on life cycle assessment, J. Clean. Prod. 174 (2018) 1262–1273, doi:10.1016/j.jclepro.2017.11.059.
[14] F.B. Jasper, J. Späthe, M. Baumann, J.F. Peters, J. Ruhland, M. Weil, Life cycle assessment (LCA) of a battery home storage system based on primary data, J. Clean. Prod. 366 (2022) 132899, doi:10.1016/j.jclepro.2022.132899.
[15] L. Vandepaer, J. Cloutier, B. Amor, Environmental impacts of lithium metal polymer and lithium-ion stationary batteries, Renew. Sustain. Energy Rev. 78 (2017) 46–60, doi:10.1016/j.rser.2017.04.057.
[16] EPRI, Program on Technology innovation: life cycle assessment of lithium-ion batteries in stationary energy storage systems, 2019. https://www.epri.com/research/products/000000003002017000 (accessed March 14, 2025).
[17] L. da Silva Lima, M. Quartier, A. Buchmayr, D. Sanjuan-Delmás, H. Laget, D. Corbisier, J. Mertens, J. Dewulf, Life cycle assessment of lithium-ion batteries and vanadium redox flow batteries-based renewable energy storage systems, Sustain. Energy Technol. Assess. 46 (2021) 101286, doi:10.1016/j.seta.2021.101286.
[18] M.L. Carvalho, A. Temporelli, P. Girardi, Life cycle assessment of stationary storage systems within the Italian electric network, Energies 14 (2021), doi:10.3390/en14082047.
[19] B. Sanduru, M. Dhyani, R. Thakur, S. Dixit, N. Bhardwaj, S. Talukdar, Life cycle analysis of energy storage technologies: a comparative study, E3S Web Conf. 537 (2024) 08004, doi:10.1051/e3sconf/202453708004.
[20] A. Kylili, P.A. Fokaides, A. Ioannides, S. Kalogirou, Environmental assessment of solar thermal systems for the industrial sector, J. Clean. Prod. 176 (2018) 99–109, doi:10.1016/j.jclepro.2017.12.150.
[21] O. Ariyakhajorn, Life Cycle assessment of Absolicon solar thermal collector field for district heating in Härnösand, KTH R. Inst. Technol. (2023) https://kth.diva-portal.org/smash/get/diva2:1801627/FULLTEXT01.pdf.
[22] O.M. Babatunde, B.D. Akintayo, M.U. Emezirinwune, O.A. Olanrewaju, Environmental impact assessment of a 1 kW proton-exchange membrane fuel cell: a mid-point and end-point analysis, Hydrogen 5 (2024) 352–373, doi:10.3390/hydrogen5020020.

[23] M. Mori, D. Iribarren, J. Cren, E. Cor, A. Lotrič, J. Gramc, B. Drobnič, L. Rey, F. Campos-Carriedo, G. Puig-Samper, E. Bargiacchi, J. Dufour, R. Stropnik, Life cycle sustainability assessment of a proton exchange membrane fuel cell technology for ecodesign purposes, Int. J. Hydrog. Energy 48 (2023) 39673–39689, doi:10.1016/j.ijhydene.2023.05.255.
[24] R. Stropnik, A. Lotrič, A. Bernad Montenegro, M. Sekavčnik, M. Mori, Critical materials in PEMFC systems and a LCA analysis for the potential reduction of environmental impacts with EoL strategies, Energy Sci. Eng. 7 (2019) 2519–2539, doi:10.1002/ese3.441.
[25] M. Pehnt, Life-cycle assessment of fuel cell stacks, Int. J. Hydrog. Energy 26 (2001) 91–101, doi:10.1016/S0360-3199(00)00053-7.
[26] A. Xu, Q. Yang, L. Yang, R. Fan, C. Liu, N. Xie, S. Yang, C. Deng, Life cycle assessment and carbon footprint evaluation of a PEMFC system integrated with different hydrogen production routes, Energy Convers. Manag. 312 (2024) 118586, doi:10.1016/j.enconman.2024.118586.
[27] D. Zhang, S. Evangelisti, P. Lettieri, L.G. Papageorgiou, Optimal design of CHP-based microgrids: multiobjective optimisation and life cycle assessment, Energy 85 (2015) 181–193, doi:10.1016/j.energy.2015.03.036.
[28] Y. Bicer, F. Khalid, Life cycle environmental impact comparison of solid oxide fuel cells fueled by natural gas, hydrogen, ammonia and methanol for combined heat and power generation, Int. J. Hydrog. Energy 45 (2020) 3670–3685, doi:10.1016/j.ijhydene.2018.11.122.
[29] E. Rillo, M. Gandiglio, A. Lanzini, S. Bobba, M. Santarelli, G. Blengini, Life cycle assessment (LCA) of biogas-fed solid oxide fuel cell (SOFC) plant, Energy 126 (2017) 585–602, doi:10.1016/j.energy.2017.03.041.
[30] C. Strazza, A. Del Borghi, P. Costamagna, A. Traverso, M. Santin, Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships, Appl. Energy 87 (2010) 1670–1678, doi:10.1016/j.apenergy.2009.10.012.
[31] K. Al-Khori, S.G. Al-Ghamdi, S. Boulfrad, M. Koç, Life cycle assessment for integration of solid oxide fuel cells into gas processing operations, Energies 14 (2021) 4668, doi:10.3390/en14154668.
[32] M. Naeini, J.S. Cotton, T.A. Adams, Dynamic life cycle assessment of solid oxide fuel cell system considering long-term degradation effects, Energy Convers. Manag. 255 (2022) 115336, doi:10.1016/j.enconman.2022.115336.
[33] G. Zhao, M.R. Kraglund, H.L. Frandsen, A.C. Wulff, S.H. Jensen, M. Chen, C.R. Graves, Life cycle assessment of H2O electrolysis technologies, Int. J. Hydrog. Energy 45 (2020) 23765–23781, doi:10.1016/j.ijhydene.2020.05.282.
[34] H. Pourrahmani, C. Xu, J. Van herle, The thermodynamic and life-cycle assessments of a novel charging station for electric vehicles in dynamic and steady-state conditions, Sci. Rep. 13 (2023) 11159, doi:10.1038/s41598-023-38387-0.
[35] S. Krishnan, B. Corona, G.J. Kramer, M. Junginger, V. Koning, Prospective LCA of alkaline and PEM electrolyser systems, Int. J. Hydrog. Energy 55 (2024) 26–41, doi:10.1016/j.ijhydene.2023.10.192.
[36] K.V. Vilbergsson, Comparative Life Cycle Assessment of Hydrogen Production Via Electrolysis in Austria and Iceland, Reykjavík University, 2021 https://skemman.is/bitstream/1946/39468/1/Comparative%20Life%20Cycle%20Assessment%20of%20Hydrogen%20Production%20via%20Electrolysis%20in%20Austria%20and%20Iceland.pdf.
[37] J. Gerhardt-Mörsdorf, F. Peterssen, P. Burfeind, M. Benecke, B. Bensmann, R. Hanke-Rauschenbach, C. Minke, Life cycle assessment of a 5 MW polymer exchange membrane water electrolysis plant, Adv. Energy Sustain. Res. 5 (2024) 2300135, doi:10.1002/aesr.202300135.
[38] J. Iso-Oja, Comparative Life Cycle Emission Study of Selected Hydrogen Production Technologies, Aalto University, 2024 https://cris.vtt.fi/ws/portalfiles/portal/103979186/eng_2024_iso-oja_jenni.pdf.
[39] A. Agostini, N. Belmonte, A. Masala, J. Hu, P. Rizzi, M. Fichtner, P. Moretto, C. Luetto, M. Sgroi, M. Baricco, Role of hydrogen tanks in the life cycle assessment of fuel cell-based auxiliary power units, Appl. Energy 215 (2018) 1–12, doi:10.1016/j.apenergy.2018.01.095.
[40] L. Ye, L. Lu, Environmental and economic evaluation of the high-pressured and cryogenic vessels for hydrogen storage on the sedan, Int. J. Low-Carbon Technol. 18 (2023) 144–149, doi:10.1093/ijlct/ctac126.
[41] E. Weiszflog, M. Abbas, Life Cycle Assessment of Hydrogen Storage Systems for Trucks - An Assessment of Environmental Impacts and Recycling Flows of Carbon Fiber, Chalmers University Of Technology, Sweden, 2022 https://odr.chalmers.se/server/api/core/bitstreams/2a16256f-2858-4f55-972f-a6889d05e252/content.
[42] A. Arrigoni, F. Dolci, R. Ortiz Cebolla, E. Weidner, T. D'Agostini, U. Eynard, V. Santucci, F. Mathieux, Environmental Life Cycle Assessment (LCA) Comparison of Hydrogen Delivery Options Within Europe, Publications Office of the European Union, 2024 https://data.europa.eu/doi/10.2760/5459 accessed March 14, 2025.
[43] J. Havukainen, M.T. Nguyen, S. Väisänen, M. Horttanainen, Life cycle assessment of small-scale combined heat and power plant: environmental impacts of different forest biofuels and replacing district heat produced from natural gas, J. Clean. Prod. 172 (2018) 837–846, doi:10.1016/j.jclepro.2017.10.241.
[44] E. Sosnina, O. Masleeva, E. Kryukov, N. Erdili, Mini CHP plants life cycle ecological assessment, in: 2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), 2020, pp. 319–323, doi:10.1109/ISGT-Europe47291.2020.9248873.
[45] L. Stamford, B. Greening, A. Azapagic, Life cycle environmental and economic sustainability of Stirling engine micro-CHP systems, Energy Technol. 6 (2018) 1119–1138, doi:10.1002/ente.201700854.
[46] P. Balcombe, D. Rigby, A. Azapagic, Environmental impacts of microgeneration: integrating solar PV, stirling engine CHP and battery storage, Appl. Energy 139 (2015) 245–259, doi:10.1016/j.apenergy.2014.11.034.
[47] A.M.M. Reza, A. Rogoža, Life cycle assessment of a condensing gas boiler and compare with an air source heat pump in a residential building, Moksl. – Liet. Ateitis /Sci. – Future Lith. 16 (2024), doi:10.3846/mla.2024.21298.
[48] H. Lin, J. Clavreul, C. Jeandaux, J. Crawley, I. Butnar, Environmental life cycle assessment of heating systems in the UK: comparative assessment of hybrid heat pumps vs. condensing gas boilers, Energy Build. 240 (2021) 110865, doi:10.1016/j.enbuild.2021.110865.
[49] S. Sevindik, C. Spataru, T. Domenech Aparisi, R. Bleischwitz, A comparative environmental assessment of heat pumps and gas boilers towards a circular economy in the UK, Energies 14 (2021) 3027, doi:10.3390/en14113027.

[50] J. Famiglietti, T. Toppi, L. Pistocchini, R. Scoccia, M. Motta, A comparative environmental life cycle assessment between a condensing boiler and a gas driven absorption heat pump, Sci. Total Environ. 762 (2021) 144392, doi:10.1016/j.scitotenv.2020.144392.
[51] R.G. Raluy, A.C. Dias, Life cycle assessment of a domestic gas-fired water heater: influence of fuel used and its origin, J. Env. Manage 254 (2020) 109786, doi:10.1016/j.jenvman.2019.109786.
[52] B. Greening, A. Azapagic, Domestic heat pumps: life cycle environmental impacts and potential implications for the UK, Energy 39 (2012) 205–217, doi:10.1016/j.energy.2012.01.028.
[53] A.C. Violante, F. Donato, G. Guidi, M. Proposito, Comparative life cycle assessment of the ground source heat pump vs air source heat pump, Renew. Energy 188 (2022) 1029–1037, doi:10.1016/j.renene.2022.02.075.
[54] M. Oehler, B.G. Bederna, R.B. Barta, U. Hesse, Life cycle assessment (LCA) of an air-cooled ORC system for waste heat recovery, 6 Th International Seminar on ORC Power Systems, Munich, Germany, 2021 https://mediatum.ub.tum.de/doc/1632933/kn0ie8cnj141g3c68c2a0en5n.pdf.
[55] Y. Yang, L. Ma, J. Yu, Z. Zhao, P. You, Life cycle assessment introduced by using nanorefrigerant of organic rankine cycle system for waste heat recovery, JRM 11 (2022) 1153–1179, doi:10.32604/jrm.2022.022719.
[56] A. Stoppato, A. Benato, Life cycle assessment of a commercially available organic rankine cycle unit coupled with a biomass boiler, Energies 13 (2020) 1835, doi:10.3390/en13071835.
[57] F. Heberle, C. Schifflechner, D. Brüggemann, Life cycle assessment of organic Rankine Cycles for geothermal power generation considering low-GWP working fluids, Geothermics 64 (2016) 392–400, doi:10.1016/j.geothermics.2016.06.010.
[58] H. Khutal, K.M. Kirchner-Ortiz, M. Blackhurst, N. Willems, H.S. Matthews, S. Rai, G. Yanai, K. Chivukula, M.B. Jamieson, T.J. Skone, Life cycle analysis of natural gas extraction and power generation: U.S, 2020 Emiss. Profile (2020).
[59] Y. Wang, T. Ni, B. He, J. Xu, Life cycle environmental impact assessment of natural gas distributed energy system, Sci. Rep. 14 (2024) 3292, doi:10.1038/s41598-024-53495-1.
[60] T.J. Skone, J. Littlefield, J. Marriott, G. Cooney, M. Jamieson, J. Hakian, G. Schivley, B.A. Hamilton, Life cycle analysis of natural gas extraction and power generation, NETL (2014) https://www.energy.gov/sites/prod/files/2019/09/f66/Life%20Cycle%20Analysis%20of%20Natural%20Gas%20Extraction%20and%20Power%20Generation%2005_29_14%20NETL.pdf.
[61] A. Gargiulo, M.L. Carvalho, P. Girardi, Life cycle assessment of Italian electricity scenarios to 2030, Energies 13 (2020) 3852, doi:10.3390/en13153852.
[62] E.A. Bouman, A life cycle perspective on the benefits of renewable electricity generation – methodology and assumptions, Eionet (2020) https://nilu.com/publication/1881540/. (accessed March 14, 2025).
[63] G. Naumann, J. Famiglietti, E. Schropp, M. Motta, M. Gaderer, Dynamic life cycle assessment of European electricity generation based on a retrospective approach, Energy Convers. Manag. 311 (2024) 118520, doi:10.1016/j.enconman.2024.118520.
[64] B. Kiss, E. Kácsor, Z. Szalay, Environmental assessment of future electricity mix – linking an hourly economic model with LCA, J. Clean. Prod. 264 (2020) 121536, doi:10.1016/j.jclepro.2020.121536.
[65] L. Petrescu, C.R. Müller, C.-C. Cormos, Life cycle assessment of natural gas-based chemical looping for hydrogen production, Energy Procedia 63 (2014) 7408–7420, doi:10.1016/j.egypro.2014.11.777.
[66] U.I. Amran, A. Arshad, O.M. Rizza, Life cycle assessment of simulated hydrogen production by methane steam reforming, Aust. J. Basic Appl. Sci. 11 (2017).
[67] N. Asaro, Comparative life cycle assessment of hydrogen production by steam reforming of natural gas, landfill gas and biomethane, Politec. Torino (2023) https://www.politesi.polimi.it/retrieve/7e7020b4-2364-445d-87bc-59eb9ba6155f/2024_07_Asaro_Tesi.pdf.
[68] A. Mehmeti, A. Angelis-Dimakis, G. Arampatzis, S.J. McPhail, S. Ulgiati, Life cycle assessment and water footprint of hydrogen production methods: from conventional to emerging technologies, Environments 5 (2018) 24, doi:10.3390/environments5020024.
[69] D. Burchart, M. Gazda-Grzywacz, P. Grzywacz, P. Burmistrz, K. Zarębska, Life cycle assessment of hydrogen production from coal gasification as an alternative transport fuel, Energies 16 (2023) 383, doi:10.3390/en16010383.
[70] S.Rajabi Hamedani, M. Villarini, A. Colantoni, M. Moretti, E. Bocci, Life cycle performance of hydrogen production via Agro-industrial residue gasification—a small scale power plant study, Energies 11 (2018) 675, doi:10.3390/en11030675.
[71] N. Hajjaji, S. Martinez, E. Trably, J.-P. Steyer, A. Helias, Life cycle assessment of hydrogen production from biogas reforming, Int. J. Hydrog. Energy 41 (2016) 6064–6075, doi:10.1016/j.ijhydene.2016.03.006.
[72] D. Iribarren, A. Susmozas, F. Petrakopoulou, J. Dufour, Environmental and exergetic evaluation of hydrogen production via lignocellulosic biomass gasification, J. Clean. Prod. 69 (2014) 165–175, doi:10.1016/j.jclepro.2014.01.068.
[73] Chr. Lamnatou, R. Nicolaï, D. Chemisana, C. Cristofari, D. Cancellieri, Biogas production by means of an anaerobic-digestion plant in France: LCA of greenhouse-gas emissions and other environmental indicators, Sci. Total Environ. 670 (2019) 1226–1239, doi:10.1016/j.scitotenv.2019.03.211.
[74] A.A.E. Sinsuw, T.-H. Chen, P. Dokmaingam, H.S. Suriandjo, C.-Y. Chu, Life cycle assessment of environmental impacts for two-stage anaerobic biogas plant between commercial and pilot scales, Int. J. Hydrog. Energy 52 (2024) 58–70, doi:10.1016/j.ijhydene.2023.06.331.
[75] S.D. Maglio, Life cycle assessment of biogas systems in the European context, Politec. Milano (2011) https://www.politesi.polimi.it/retrieve/a81cb05a-04cc-616b-e053-1605fe0a889a/2012_04_DonidaMaglio.PDF.
[76] T. Pacetti, L. Lombardi, G. Federici, Water–energy Nexus: a case of biogas production from energy crops evaluated by water footprint and life cycle assessment (LCA) methods, J. Clean. Prod. 101 (2015) 278–291, doi:10.1016/j.jclepro.2015.03.084.
[77] A.S. Varling, T.H. Christensen, V. Bisinella, Life cycle assessment of alternative biogas utilisations, including carbon capture and storage or utilisation, Waste Manag. 157 (2023) 168–179, doi:10.1016/j.wasman.2022.12.005.

[78] F. Pierobon, I.L. Eastin, I. Ganguly, Life cycle assessment of residual lignocellulosic biomass-based jet fuel with activated carbon and lignosulfonate as co-products, Biotechnol. Biofuels 11 (2018) 139, doi:10.1186/s13068-018-1141-9.
[79] A. Prasad, M. Sotenko, T. Blenkinsopp, S.R. Coles, Life cycle assessment of lignocellulosic biomass pretreatment methods in biofuel production, Int. J. Life Cycle Assess. 21 (2016) 44–50, doi:10.1007/s11367-015-0985-5.
[80] V.P. Aravani, S. Wang, W. Wang, V.G. Papadakis, LCA analysis on the management of typical lignocellulosic agricultural wastes: case studies and comparison in Greece and China, Biomass Bioenergy 190 (2024) 107386, doi:10.1016/j.biombioe.2024.107386.