Handbook of Existing Technologies for Energy Conversion and Energy Storage from Renewable Sources in the Programme Area

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LIST OF PROJECT PARTNERS

LP	University of Udine (UNIUD)
PP1	Research Studios Austria Research company mbH (RSA FG) iSPACE
PP2	Iuav University of Venice (IUAV)
PP3	Consortium of the Basin River basin of the Piave (BIM Piave)
PP4	CML S.r.l
PP6	Consortium for the Nucleus of Industrialisation of the Province of Pordenone (NIP)
PP7	Ökostrombörse Salzburg

Partners' contribution:

LP; PP1; PP2; PP3; PP4; PP5; PP6

Working group decision process (minutes of the validation process meetings available)

- Kick off meeting 19.12.2023: Aim of calculation model

- n°2 Cross Border meeting 11.07.2024: Technology Assessment

- n°3 Cross Border meeting 08.11.2024: Technology Assessment

- n°4 Cross Border meeting 11.07.2025: Validation of calculation model and integration under Wp5

In addition, n°16 online meetings between January 2024 and May 2026.

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ACRONYMS

AEM	Anion exchange membrane	NCA	Lithium nickel cobalt aluminum oxide
AEP	Annual energy production	NMC	Lithium nickel manganese cobalt oxide
AFC	Alkaline fuel cell	$NMVOC_{eq}$	Non-methane volatile organic compound equivalent
AP	Acidification potential	NOx_{eq}	Nitrogen oxides equivalent
ARC	Anti-reflective coating	P2H2P	Power-to-Hydrogen-to-Power
AWE	Alkaline water electrolysis	OPEX	Operation and maintenance costs
BESS	Battery energy storage system	PAFC	Phosphoric acid fuel cells
BMS	Battery management system	PAT	Pump-as-turbines
BoP	Balance of plant	PCR	Product category rules
CAPEX	Capital expenditure cost	PEM	Proton exchange membrane
DD	Direct drive	PEMFC	Polymer electrolyte membrane fuel cell
DMFC	Direct methanol fuel cell	PGMs	Platinum group metals
DoD	Depth of discharge	PMSG	Permanent magnet synchronous generator
EP	Eutrophication potential	PtP	Power-to-Power
EU	European Union	WEEE	Waste electrical and electronic equipment
EV	Electric vehicle	SHP	Small hydropower plants
HPP	Hydropower plants	SoC	State of charge
IPCEI	Important Project of Common European Interest	SOEC	Solid oxide electrolyser cell
LCO	Lithium cobalt oxide	SOFC	Solid oxide fuel cell
L_{eq}	Equivalent continuous sound level	TRL	Technology readiness level
LFP	Lithium iron phosphate		
MCFC	Molten carbonate fuel cell		

1 INTRODUCTION

1.1 THE PANORAMA PROJECT AND THE HANDBOOK

The PANORAMA project utilises and promotes cooperation between research institutes, businesses, stakeholders and local authorities with the aim of identifying and providing decision-making support for the implementation of innovative solutions in the fields of energy efficiency, the use of renewable energy, and collaboration between producers and consumers within the framework of energy communities.

The growing urgency of the energy transition, driven by the climate crisis and the current political situation in Europe and globally, makes it necessary to rapidly and effectively scale up the sustainable use of renewable energy sources at regional level.

This new scenario calls for the rapid delivery of research findings on the integration of solar, hydro and wind energy that can be immediately applied in a regional and local context, particularly with regard to the integration of systems into the environment and the practical implementation of renewable energy communities or similar forms of self-generation of electricity.

The aim of the project is to pool and systematise the expertise needed to assess the technical and economic feasibility and the best possible integration of new energy systems into the landscape. The following pilot areas: a) two Italian zones, the Maniago industrial area in Province of Pordenone, Friuli Venezia Giulia, municipalities in the Province of Belluno, Veneto, and b) Land of Salzburg, Austria. The outcome of PANORAMA will be the creation of geographical and technical information tools, which will incorporate the various areas of expertise of the partners involved.

This document, entitled 'Handbook of existing technologies for the conversion and storage of energy from renewable sources in the programme area', has been drawn up with the aim of providing an overview of the technologies currently available for the conversion and storage of energy from renewable sources, which could potentially be implemented within a Renewable Energy Community (REC).

The authors point out that the information provided may be subject to changes, given the rapid evolution of technologies and economies, and that the data have often been compiled by the authors of this document or within the source itself. Readers are therefore advised to refer to the citations provided in the text and to examine the available data further before making engineering and economic decisions. Technologies and their applicability to RECs also depend on the local context; therefore, readers should carry out further assessments when intending to implement a technology.

This handbook is structured as follows. Chapter 1, the introductory chapter, presents the project, the concept of RECs and the quantification of environmental impacts. Chapter 2 outlines the financial incentives available for RECs in Italy and Austria, the countries in which the project's pilot communities are located. Chapters 3 to 7 are devoted to the various technologies for the production and storage of energy from renewable sources. In particular, the energy conversion technologies analysed include photovoltaic panels, wind turbines and hydroelectric power. As regards storage technologies, the report examines hydroelectric storage, lithium-iron-phosphate batteries and the 'power-to-hydrogen-to-power' system in depth. Each of these chapters follows a similar structure, addressing the possible areas of integration within a REC, the technical aspects, the economic data and the associated environmental impacts. The section on photovoltaic panels constitutes the largest part of the handbook, as this technology is currently the easiest to implement within RECs.

1.2 WHAT IS A REC: LEGISLATION, PARTICIPANTS AND OBJECTIVES

A REC is a collaborative agreement between several parties, aimed at sharing electricity and supporting the grid through the generation of energy from renewable sources. The recognition of RECs forms part of the broader European regulatory framework for the promotion of renewable energy, which was established by Directive 2009/28/EC and subsequently updated by EU Directive 2018/2001, known as

RED II. The latter formally introduced the definition of a REC, outlining its role within the European energy system. The current EU Directive 2023/2413, known as RED III and adopted in 2023, further refines the regulatory framework relating to RECs and strengthens European targets for renewable energy. In particular, the directive sets a binding target at EU level: to achieve a 42.5% share of energy from renewable sources in the overall energy mix by 2030. RED III also sets out the deadlines by which each Member State must transpose these provisions into its national legislation. The Directive also assigns a significant role to national, regional and local authorities, which are called upon to facilitate the integration of RECs into the energy system and to promote self-consumption. To this end, it encourages the reduction of administrative barriers, the adoption of regulations designed to facilitate the integration of renewable energy sources, and the dissemination of transparent and accessible information. This includes, for example, information on the availability of qualified installers, which is considered important for building public confidence and encouraging wider participation in the energy transition (European Court of Auditors, 2026; RED III, 2023).

Different countries have adopted different regulatory frameworks for renewable energy communities, particularly with regard to participation arrangements, limits on installed capacity and incentive mechanisms. In Italy, the regulatory framework is set out in Legislative Decree 199/2021 and subsequent implementing measures, including ARERA Resolution 727/2022 and Ministerial Decree 414/2023. These provisions stipulate that members of an energy community must be connected to the same primary substation and that the capacity of eligible installations must not exceed 1 MW per individual installation (Italian Republic, 2021). In Austria, the Erneuerbaren-Ausbau-Gesetz (EAG) was adopted in 2021, published in the Federal Law Gazette (BGBl.) I No. 150/2021, alongside the Electricity Industry and Organisation Act (ElWOG), BGBl. I No. 110/2010. These regulations aim to achieve 100% electricity generation from renewable sources by 2030 and climate neutrality by 2040 (Grantham Research Institute, 2026a).

Participation in a REC is also encouraged by specific economic mechanisms, which will be examined in more detail in Chapter 2. Participants in a REC may include individual citizens, housing estates, public and private bodies, and small and medium-sized enterprises (ENEL, 2023). Within the community, members fall into three main categories: producers, consumers and prosumers. Producers are those who install photovoltaic systems and feed the electricity they generate into the grid. Consumers, by contrast, do not generate energy and meet their needs by purchasing it from the grid. Prosumers combine both functions, generating electricity, consuming some or all of it themselves, and feeding any surplus back into the grid (Becchetti & Salustri, 2025).

It is important to emphasise that members of a REC who purchase energy from the grid do not physically draw electricity directly from other producers or prosumers within the community. However, the energy exchanged remains at low voltage as it passes from the producer to the grid and subsequently to the consumer, thereby reducing transmission losses compared with long-distance energy flows (Mocci et al., 2024). The main objective of an Energy Community (EC) is to maximise the alignment between generation and consumption within the community, promoting the local use of the energy produced, both in real time and via storage systems such as batteries. Excess energy can, however, be fed into the grid, helping to supply electricity from renewable sources to consumers outside the REC as well. Consequently, the benefits of energy communities also extend to non-members, as the electricity grid as a whole becomes progressively more sustainable and based on renewable sources.

A REC may incorporate one or more renewable energy sources. In 2024, 48% of the electricity generated in Europe came from renewable sources (Council of the EU and the European Council, 2026). Among these, photovoltaic panels are one of the main technologies that can be used within a REC. Other technologies that can be used include wind turbines and hydroelectric power stations. In Europe, a REC based exclusively on photovoltaic generation achieves an average self-consumption rate of 39.4%, with a payback period of approximately 2.57 years. The integration of a hybrid system, comprising 50% solar energy and 50% wind power, allows for a significant increase in self-consumption, which can reach up to 66% (Papapietro, 2024).

Renewable energy sources are more widely distributed across the territory, but they are also more intermittent and less predictable; they therefore require integration with electrical energy storage (EES) systems, which play a vital role in providing flexibility and ensuring a continuous power supply to the grid. An EES is defined as the process by which electrical energy from a source is converted, via a conversion module, into another form or into a storage medium, which may be chemical, mechanical, thermal or magnetic. This process takes place when there is a surplus of energy, for example during peak hours of solar generation. The converted energy is stored for a limited period, before being converted back into electrical energy when required (Medina et al., 2014); this typically occurs when energy generation is insufficient to meet demand, such as at night, when there is no solar generation, or during periods of low wind power generation.

Although the aim of the REC is to maximise real-time consumption, the presence of EES systems is necessary for it to function optimally. Naturally, due to losses, the aim is to minimise the use of EES as much as possible and, in any case, to implement the type of EES best suited to the situation.

The simplest and most widespread solution is battery energy storage systems (BESS), which are particularly versatile as they are modular and scalable. There are also more advanced storage solutions, such as hydrogen-based systems that include electrolysers, storage and fuel cells, enabling further improvements in energy performance. In particular, a hybrid system comprising 55% solar generation and 45 per cent wind generation can achieve self-consumption levels of up to 83.7%. However, at present, such configurations are still not economically viable (G. Raimondi & Spazzafumo, 2023).

There are numerous EU-supported initiatives aimed at promoting the growth of RECs, such as the Citizen Energy Advisory Hub. This body helps to encourage the involvement of the public and private sectors, disseminate technical and regulatory information, and raise awareness of European legislation and planning (financial, technical and social aspects). Furthermore, there are various sources for locating and identifying existing RECs in Europe. For example, in Italy, the Gestore Servizi Energetici (GSE) provides a list and a map of existing primary substations and RECs, including information such as their capacity, the number of users, the municipality, the province and the network operator (Gestore Servizi Energetici, n.d.-c) In Austria, Salzburg had around 200 RECs as of January 2025 (The Salzburg Institute for Spatial Planning and Housing, n.d.).

1.2.1 Economic Assessment

For each technology analysed, the capital expenditure (CAPEX) and operation and maintenance expenditure (OPEX) are presented. CAPEX represents the initial investment required to build a plant and includes, for example, the purchase of components, taxation, transport, installation and commissioning costs. OPEX refers to management and maintenance activities during the operational phase of the plant and is generally related to installed power and plant lifetime (Cristea et al., 2025).

1.2.2 Environmental Assessment

A life cycle assessment (LCA) measures the environmental impact of a product or of a process throughout its life cycle, called “cradle to grave”, or during a specific segment of the life cycle. For example, the production phase is called “cradle to gate”. The LCA is a useful tool to assess which technology, or combination of technologies, is most suitable for a REC.

An LCA analysis consists of four phases: goal and scope definition, inventory analysis, life cycle impact assessment (LCIA) and interpretation (Muralikrishna & Manickam, 2017). The goal and scope section defines the purpose of the LCA, the system boundaries and the functional unit (FU). The system boundary of an LCA defines which life cycle stages are included in the analysis and will vary between studies. In some cases, the differences are explicit, such as inclusion or exclusion of the end-of-life (EoL) stage; in other cases they are less evident. For example, one study may consider the transport of raw materials to the production site but not the transport of the finished product to the installation site, while another may include both transport stages. The inventory analysis phase accounts for all inputs (raw materials, processed components and energy) and outputs (products, emissions and waste) over the life cycle. Studies often do not provide a full inventory list; therefore, it can be difficult to understand which components were included in the analysis (Zampori et al., 2016). The LCIA phase calculates different environmental and human-health impacts across several categories. The interpretation phase includes review of the results, post-processing (weighting and normalisation) and sensitivity analyses.

The impact categories assessed depend on the selected LCIA methodology (Athena Sustainable Materials Institute, 2025). Examples of LCIA methods are ReCiPe (Huijbregts et al., 2016), Environmental Footprint (EF) (Andreasi Bassi et al., 2023), Intergovernmental Panel on Climate Change (IPCC) 2021 (Bashmakov et al., 2023), and the Tool for Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) (Bare, 2012). The methods provide results for midpoint categories, endpoint categories or both (Rybaczewska-Błażejowska & Jezierski, 2024a), but each uses a different number of categories and different calculation methodologies. Examples of midpoint categories are climate change potential (also known as carbon footprint or global warming potential), freshwater eutrophication, marine eutrophication, ionising radiation, water use, fossil resources, ozone depletion, particulate matter and land use. Examples of endpoint categories are human health, resources and ecosystem quality (Andreasi Bassi et al., 2023; Huijbregts et al., 2016). Midpoint categories assess risk, whereas endpoint categories assess damage. Multiple midpoint impacts are grouped and presented as an endpoint category.

Comparing results between different studies can be difficult because of different the) LCIA methods, ii) functional units, iii) boundaries of the system, iv) replacement of the components, v) strategies of EoL and vi) final units submitted (raw values, normalised, weighted) (Bogacka et al., 2017). To compare results obtained with different LCIA methods, it is necessary to harmonise the data.

2 INCENTIVES AND SUBSIDIES

This chapter focuses on the incentives and subsidies for implementing renewable energy in Austria and Italy, countries in which the project PANORAMA uses as theoretical REC pilot areas. The section focuses on PV technology.

2.1 AUSTRIA

The 2021 Renewable Energy Expansion Act (EAG) is the main piece of legislation governing the implementation, promotion and financing of renewable energy installations, including within the framework of RECs (Grantham Research Institute, 2026b). National subsidies and incentives for energy plants powered by renewable sources (solar, wind, biomass and hydroelectric) are provided by various funding agencies in Austria, notably the Abwicklungsstelle für Ökostrom AG (OeMAG) and the Klima- und Energiefonds (KLIEN) (Eriksson Berggren et al., 2023). In addition, federal states and municipalities may have their own funding programmes aimed at different target groups.

The subsidies are divided into investment and production. Using PV plants as an example, investment subsidies depend on the size (peak power of the PV and usable battery capacity) of a new PV installation or of the plant extension. The award may be a fixed rate (€/kWp or €/kWh) (e.g. EAG investment grant categories A and B) or depend on the quantity requested (e.g. EAG investment grant categories C and D). EAG investment grant categories A and B are awarded on a "first come first serve" basis. EAG investment grant categories C and D operate by ranking the applicants at the end of the application period. Those requesting the lowest funding (€/kWp) are awarded funding first. The further an applicant undercuts the maximum rate, the greater the chances of receiving the subsidy, therefore a sort of risk. Production subsidies, such as the Market Premium, are based on the electricity fed into the grid. Financial programs are usually mutually exclusive but some can be combined with local funding. The applicant must check the rules of each program. Incentives provided in this chapter can be applied to RECs and systems that are larger than a realistic REC (Photovoltaic Austria, 2026).

Additionally, there are financing opportunities from outside of Austria that support renewable energy projects. For example, The European Investment Bank has approved a loan of 400 million euros to Austria to support the construction of a pumped storage (150 MW) and a run-of-river (28 MW) hydropower plant, which will be constructed by Energie AG Oberösterreich (Energie AG) (European Investment Bank, 2025).

With regard to the Land of Salzburg, the OeMAG has offered funding for the installation of photovoltaic systems, but the deadline for the submission of the applications expired in December 2025. Currently Salzburg has a funding programme for biomass heating plants. The grant is equal to 25 % plus a possible surcharge (maximum 40 %) of the eligible costs of project (Land Salzburg, n.d.-a). With regard to the hydropower, a campaign has been under way since 2012 to modernise, expand, and renovate small hydropower plants up to 10 MW. In phase 1, applicants complete an application and commission an assessment of the current plant. The phase 2 consists in an on-site assessment, performed by an expert selected by the processing agency, of the hydrological conditions, technical, ecological and legal, with the identification of potential improvements. The beneficiary bears no cost for the phase 1, because these are covered by the agency. For the phase 2, the beneficiary pays 1/3 of the consultancy with a maximum of 500 €. The hydropower plants with a peak capacity up to 30 kW have a separate process, where for phase 2 the beneficiary pays 1/3 of the consultancy with a maximum of 200€. The agency responsible is the Office of the Government of the Land of Salzburg, General Water Management (Land Salzburg, n.d.-b).

The following tables illustrate the current national programmes of incentive for photovoltaics. **Error! Reference source not found.** provides a summary of the National EAG market premium EAG, also known as feed-in premium; Table 2-2 provides a summary of the investment grant KLIEN for the energy communities; **Error! Reference source not found.** provides a summary of the investment grants EAG for new photovoltaic systems and expanded, funded by the OeMAG. Moreover, the OeMAG funds other renewable energy installation projects of renewable energy (wind, hydropower and biomass) in 2026; further details are available here: (https://www.eag-abwicklungsstelle.at/foerderkalender).

Table 2-1. Market premium for photovoltaic electricity fed into the grid

Summary	The market premium is a subsidy for photovoltaics electricity fed into the grid, namely an additional premium compared with the reference market value (roughly equivalent to the average price of electricity traded on the market). During the tender phase, the economically required electricity price must be registered the price of electricity economically necessary for photovoltaics system. The ranking is carried out on the basis of the bid (by the lowest). At the time of the acceptance of the contract it is necessary to provide a financial guarantee; in case of acceptance of the contract is required the deposit of a second guarantee. For photovoltaics systems on agricultural land and meadows, a 25% reduction applies (except the plants Agri-PV). The maximum value for the price of electricity registered is established by the legislator (determination through guidelines). The market premium is granted monthly for a period of 20 years. The repayment of the additional proceeds arising from the marketing of electricity is required for photovoltaics systems with a capacity equal or higher than 5 MWp. Volume of the call for date of bid: minimum 175 MWp Combinability: This funding cannot be combined with the investment grant EAG. The combinations with other federal subsidies must be checked. The combination with state subsidies or municipal is not allowed.
Information on the funding body	OeMAG Abwicklungsstelle für Ökostrom AG, Alserbachstraße 14-16, 1090 Vienna +43 5 787 66 10, eag@oem-ag.at, https://eag-abwicklungsstelle.at/
Type funding	Premium over the reference market value
Minimum size subsidised of the PV plant:	10 kWp
Maximum size subsidised of the PV plant:	No limit
Maximum financial support	7,77 ct/kWh
Start and end date of the funding application	Call of tender 2026: 02.03.2026 - 17.03.2026 27.05.2026 - 11.06.2026 09.09.2026 - 24.09.2026 25.11.2026 - 10.12.2026 Call of tender 2027: 26.01.2027 - 10.02.2027 07.04.2027 - 22.04.2027 23.06.2027 - 08.07.2027 22.09.2027 - 07.10.2027

Table 2-2. KLIEN grants for energy communities

Summary	The further development of renewable energy communities (EEG), of citizens' energy communities (BEG) and of the shared generation plants (GEA) is supported in relation to the following priority thematic areas: • The expansion of the community, the opening to new groups of participants and the measures of awareness raising on the social innovation and technological. • Measures for the digitalisation, the automation, the improvement of the predictability and the implementation of smart applications for a greater control/flexibility. The services and the purchases of support for the implementation of measures in one or both of the priority areas are eligible for funding. In the context of the priority calls 1, at the time of the application or through the implementation of the measures submitted for the funding, at least two criteria must be met at least two criteria for the achievement of the social innovation in the energy community. In the context of the call priority 2, must be met at least two criteria set in the funding guide for the implementation of the technological innovations in the energy community. Combinability: The combination with other federal subsidies for identical measures or shares of investment is not allowed. Moreover, the combination with state and municipal subsidies is eligible within the ceilings of subsidy.
Information on the funding body	Team of management of energy communities of Municipal Credit Public Consulting, Türkenstraße 9, 1090 Vienna +43 1 316 31 716, umwelt@kommunalkredit.at
Type funding	Investment grant one-off
Funding maximum available	Call priority 1: max. 10.000 € Call priority 2: max. 20.000 € but maximum 50% of the costs eligible Allocation of the subsidy: 5,3 million €
Start and end date of the funding application	20.01.2026 - 16.07.2026 (hours 12:00) or up tod exhaustion of the budget

Tabe 2-3. EAG investment grants A-D

Summary	The funding where applicable for the construction or the expansion of a PV plant and, optionally, of an electricity storage system of newly built and connected to it. The funding application can be submitted after the start of the works, but must in any case take place before the measure to be funded is put into operation. The funding applications for photovoltaic systems and energy storage systems can be submitted to the respective calls. It is necessary to obtain the "number of point of metering PV"* from the grid operator and may be required authorisations by the local authorities (for example building and electrical permits). This is a one-off grant. the eligibility of a storage system is linked to the funding application for photovoltaics system. It is not possible to fund the storage system alone. Similarly, the expansions of electricity storage and the balcony systems are not included in the subject of this funding. photovoltaics innovative systems+ can receive an increase of the 30% on the rates of subsidy (therefore a maximum of the 130% of the subsidy rate). For photovoltaics systems built on a area agricola or a area green, a 25% reduction applies on the subsidy rate. The exceptions for the PV plants are available on https://www.oem-ag.at/foerderung. Bonus "Made-in-Europe": photovoltaics systems with PV modules and/or inverter that have undergone a value-creation process within the European Economic Area and Switzerland receive a surcharge of up to 20% (+ 10% for component) on the applicable subsidy rate. For the electricity storage, an increase applies of the 10% on the value added. Combinability: This subsidy cannot be combined with the subsidy of the market premium EAG. The combinations with other funding federal or state must be examined in the respective funding guidelines.			
Information on the funding body	OeMAG Abwicklungsstelle für Ökostrom AG, Alserbachstraße 14-16, 1090 Vienna +43 5 787 66 10, eag@oem-ag.at, https://eag-abwicklungsstelle.at/			
Type funding	Investment grant one-off			
Grant	A	B	C	D
Minimum size subsidised of the PV plant	-	>10 kWp	>20 kWp	>100 kWp
Maximum size subsidised of the PV plant:	10 kWp	20 kWp	100 kWp	1000 kWp
Capacity subsidised of the storage system	Minimum 0,5 kWh/kWp installed up to 50 kWh			

Table 2-3. EAG investment grants A-D (continued)

Maximum support (kWh is the usable capacity)	150 €/kWp (PV) and 150 €/kWh (storage) but max 30% of the investment costs eligible#	140 €/kWp (PV) and 150 €/kWh (storage) but max 30% of the investment costs eligible#	Up to 130 €/kWp (PV) and 150 €/kWh (storage) but max 30% of the investment costs eligible#	Up to 120 €/kWp (FV) and 150 €/kWh (storage) but max 30% of the investment costs eligible#
Available funding	9.000.000 €		21.000.000 €	
Start and end date of the funding application	23.04.2026 - 11.05.2026 16.06.2026 - 30.06.2026 08.10.2026 - 22.10.2026			

*Metering point is the identification number for an individual grid connection. When a PV system is installed, there is an additional metering point allocated.
+Innovative system definitions can be located here: https://www.oem-ag.at/foerderung
#Between the two calculation methods, the fixed rate and the 30 % of investment cost, the lowest value will be awarded.

2.2 ITALY

Widespread self-consumption (AD, autoconsumo diffuso in Italian) is a model of energy consumption in which one or more users share energy produced locally by installations, optimising grid flows within the relevant primary substation. It is governed by the European regulatory framework (RED II Directive) and transposed into Italian law via Legislative Decree 199/2021, Ministerial Decree No. 414/2023 ('CER Decree') and ARERA/GSE measures.

Below is a summary of the incentives available throughout the Panorama project and support for the development of widespread self-consumption, starting at national level and going down to the provincial level where the program operates. Incentives relevant to self-consumption are presented, whilst those for photovoltaic systems that do not involve assessments or participation in self-consumption arrangements are excluded.

National

At national level, non-repayable grants are available under the PNRR call for proposals, as well as energy account incentives.

Information on the non-repayable grants can be found at the following link: https://www.gse.it/servizi-per-te/attuazione-misure-pnrr/comunit%C3%A0-energetiche-5000abitanti. The grant is provided in the form of a capital contribution for electricity generation plants powered by renewable sources and forming part of CER schemes or self-consumption groups, located in municipalities with a population of fewer than 50,000 inhabitants, up to a maximum of 40% of eligible expenditure. The projects must become operational within 24 months of the date of notification of the concession agreement and, in any event, no later than 31 December 2027 (Gestore Servizi Energetici, s.d.-a).

The production plant powered by renewable energy sources, for the construction of which a capital grant is required, must:

- be a new build or an upgrade to an existing plant
- have a capacity not exceeding 1 MW
- be located in municipalities with a population of fewer than 50,000 inhabitants (for this purpose, reference will be made to ISTAT data on municipalities, updated as at the date the application is submitted)
- have a start date for works after the date of submission of the grant application
- hold the necessary authorisation for the construction and operation of the plant, where required
- hold a definitively approved quote for connection to the electricity grid, where required
- be located within the area served by the same primary substation to which the CER configuration or self-consumption group—of which the plant will form part—relates
- comply with the requirements for generation installations, including those set out by the DNSH (Do No Significant Harm) principle and climate tagging
- once completed, be included in a CER or self-consumption group configuration for which the contract for the provision of the incentive tariff is active.

Information is available at the following link regarding the incentives for shared energy: https://www.gse.it/servizi-per-te/autoconsumo/gruppi-di-autoconsumatori-e-comunita-di-energia-rinnovabile. The Ministerial Decree of the Environment and of the Energy Security of December 7, 2023 n. 414 has defined the new procedures of granting of incentives, aimed a promote the realisation of plants powered by renewable sources included in configurations of energy communities, groups of self-consumers and self-consumers remote. The Consolidated Text for Distributed self-consumption, annexed to the Resolution 727/2022/R/eel of the ARERA, regulates the mechanism of operation and the grants of value creation that due to the energy self-consumed within the configurations eligible (Energy Services Operator, n.d.-b).

One can find information on the shared energy incentives at the following link: https://www.gse.it/servizi-per-te/autoconsumo/gruppi-di-autoconsumatori-e-comunita-di-energia-rinnovabile. Decree No. 414 of December 2023, also known as the CACER Decree, was issued by the Minister for the Environment and Energy Security and set out the new procedures for granting incentives, aimed at promoting the construction of renewable energy installations within energy communities, self-consumption groups and remote self-consumers. The Consolidated Text on Widespread Self-Consumption, annexed to ARERA Resolution 727/2022/R/eel, regulates the operating mechanism and the value-added contributions applicable to self-consumed energy within the permitted configurations (Gestore Servizi Energetici, s.d.-b).

Under the CACER Decree, the types of installation eligible for the incentive tariff are as follows:

- remote self-consumer
- group of self-consumers
- REC

Regional

At the regional level of Friuli-Venezia Giulia, a call for REC proposals was launched for the period of 2024–2026 with the application submission window between February and April. The funding offered was 40% non-repayable funding. Further information can be found at the following link: https://www.regione.fvg.it/rafvg/cms/RAFVG/ambiente-territorio/energia/FOGLIA130/ (Autonomous Region of Friuli-Venezia Giulia, 2026).

The Veneto Region issued calls for proposals with varying deadlines for public and private sector beneficiaries. For example, in July 2024, a call for proposals was available, funded under the 2021–2027 ERDF Operational Programme – Action 2.2.1, for the construction of renewable energy power generation plants within a CER. This call for proposals provided for a grant, in the form of a non-repayable subsidy, up to a maximum of €300,000.00, equivalent to 40% of the eligible expenditure for the implementation of the submitted project, and was aimed at Renewable Energy Communities established in accordance with Directive 2018/2001/EU and the national legislation transposing it: Decree-Law 162/2019, converted into Law 8/2020, and Legislative Decree 199/2021; as well as local authorities and public administrations. Further information can be found at the following links: https://www.regione.veneto.it/web/guest/article-detail?articleId=14248097 and https://bur.regione.veneto.it/BurvServices/pubblica/DettaglioDgr.aspx?id=560014) (Veneto Region, n.d., 2026

Provincial

At the provincial level, the Udine and Pordenone Chamber of Commerce has funded vouchers for the design and implementation of CERs (for 2024 and 2025), 70% of which are non-repayable grants. Further information can be found at the following link: https://www.pnud.camcom.it/amministrazione-trasparente/sovvenzioni-contributi-sussidi-vantaggi-economici/criteri-e-modalita (Pordenone–Udine Chamber of Commerce, 2026).

3 PHOTOVOLTAIC PANELS

3.1 POTENTIAL FOR INTEGRATION INTO A RENEWABLE ENERGY COMMUNITY

Photovoltaic solar panels (PV) represent a technology particularly suitable to the generation of electricity within a REC, thanks to their high versatility. They are indeed modular and scalable, feature that of them allows the use both in installations of small scale both in plants of further sizes, adapting a different levels of energy production. Moreover, can be installed both a ground both on surfaces existing, as roofs and facades of the buildings. The presence on the market of numerous technologies and types of photovoltaic modules entails a significant variability in terms of investment costs and of energy performance, making this solution flexible and adaptable a different contexts application.

PV can be connected to the electric grid or provide energy to off-grid structures. In all the cases, the electricity is generated in the form of direct current (DC) and then converted thanks to an inverter in alternating current (AC), that can be used by the consumers end or fed in the electric grid.

Figure 3-1 shows a dwelling equipped of solar panels on the roof connected to the electric grid in low voltage (LV): the building uses the electricity produced and the possible excess energy is fed in the grid.

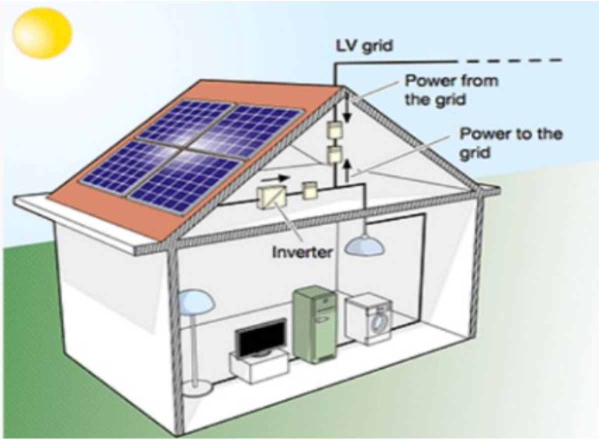


Figure 3-1. Domestic rooftop photovoltaic system connected to the grid (Electrical Engineering Portal, 2023)

Figure 3-2 shows a ground-mounted system that sends the electricity directly to the grid (Electrical Engineering Portal, 2023). This configuration requires that the electric current, over a be converted by the inverter, passes through a framework electric on the side in DC (combiner box) and a framework electric on the side in AC (switchboard), for the management and to the protection of the electric flows.

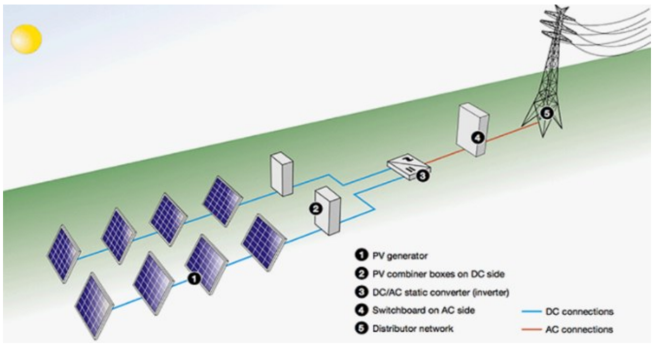


Figure 3-2. Ground-mounted photovoltaic system connected to the grid (Electrical Engineering Portal, 2023)

In Figure 3 3, however, the system is not connected to the grid and the electricity generated is supplied directly to consumers; any surplus energy is either stored in a battery or dissipated. In the latter case, a load controller and a storage system are used.

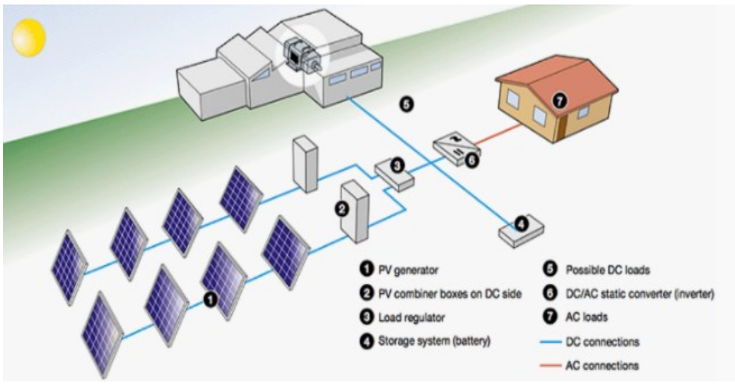


Figure 3-3. Operating diagram of an off-grid photovoltaic system (Electrical Engineering Portal, 2023)

3.2 Technical Information

3.2.1 Components and Schematics of Silicon Cells

A photovoltaic cell converts sunlight into electrical energy through the photovoltaic effect. Photons strike a semiconductor material, typically silicon, releasing electrons and creating a potential difference. Silicon cells consist of a p–n junction, formed by combining p-type silicon (usually doped with boron) and n-type silicon (usually doped with phosphorus). When sunlight strikes a solar cell, electrons gain energy and move from their original positions, creating a hole. The internal electric field of the p–n junction separates the charges, generating a usable direct current. Recombination occurs when a free electron falls back into its corresponding hole.

An n-type silicon cell consists mainly of an n-type layer with a thin p-type layer, and vice versa; a p-type cell consists mainly of a p-type layer followed by a thin n-type layer.

A set of electrically connected photovoltaic cells constitutes a module, as shown in Figure 3 4; one or more modules, together with the balance-of-system (BOS) components, form a PV panel, whilst several interconnected panels constitute an array (University of Michigan Centre for Sustainable Systems, 2025). In the literature, the terms 'PV module' and 'PV panel' are often used interchangeably, and this usage will also be adopted in this paper.

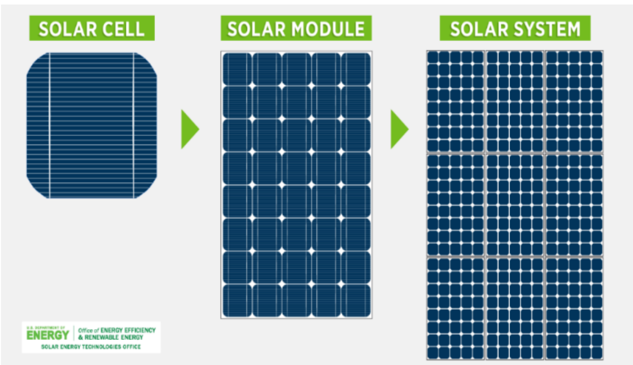


Figure 3-4. Schematic representation of the structure of a photovoltaic system: cell, module and system (U.S. Department of Energy, 2019)

The BOS comprises additional components, such as the junction box and the inverter, which convert electricity from DC to AC; the mounting structure, which supports the panel and secures it to a roof or the ground; and the battery, which enables the storage of surplus electricity (University of Michigan Centre for Sustainable Systems, 2025).

As explained above, there are numerous types of photovoltaic panel technology and various possible system configurations. This chapter will focus exclusively on the most widely used solutions and those most commonly found in contexts related to CERs. The most widely used photovoltaic cell technology is crystalline silicon (c-Si), with a prevalence of monocrystalline silicon (mono-Si) and multi-crystalline silicon (multi-Si) cells, also known as polysilicon.

The following is a description of the composition of a typical mono-Si and multi-Si photovoltaic module. The analysis of materials does not include BOS components. As shown in Figure 3 5, a module consists of several layers: the aluminium frame, the glass pane (usually tempered), a layer of ethylene vinyl acetate (EVA) encapsulant, the c-Si cells (mono-Si or multi-Si), a further layer of EVA and the backsheet. Table 3 1 sets out the material composition of a crystalline silicon photovoltaic module, the mass percentage ranges per panel and the function of each material.

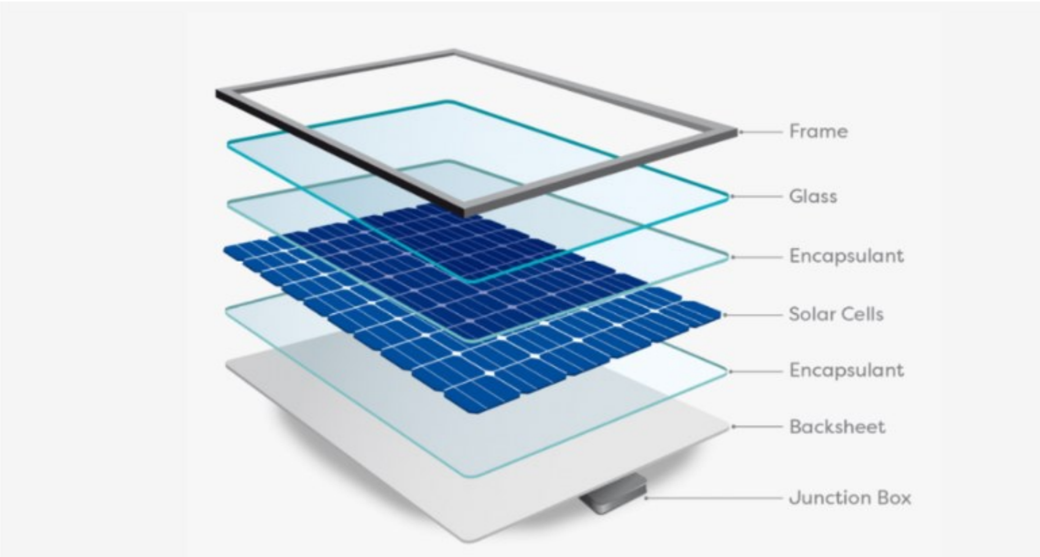


Figure 3-5. Schematic of a photovoltaic module composition (RELiON, 2022)

Table 3-1. Mass percentages and functions of the major PV module materials

Material	**Mass of Module (%)**	**Function**	**Citation**
Glass	65,4 – 76,0	Surface of the panel	(Aryan et al., 2018a; Bošnjaković et al., 2023; Buerhop-Lutz et al., 2021; Chowdhury et al., 2020; Divya et al., 2023; IRENA & IEA-PVPS, 2016; Maani et al., 2020; Trivedi et al., 2023; U.S. EPA, 2024; X. Wang et al., 2022)
Polymers	7,0 – 10,0	Encapsulant and backsheet	
Polymer (EVA)	5,0 – 6,8	Encapsulant	
Polymers additional (poliammide, polyethylene terephthalate, polymers fluorinated generic, poliolefine)	0,8 – 3,6	Backsheet	
Aluminium	8,0 – 18,5	Frame, conductor, backsheet	
Silicon	0,8 – 6,1	Solar cells	
Copper	0,1 – 7,0	Busbar, connections and interconnectors	
Other elements (silver individually or in mixture, tin, lead, aluminium, boron, phosphorus)	0,05 – 1,0	Silver: contact lines/busbars Tin: anti-reflective coating, soldering, busbars and connections Lead: soldering	

3.2.2 Photovoltaic Cell Technologies

There are various technological variants for both mono-Si and multi-Si cells. Among those currently undergoing the most development and widespread adoption are the Passivated Emitter and Rear Cell (PERC), the Tunnel Oxide Passivated Contact (TOPCon) and the Silicon Heterojunction (SHJ).

The three c-Si cell technologies – PERC, TOPCon and SHJ – are analysed below, comparing them with a thin-film technology, specifically the cadmium telluride (CdTe) cell. Schematic diagrams of the structure of the four cell technologies are shown in Figures 3.6–3.9. The cells are usually black in colour, but may also be other colours, such as blue, green, red, brown, grey or white.

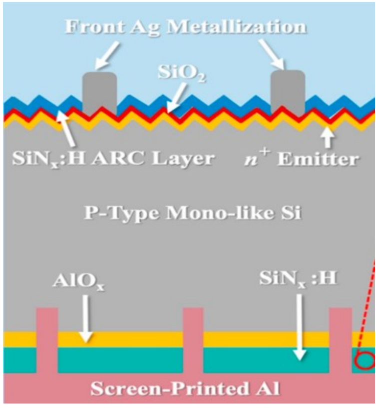


Figure 3-6. Structure diagram of a PERC cell (p-type) (Lv et al., 2020)

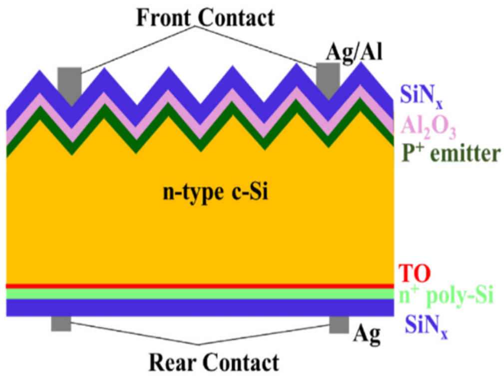


Figure 3-7. Structure diagram of a cell TOPCon n-type (Rahman et al., 2024)

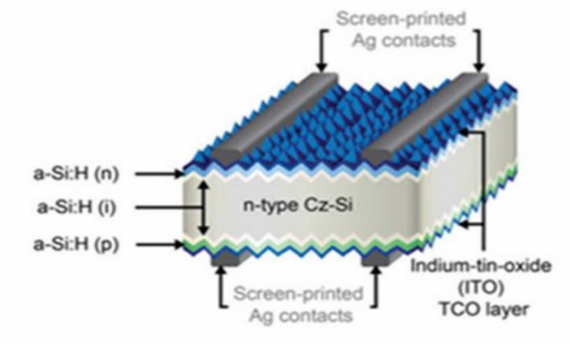


Figure 3-8. Structure diagram of a SHJ cell n-type (Mahim et al., 2024)

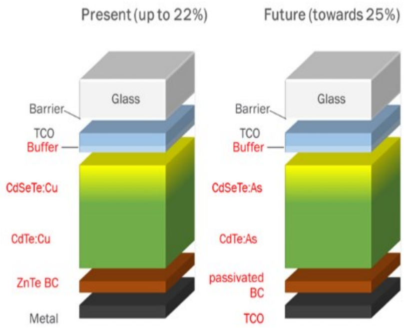


Figure 3-9. Structure diagram of a cell CdTe (Scarpulla et al., 2023)

3.2.2.1 PERC Cells

PERC cells have overtaken traditional aluminium back surface field (Al-BSF) cells on the global market because they feature a passivation layer on the rear side of the cell, which reduces losses and thus increases power conversion efficiency (PCE). A dielectric passivation layer reflects light that is not absorbed within the silicon cell, thereby reducing recombination, increasing the potential to generate more electrical energy and, consequently, boosting overall efficiency. The passivation layer is usually composed of SiO_2, Al_2O_3 and SiNX. The cells can be single-sided or double-sided, and the PEC generally ranges between 20.8% and 22.5% (Kashyap et al., 2020; Lv et al., 2020).

3.2.2.2 TOPCon Cells

TOPCon cells also feature a passivation layer on the rear of the cell, but their distinctive feature is that they have a thin tunnelling oxide layer which ensures that the wafer is not in direct contact with the metal. Commercial TOPCon modules can achieve an efficiency of 22.8%, whilst laboratory modules can reach efficiencies of 25% (Banerjee et al., 2024).

3.2.2.3 SHJ Cells

SHJ cells combine crystalline silicon with thin layers of hydrogenated amorphous silicon, which provides high-quality chemical passivation. As a result, cell efficiency can reach as high as 26.8% (Lin et al., 2023). Given their structure, these modules feature a relatively streamlined production process, characterised by a reduced number of processing stages, which allows for lower production costs and reduced material usage (Cristea et al., 2025).

3.2.2.4 CdTe Cells

CdTe thin-film photovoltaic modules are currently the leading thin-film product on the global market, with over 30 GWp installed. Thin-film modules have lower efficiencies than c-Si modules, but are also cheaper. Commercial cells have an efficiency ranging from 16% to 19%, with the highest values recorded at between 22% and 23%. CdTe modules are mainly used in large-scale installations. Current technology is based on a boron-doped (p-type) polycrystalline absorber layer made of CdTe. In most commercial modules, to ensure long-term reliability whilst minimising degradation, the laminate is hermetically encapsulated with a second sheet of glass and perimeter seals; this solution opens up significant opportunities for bifacial modules equipped with transparent rear electrodes, allowing solar radiation to be absorbed from the rear of the module as well, thereby increasing overall energy production (Scarpulla et al., 2023).

3.2.3 Technical Parameters

Table 3-2 provides parameters of various photovoltaic modules, sourced from data sheets of producers. The parameters include the type of cell, the efficiency, the voltages maximum, the coefficients of temperature, the sizes and the ranges of temperature of operation.

Table 3-2. Technical data of different photovoltaic module brands using stand test conditions

Model	**66HL4M-(V) Jinko Solar**	**JAM72S30 540/MR JA Solar**	**MB-W120AyB-400 Meyer Burger**	**FS-7550A-TR1 First Solar**
Type of cell	N-type TOPCon	P-type PERC	HJT with SmartWire connection technology	CdTe Semiconductor
Type of cell	Mono-Si	Mono-Si	Mono-Si	CdTe
Number of cells	132	144	120	268
Power maximum	615 W	540 W	400 W	550 W
Voltage to the power maximum, Vmp	40,7 V	41,6 V	38,6 V	190,4 V
Current to the power maximum, Imp	15,1 A	13,0 A	10,4 A	2,9 A
Open-circuit voltage, Voc	48,8 V	49,6 V	44,6 V	228,8 V
Short-circuit current, Isc	16,1 A	13,9 A	10,9 A	3,1 A
Efficiency of the module	22,8%	20,9 %	21,7%	19,7%
Coefficient of temperature of Pmax, γ	-0,29 %/°C	-0,35 %/°C	-0,26 %/K	-0,32 %/°C
Coefficient of temperature of Isc, α	+0,045%/°C	+0,045%/°C	+0,033%/K	+0,040%/°C
Coefficient of temperature of Voc, β	-0,25%/°C	-0,28%/°C	-0,23%/K	-0,28%/°C
Size	2382 x 1134 x 30 mm	2278 x 1134 x 30 mm	1767 x 1041 x 35 mm	2300 x 1216 mm
Weight	28,0 kg	27,3 kg	19,7 kg	39,7 kg
Temperature of operation	-40 – 70 °C	-40 – 85 °C	-40 – 85 °C	-40 – 85 °C
Citation	(Jinko Solar Co., Ltd., 2024)	(JA Solar, 2025)	(Utopia S.r.l., 2021)	(First Solar, Inc., 2024)

The panels are usually black, but they can also be coloured, for example blue, green, red, brown, grey or white. Table 3-3 provides the various panel colours, their performance ranges, and the related performance losses. The performance values are normalised with respect to conventional black panels (Y. Zhang et al., 2025).

Table 3-3. Efficiency of photovoltaic panels of various colours

Colour Category	**Range of Efficiency (%)**	**Relative Loss of Efficiency (%)**
Black conventional	22 – 23	-
Blue tone	20 – 22	3 – 15
Green tone	20 - 21	5 – 18
Terracotta	19 – 21	3 – 11
Light grey	19 – 22	4 – 17
White (aluminium white)	20 - 24	-4 - 13

Note: Efficiency values normalized to conventional black panel. Conventional black panel represents a non-colored building-integrated PV module baseline under standard test conditions.

3.2.4 Characteristic Curves

In this section, the characteristic curves of PV modules sourced from data sheets are provided. Included is the current-voltage (I-V) curve, which describes the relationship between the current and voltage output by the module under different irradiance conditions, and the power-voltage (P-V) curve, which shows how power varies with voltage under different irradiance conditions and enables the maximum power point to be identified. Together, these curves enable the electrical behaviour and performance of the photovoltaic module to be assessed under various operating conditions.

In Figure 3-6 and Figure 3-7 are shown the I-V and P-V curves for the panel PERC and for the panel TOPCon (JA Solar, 2025; Jinko Solar Co., Ltd., 2024). In Figure 3-8 is represented the I-V curves for the panel SHJ of (Utopia S.r.l., 2021).

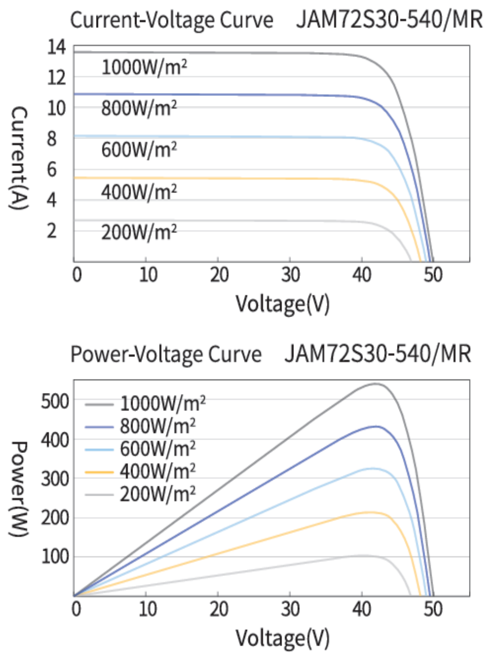


Figure 3-6. I-V and P-V curves for PERC Cells JAM72S30-540

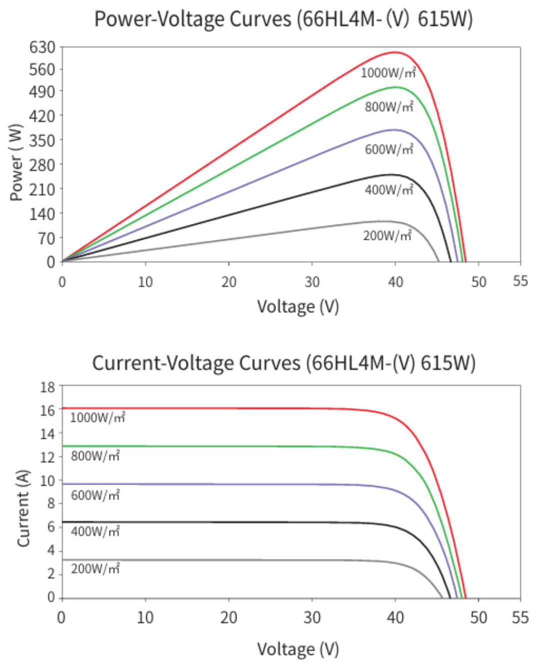


Figure 3-7. I-V and P-V curves for cells TOPCon 66HL4M-(V)

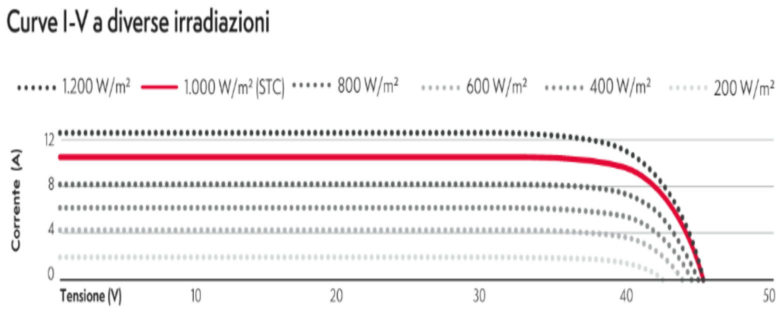


Figure 3-8. I-V curves for SHJ Cells MB_W120AyB_400

With regard to the CdTe module, the manufacturer (First Solar, Inc., 2024) does not provide any characteristic curves. Therefore, the I-V and P-V curves for the CdTe photovoltaic panel type were taken from the technical datasheet available on the OGT Solar website (OGT Solar, 2022a). This module has the following characteristics: Pmax = 180 W, Vmp = 129.3 V, and Imp = 1.46 A. The I-V and P-V curves are presented in the same chart in Figure 3-13.

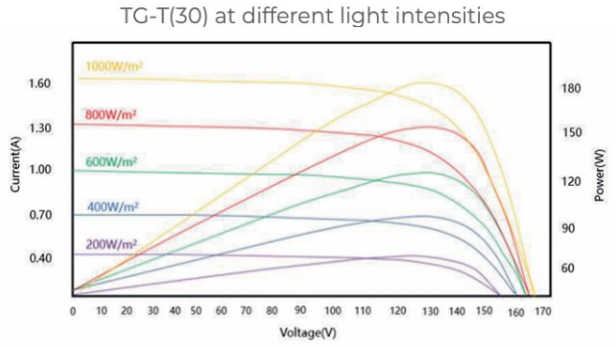


Figure 3-9. I-V and P-V curves for cells CdTe TG-T30 180W (OGT Solar, 2022b)

3.3 Economic Data

Global shipments of photovoltaic modules doubled between 2022 and 2023, reaching a total volume of approximately 564 GW. During the same period, monocrystalline silicon (mono-Si) technology recorded particularly marked growth, rising from 35% to 98% of the composition of global photovoltaic module shipments between 2015 and 2023 (Feldman et al., 2024). The graph on the left in Figure 3 14 shows the evolution of global shipments, over the period 2014–2023, of the main cell technologies: crystalline silicon types, such as multi-Si, also known as polysilicon, and n-type and p-type monocrystalline silicon (Mono c-Si), as well as thin-film technologies, including CdTe and copper indium gallium selenide/copper indium selenium (CIGS/CIS).

Within c-Si technologies, technological leadership has gradually shifted from back surface field (BSF) cells, which accounted for around 90% of the market in 2013, towards PERC technology on p-type silicon, which reached a market share of around 65% in 2023, as illustrated in Figure 3 15 (Philipps & Warmuth, 2025).

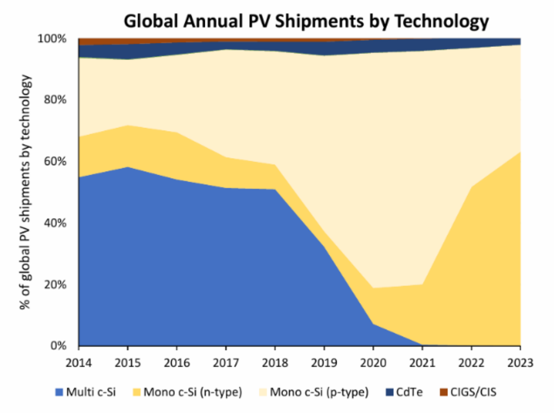


Figure 3-14. Annual global shipments of PV by technology (Feldman et al., 2024)

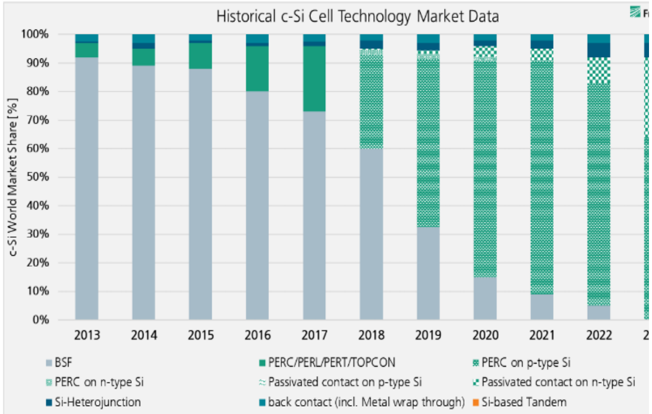


Figure 3-10. market data of the technologies of crystalline silicon cells (c-Si)(Philipps & Warmuth, 2025, 2025)

Finally, as shown in Figure 3-16, in 2023 global production of photovoltaic cells and modules was heavily concentrated in China, which accounted for 91,4% of cell production and 84,6% of module production, taking into account both crystalline silicon and thin-film technologies (IEA, 2024).

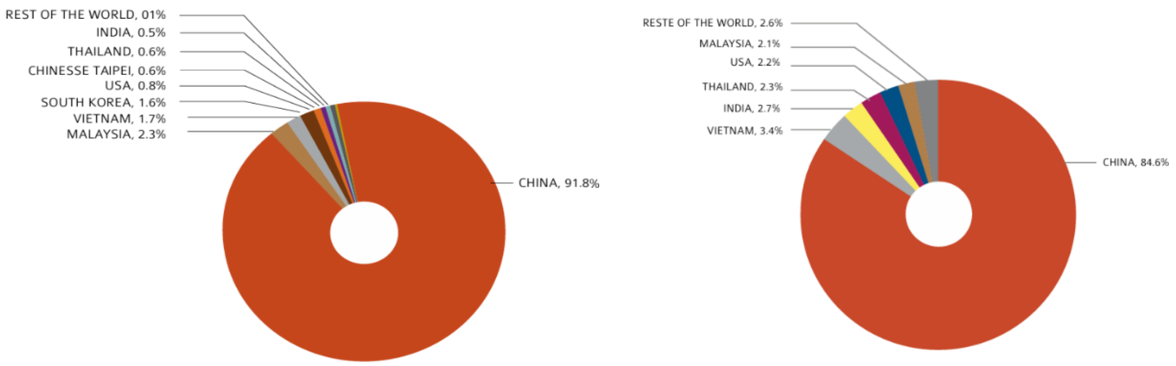


Figure 3-11. Production share of photovoltaic cells (on the left) and of photovoltaic modules (on the right) per country in 2023 (IEA, 2024)

With reference to the same four technologies analysed in the previous chapter, Table 3-4 shows the main economic parameters of PV modules. The three silicon-based technologies have comparable capital costs, amounting to approximately 0,5 €/W, whilst the CdTe technology has a capital cost that is roughly double that. Operating costs (OPEX), on the other hand, are more comparable between c-Si and thin-film technologies. Furthermore, Table 3-5 sets out the average turnkey costs and the cost per kilowatt of small, medium and large-scale installations built using standard and coloured modules.

Table 3-4. Cost parameters from literature

Technology	**TOPCon**	**PERC**	**SHJ**	**CdTe**
CAPEX	0,545 €/W (for a plant from 5kW)	0,544 €/W (for a plant from 5kW)	0,634 €/W(for a plant from 5kW)	1,083$/W(0,3 module + 0,783 other costs of capital) (for a plant from utility scale)
OPEX	203 €/year(for a plant from 5kW)	203 €/year(for a plant from 5kW)	203 €/year(for a plant from 5kW)	48 $/kW-year
Citation	(Cristea et al., 2025)			(Meagle et al., 2025; U.S. Department of Energy, n.d.-b)

Table 3-5. *Turnkey cost and specific cost for black and coloured modules*

	Modules Standard		**Modules Coloured**	
Size Plant	Turnkey Cost	Cost Specific	Turnkey Cost	Cost Specific
[kWp]	[€]	[€/kWp]	[€]	[€/kWp]
3,5	6400	1829	9335	2667
5,2	7136	1372	10210	1963
7	7801	1114	10961	1566
136,4	69000	506	85568	627
376,75	140000	372	158341	372

3.4 ENVIRONMENTAL IMPACTS

In LCA analyses of solar panels, the general life cycle stages are production, construction, use and end-of-life (EoL). Table 3.6 provides some LCA studies and the respective life cycle stages included in the analysis. The orange Xs indicate the life cycle stages included in the carbon change potential (CCP) of production, highlighting how the boundaries of the LCA system vary considerably between different studies.

Table 3-5. Life cycle assessments of solar panels taken from the literature. The life cycle stages included in the respective study are marked with an "X".. The symbol "-" indicates the phases of the life cycle not included in the study or not explicitly mentioned.

A	**B**	**C**	**D**	**AND**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**OR**	**P**	**Q**	**R**	**Citation**
Production									Installation			Operation				EoL		
-	-	X	X	X	X	X	-	-	X	-	-	-	-	-	-	X	-	(Müller et al., 2024)
-	X	X	X	X	X	-	-	X	-	-	-	-	-	-	-	-	-	(Chen et al., 2016)
X	-	X	X	X	X	X	X	-	-	-	-	X	-	-	-	X	-	(Roy & Pearce, 2024)
-	-	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	(Fthenakis & Leccisi, 2021a)
-	-	X	X	X	X	X	X	-	X	-	-	-	-	-	-	-	-	(De Simón-Martín et al., 2017a)
-	-	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	(Leccisi et al., 2016a)
X	-	X	X	X	X	X	X	-	X	-	-	-	-	-	-	-	-	(Talebian et al., 2020)
X	X	X	X	X	X	X	X	-	X	X	-	X	X	X	-	X	-	(Hou et al., 2016a)
X	-	X	X	X	X	X	X	-	X	X	-	X	X	-	-	-	-	(Malode et al., 2024)
-	-	X	X	X	X	X	X	-	-	X	-	-	-	-	-	-	-	(Krebs et al., 2020)
-	X	X	X	X	X	X	X	-	X	X	X	X	X	-	X	X	-	(Mohd Nordin et al., 2022)
-	-	X	X	X	X	X	X	-	-	X	-	X	-	-	-	X	X	(Beylot et al., 2014)

A = Extraction of the resources, B = Transport of the raw materials, C = Purification of the silicon (by the quartz a UMG-It a SoG-It), D = Casting of the ingots, AND = Cutting of the wafer, F = Production of the cells, G = Production of panels/modules, H = Production of the components auxiliary (BOS) and/or integration of photovoltaic systems, I = Management of the waste of production, J = Transport of photovoltaic panels/BOS to the site, K = Installation (construction of BOS + modules), L = Use of the land, M = Use, N = Cleaning/maintenance/replacement, OR = Transmission of electricity, P = Transport towards the disposal, Q = Dismantling and/or disposal (landfill, incineration and/or recycling), R = End of the life cycle (EOL) of the BOS

This chapter discusses some of the environmental impacts associated with solar panels and photovoltaic systems. The topics considered include energy demand (ED) and energy production (also known as yield), CCP, land use (LU), biodiversity and ecosystem health, human health (HH), water footprint, terrestrial and aquatic ecosystems, and end-of-life (EoL).

A literature review approach was adopted, and not all impacts were calculated using standardised LCA or LCIA methodologies. It should be noted that the data presented are drawn from various sources, each with different system boundaries; therefore, readers are advised to refer to the individual citations for further details. Furthermore, literature presenting normalised and weighted LCIA results has not been included. Finally, Section 3.4.9 introduces environmental product declarations (EPDs) and presents the results.

Table 3.7 shows the LCA analyses examined, indicating for each one the FU and the assessment boundary. Studies that provide numerical values but are not LCAs are listed in the last row. The functional unit given corresponds to the formulation used in the study. As regards the system boundary, the term ‘cradle to gate’ is applied to studies that assess stages ranging from production up to use.

Table 3-6. Summary of the literature considered in this chapter, specifying the functional unit and system boundary

Citation	Functional Unit	System Boundary
(Wings et al., 2022)	1 kWh of electricity net generated	Cradle to grave
(Alam & Xu, 2023a)	1 kWh of electricity produced	Cradle to gate
(Krebs et al., 2020)	Generation of 1 kWh of electricity for self-consumption from a system PV-battery coupled in AC	Cradle to gate
(Roy & Pearce, 2024)	1 kWh of electricity in AC fed into the grid	Cradle to grave
(Tsang et al., 2016a)	kWh average of electricity generated in 25 years through a photovoltaic system on roof	Cradle to grave
(De Simón-Martín et al., 2017b)	The system is of 101,01 kW_p*	Cradle to gate**
(Fthenakis & Leccisi, 2021a)	Rated power (kWp) of the modules	Cradle to gate
(Fu et al., 2015a)	1 kWh based on a PV module in multi-Si with capacity of 200 Wp	Cradle to gate
(Duan et al., 2024)	A photovoltaic module in multi-Si of 1 m²	Cradle to grave
(Hong et al., 2016a)	Production of 1 kWp of PV cells in multi-Si	Cradle to gate
(Stolz et al., 2017a)	1 kWh of electricity in AC, at the delivery point, generated from a system PV residential from 3 kWp in mono-Si installed on roof inclined	Cradle to grave
(Shah et al., 2023)	1 kWh based on a PV module in multi-Si with capacity of 200 Wp	Cradle to gate
(Fares et al., 2024)	1 kW of capacity of production combined of heat and electricity for the system PV	Cradle to gate
(Bolinger & Bolinger, 2022a; Bošnjaković et al., 2023; Bukhary et al., 2018; Kozlovas et al., 2023a; Marzouk, 2022; Mukherji et al., 2020a; Sukumaran et al., 2022a; Tröndle, 2020)	Non-LCA studies	

*The study does not indicate explicitly the functional unit; however, because the results of impact are expressed for kWp, these results have been normalised dividing for the peak power of the system (kW_p)
**The study declares of adopt a “cradle-to-grave” approach, but the reported environmental values in this document refer exclusively to the “cradle-to-gate” phase

3.4.1 Energy Demand

The ED impact category encompasses the energy used throughout the entire life cycle or during a specific phase of the life cycle of a PV system. ED, often referred to as Cumulative Energy Demand or calorific value, may include only primary energy consumption (Frischknecht et al., 2015) or both primary and secondary consumption, the latter also referred to as cumulative energy demand (Dolgun et al., 2023). A primary energy source is directly available in nature, such as crude oil, coal or solar energy, whilst a secondary energy source is derived from a conversion process (European Commission Eurostat, 2025). Depending on the literature, ED can be expressed in various units of measurement: total energy (MJ), electricity per m² of panel (MJ/m² of panel), energy ratio (MJ/kWh) (Krebs et al., 2020), or energy per installed peak power (MJ/kW_p or kWh/kW_p) (Mariska De Wild-Scholten, 2013; Roy & Pearce, 2024), where the value in kWh/kWp is frequently referred to as ‘yield’.

Much of the energy consumption over the life cycle is concentrated in the production phase, which requires electricity to power equipment and machinery. Furthermore, quartz extraction and the production of silicon cells require large amounts of electricity (Bošnjaković et al., 2023); (Fu et al., 2015b) estimate that 48.5% of the energy associated with module production is attributable to the production of solar-grade silicon. Photovoltaic panels do not require electricity during the operational phase. Further energy consumption occurs during the end-of-life (EoL) phase, when the panels are dismantled and the components are processed.

Although the energy required to manufacture the panels is the same for rooftop systems and ground-mounted systems (also known as large-scale or utility-scale systems), the main differences in energy demand stem from the mounting structure and installation. Ground-mounted systems often have capacities ranging from 1 to 5 MW, but may also be larger (U.S. Energy Information Administration, 2019). Panel production is frequently cited as accounting for 80,0–88,7% of the system's total energy demand (De Simón-Martín et al., 2017b; Hou et al., 2016b), but this proportion can fall to around 32–64% when certain mounting structures are included, particularly those based on concrete. Overall, rooftop systems can have an energy requirement that is 21–54% lower than that of ground-mounted systems (Roy & Pearce, 2024). Table 3-8 provides a summary of the ED values reported in the literature. The values describe total energy demand and, where specified in the literature, indicate whether the energy considered is primary, secondary, renewable or non-renewable.

Table 3-7. Values of energy demand from the literature

Results of the Impact Assessments	**Citation**
4,8 MJ oil-eq/kWh (primary, renewable and non-renewable)	(Krebs et al., 2020)
1,5x10^4 MJ/kW$_p$	(Tsang et al., 2016b)
1,2x10^4 MJ/kW (non-renewable)	(Fares et al., 2024)
1,3 x10^4 MJ/kW$_p$ (primary, renewable and Non-renewable)	(Shah et al., 2023)
1,4 x10^3 kWh/kW$_p$ (installation on roof)	(Roy & Pearce, 2024)
3,0 x10^3 kWh/kW$_p$ (ground mounted, concrete base)	
1,7 x10^3 – 1,8 x10^3 kWh/kW$_p$ (ground mounted with poles fixtures (pile-driven))	
4,2 x10^4 MJ/kW$_p$ (ground mounted, steel base) (primary)	(De Simón-Martín et al., 2017a)
1,4 x10^4 – 1,5 x10^4 MJ/kW$_p$ (3,8 x10^3 – 4,1 x10^3 kWh/kW$_p$) (primary)	(Fthenakis & Leccisi, 2021a)
1,3 x10^4 MJ/kW$_p$ (2,4 x10^4 kWh/kW$_p$) (primary, renewable and non-renewable)	(Fu et al., 2015b)

3.4.2 Climate Change Potential

The CCP measures greenhouse gas (GHG) emissions, converted to carbon dioxide equivalent (CO_2eq), released over a specific period of time (usually 100 years) during a product's life cycle. As the scope of studies varies, this report analyses the CCP relating to the production phase of photovoltaic systems, in order to facilitate comparison. This phase of the life cycle has the highest CCP, due to the GHG emissions associated with the manufacture and assembly of components. In the literature, studies may consider Scope 1, 2 or 3 emissions. Scope 1 emissions are direct emissions resulting from energy production at the manufacturer's site; Scope 2 and 3 emissions are indirect. Scope 2 comprises emissions associated with the production of energy used by the manufacturer but generated off-site. Scope 3 emissions occur upstream or downstream along the supply chain (U.S. EPA, 2025b). For example, the total Scope 2 CCP of a plant using electricity generated from fossil fuels will generally be higher than that of a plant using electricity from renewable sources (Gan et al., 2023; Gibon et al., 2021).

The CCP values for panels (mono-Si, multi-Si), mounting structures (pitched roof, flat roof, ground-mounted), inverters and batteries, such as lithium-iron-phosphate (LFP), are set out in Table 3-9.

The emissions of the phase of production represent often the 80–90% of the emissions total and are in large part attributed to the production of the wafer (purification and crystallisation of the silicon, cutting of the wafer and manufacturing of the cells). Considering also the structure of mounting, the systems PV on roof can show a CCP lower of the 18–59% compared to the systems installed on the ground (Roy & Pearce, 2024). In a case-study conducted in Romania on panels installed on the roof, the panels oriented east-west showed a CCP lower, thanks to the lower amount of aluminium and ballasts necessary in the support. In general, the south oriented panels receive stronger loads of snow and wind; therefore, the structure of mounting must be more robust (Rus et al., 2024).

The operational phase can contribute approximately 0.3–1% of the CCP (Bošnjaković et al., 2023). The EoL phase can account for 5–20% of emissions, but this figure remains poorly understood. As highlighted in Table 3-6, the EoL phase is often not included or not comprehensively analyzed in CCP studies.

Several studies make comparisons, often hypothetical, between CCP values as a function of production location, as this indicator is strongly influenced by the local energy mix. Literature suggests that CCP is lower when electricity is produced with a renewable energy mix compared to fossil fuels. Coal is widely used in the main producing country, China (Collins et al., 2015; Frischknecht et al., 2020; Mehedi et al., 2022). A full transition to production in countries with cleaner electricity grids is currently complex, given the established level of dependence on China (Chadly et al., 2024; Jackson et al., 2021. In one Chinese plant, hydropower accounted for 71% of the energy supply in the product processing, assembly, and testing phases of cells (Sunwoda Mobility Energy Technology Co., Ltd., 2025). China and other countries in Asia-Pacific produce approximately 78% of the global multi-Si market and 93.5% of modules (Frischknecht et al., 2020). Other studies analyze differences in CCPs related, for example, to material quality and the geographical origin of raw materials (Heidari & Anctil, 2022).

Table 3-8. Ranges of climate change potential of photovoltaic system components

Component of the PV System	Values	Average	Unit	Citation
Panel mono-Si	285,2 – 1700,0	643,7	kg CO_{2eq}/kW_p	(Chen et al., 2016; De Simón-Martín et al., 2017a; Fthenakis & Leccisi, 2021a; Kouloumpis et al., 2020; Leccisi et al., 2016b; Müller et al., 2024; Roy & Pearce, 2024)
Panel multi-Si	773,8 – 1570,7	1147,6	kg CO_{2eq}/kW_p	(Beylot et al., 2014; Fthenakis & Leccisi, 2021b; Hou et al., 2016b; Kouloumpis et al., 2020; Krebs et al., 2020; Leccisi et al., 2016b; Malode et al., 2024; Mohd Nordin et al., 2022; Talebian et al., 2020)
Mounting structure, installation on roof, inclined roof	3,2 – 71,0	42,0	kg CO_{2eq}/structure for 1 m2 of the panel	(Brivio et al., 2024; GreenDelta, 2020; Krebs et al., 2020; Malode et al., 2024; Neumüller et al., 2023; Roy & Pearce, 2024)
Mounting structure, installation on roof, level roof	44,1 – 83,0	61,7	kg CO_{2eq}/structure for 1 m2 of the panel	(GreenDelta, 2020; Neumüller et al., 2023)
Structure of mounting, installation a ground	7,0 – 658,0	119,8	kg CO_{2eq}/structure for 1 m2 of the panel	(Beylot et al., 2014; Brivio et al., 2024; De Simón-Martín et al., 2017a; GreenDelta, 2020; Mohd Nordin et al., 2022; Neumüller et al., 2023; Roy & Pearce, 2024)
Inverter	12,1 – 127,4	59,6	kg CO_{2eq}/kW_p	(Brivio et al., 2024; De Simón-Martín et al., 2017a; GreenDelta, 2020; Huawei Technologies Co., Ltd, 2020; Kouloumpis et al., 2020; Malode et al., 2024; Mohd Nordin et al., 2022; Roy & Pearce, 2024)
Battery (LFP)	46,4 – 281,1	135,6	kg $CO_{2eq}/kWh_{nominal\_capacity}$	(Botejara-Antúnez et al., 2024; Carvalho et al., 2021; Feng et al., 2022a; GreenDelta, 2020; Guo et al., 2023a; Jasper et al., 2022; Krebs et al., 2020; Quan et al., 2022; Shu et al., 2021a)

3.4.3 Land Use

There are different definitions of LU, particularly between the different LCIA methods. In the ReCiPe method, the Land use/transformation category measures the loss of species (plants, mammals, birds, etc.) due to changes in land use (Huijbregts et al., 2016). In the Environmental Footprint method, the land use category assesses soil quality (Andreasi Bassi et al., 2023), while IMPACT 2002+ focuses on farmland (Jolliet et al., 2003). (Rybaczewska-Błażejowska & Jezierski, 2024b) compare four LCIA methods in their respective LU midpoint categories and find similarities between ReCiPe and IMPACT 2002+.

A further definition, often used in non-LCA studies, concerns the land area required by photovoltaic systems, generally expressed in units of $(distance)^2$ per kWp or per kWh. In the literature, two definitions of space requirements are distinguished: panel space and total project space. The panel space includes the surface area occupied by the panels and the space between them. The total project area (also called utility space) includes panels, space between panels, transmission equipment (transformers, inverters) and infrastructural elements (e.g. access roads).

Since rooftop PV panels are installed on existing buildings, they do not require new land and therefore have a low LU requirement. The total project area is instead generally associated with ground-mounted plants; It is estimated that it involves an additional space of 30–50% compared to panel space alone (Sukumaran et al., 2022b; Tröndle, 2020).

There are different types of mounting structures that fix the panels in a static position or allow the sun to be tracked. However, it is necessary to provide a minimum space between the panels to avoid contact and shading. Solar tracking systems require more land area (Bukhary et al., 2018). Among the four types analyzed by (Marzouk, 2022), fixed panels, single-axis vertical, single-axis horizontal and double-axis tracking, the single-axis horizontal systems have the highest average values of ground cover average (ratio between the total surface area of the panels and the land required) and energy generation intensity (kWh/year·m²), both indicators of efficient use of space, while PVV systems show the lowest values for both indicators (Marzouk, 2022).

To achieve the International Energy Agency's targets, i.e. 600 GW of solar power installed globally by 2030 and 4400 GW by 2050, 7.452 km² of surface area (of which 53% is utility scale) would be needed by 2030 and 58.344 km² (of which 59% is utility scale) by 2050 (Bošnjaković et al., 2023). As for the European Union (EU), a current estimate of 11.664,4 km²/GWh-year of potential roof area is available (Bódis et al., 2019).

Solar panels can compete with other sectors for land use, such as agriculture, forestry and urban development (residential, commercial, office, etc.), but they can also coexist with such activities. Installation on buildings, for example, does not interfere with the activity carried out within the buildings themselves. (Kruitwagen et al., 2021) estimates that most land-based plants are located on man-made soils, such as farmland, and in ecosystems such as arid areas and grasslands.

PV systems used in collaboration with agriculture, known as agrivoltaic systems, requires careful logistical planning, including defining the methods of sowing between the panels, the harvesting techniques (type and size of agricultural machinery) and the response of the crops grown under the panels. Agrivoltaics research analyzes variations in plant water consumption, rainfall distribution (Elamri et al., 2018a), in the characteristics of the soil and microclimate (air temperature and humidity), in the amount of light received (Thompson et al., 2020) and the impact on crop growth (Marrou et al., 2013; Weselek et al., 2021). The air temperatures under the panels can be lower than the ambient ones, as observed by (Giri & Mohanty, 2022) e (Barron-Gafford et al., 2019), with reductions of between 1 and 1,5°C. Table 3-9 provides LU values taken from the literature, both from non-LCA and LCA studies.

Table 3-9. Land use values taken from the literature

Results of Impact Assessments	Citation
Roof	
5,0 m²/kW	(Bošnjaković et al., 2023)
Creates a microclimate under and around the panel, because of variations in light and in precipitation.	(Mukherji et al., 2020b)
Residential (condominium buildings): 15,4 m²/kW_p Buildings commercial: 18,1 m2/kW_p Buildings public: 15,6 m2/kW_p	(Kozlovas et al., 2023b)
Utility scale	
11,4 m²/kW	(Tröndle, 2020)
19,0 m²/kW	(Bošnjaković et al., 2023)

Table 3-10. Land use values taken from the literature (continued)

Results of Impact Assessments	Citation
8,8 m^2/kW	(Sukumaran et al., 2022b)
14,5 m^2/kW fixed inclination 14,5 m^2/kW for tracking system	(Bolinger & Bolinger, 2022b)
Total project area: 8,3 – 19,4 m^2/kWp Panel area: 4,9 m^2/kWp	(Marzouk, 2022)
Total project area: 0,0094 –0,011 m^2/kWh-year Panel surface: 0,0067 – 0,0076 m^2/kWh-year	(Bukhary et al., 2018)
LCA values	
4,2 m^2 annual $crop_{eq}$/1 m^2 multi-Si PV module	(Duan et al., 2024)
4,2 m^2 of organic arable land per year/kWp (cell)	(Hong et al., 2016b)

3.4.4 Biodiversity and Ecosystem Health

Solar panels are an anthropogenic element introduced into the ecosystem and can have an impact on flora and fauna. (Moore-O'Leary et al., 2017) It discusses five concepts related to the relationship between large-scale solar installations and the landscape, which can serve as a guide for solar deployment:

- Evaluation of trade-offs between land, energy and ecology
- Monitoring of species reactions to human development
- Mitigation of cumulative ecological impacts
- Each ecosystem requires a specific implementation approach
- Monitoring ecological reactions over time

The impact of solar energy on animal, entomological and plant species varies depending on the location and species in focus. (Randle-Boggis et al., 2020a) created a decision support tool called Solar Park Impacts on Ecosystem Services (SPIES). This tool helps to guide large-scale plant management strategies with a view to safeguarding ecosystem services. Another decision-making tool for assessing the compatibility between solar energy and landscape is the Carnegie Energy and Environmental Compatibility model (Hernandez, Hoffacker, & Field, 2015). Reconciling supporting the health of ecosystems with maintaining the efficiency of solar panels is a challenge. An example concerns the increase in pollinators through the introduction of native plant species: while this practice can promote biodiversity, it could also increase the presence of pollen, with possible negative effects on the efficiency of photovoltaic panels (Blaydes et al., 2021). (Damiani et al., 2023) proposes a literature review based on 23 LCA studies and models assessing impacts on different dimensions of biodiversity. These include pressure categories, such as land use, pollution, and overpopulation; types of ecosystems, including terrestrial and marine environments; taxonomic groups, such as mammals, birds, plants, and fungi; classes of Essential Biodiversity Variables, such as genetic composition and community composition; and fundamental aspects of biodiversity, such as extinctions and multifunctionality. The authors point out that the available assessment methods have different system boundaries and application areas. As a result, no single method can comprehensively capture all aspects of changes in biodiversity. Table 3-10 It illustrates the impacts on ecosystems that can result from the installation of solar panels and provides suggestions for fostering the coexistence between ecosystems and panels. Table 3-11 presents three case studies related to the reactions of ecosystems to the installation of solar panels.

Table 3-10. Impact of solar panels on the ecosystems

Impacts and Recommendations		Citation
Possible impacts	Create a microclimate under and around the panel, due to variations in light and rain	(Bošnjaković et al., 2023; Lambert et al., 2023, 2024; Mamun et al., 2022; Tinsley et al., 2024; Uldrijan et al., 2021)
	Encourage more seed growth if maintenance is low	
	Result in habitat loss and displacement of animals due to construction work	
	Animal species lose their bearings due to the reflection of solar panels, especially near the sea	
	Compacting the soil, increasing bulk density and reducing porosity	
	Modify plant communities in favor of more shade-tolerant species or promote shade-preferring crops	
Recommendations	Create or maintain buffer zones of the ecosystem around the panel field	(Hernandez, Hoffacker, Murphy-Mariscal, et al., 2015; Lambert et al., 2023, 2024; Randle-Boggis et al., 2020b; Tinsley et al., 2024; Uldrijan et al., 2021)
	Install animal habitats, such as birdhouses and bats	
	Mow later in the year or replace the lawn mower with pasture	
	Reduce the use of pesticides and fertilizers	
	Create or maintain areas of bare land	
	Perennial grasses and perennial grasses can be ideal to plant under panels to increase water infiltration due to their root system and ability to control erosion	
	Limit tall grasses and pollinators as they may damage the panels	
	Locate solar farms in places already affected by anthropogenic sources, such as low-quality areas or previously developed sites	
	Pay attention to the surrounding ecosystems as solar panel zones could be used to move between habitats and non-native species could take advantage of habitat fragmentation	
	Composting can help maintain the carbon and nitrogen content in soils	
	Increasing the space between panels can promote grassland growth	

Table 3-11. Case studies of solar panels in the environment

Case Studies	Citation
A study on bat reactions in a field with solar panels, England • 6 of the 8 species or groups of bat species were negatively affected by the presence of solar panels, as demonstrated by lower activity, probably due to the loss or fragmentation of habitat used for food and movement • In the presence of solar panels, species richness was not affected, while in fields without panels species richness was higher in border areas • Activity was greater in the border areas than in the center of the fields, both in the presence and absence of panels	(Tinsley et al., 2023)

Assessment of landscape compatibility in California with power generation plants (>1 MW), USA
• The landscape types are listed in descending order of installed capacity MW_{dc}: scrubland/scrub (36%), agricultural crops (22%), arid soils (rock/sand/clay) (12%), urbanized land (open, low, medium and high intensity spaces) (12%), meadows/herbaceous (9%), pastures/hay (8%) and emerging herbaceous wetlands (0%)
  ○ 48% of the installed km^2 are located in shrub/scrub areas, a landscape with high levels of biodiversity
• Compatibility of the plants with the landscape in which they are located (based on various solar, hydrological, topographical, ecological and energy criteria, described in the study supplement):
  ○ 11,2% are located in compatible areas, 71,7% in potentially compatible areas, 17,1% in non-compatible areas
• Average distance of the service facility to the nearest protected area: 7,2 ± 0,9 km
	(Hernandez, Hoffacker, Murphy-Mariscal, et al., 2015)

A study comparing man-made land (solar park and abandoned vineyard) and semi-natural land (forest and scrubland), France
• Inside the solar park
  ○ The presence of plants in succession and the richness of species were not affected by solar panels
• Between the different types of terrain
  ○ The overall soil quality indicator was 4 times lower in anthropogenic soils than in semi-natural soils
  ○ The quality of soil aggregates was reduced in anthropogenic soils
  ○ The amounts of carbon, nitrogen and microbial biomass were higher in semi-natural soils than in anthropogenic soils
	(Lambert et al., 2021)

3.4.5 Human Health

Humans can suffer negative effects from solar panels due to the emissions released during their life cycle or from the use of the system. Emissions can enter the human body through different routes of exposure: skin contact, breathing, ingestion, or oral intake (U.S. EPA, 2025a). Humans can suffer negative effects from solar panels due to the emissions released during their life cycle or from the use of the system. Emissions can enter the human body through different routes of exposure: skin contact, breathing, ingestion, or oral intake (Pizzol et al., 2011) and the following discussion does not offer an exhaustive list of categories or units.

The impact category toxicity, which can be split into carcinogenic and non-carcinogenic to humans, describes the possible health implications of a toxic substance. The unit of measurement is comparative toxic unit for humans (CTUh), Photochemical ozone formation, also known as photochemical smog formation, measures tropospheric ozone production and its ultimate impact on the human respiratory system; units are kg of non-methane volatile organic compounds (NMVOCeq), kg of nitrogen oxides equivalent (NOx_{eq}), or kg of ozone equivalent (O_{3eq}) (Bare, 2012; Huijbregts et al., 2016; Zampori et al., 2016). Fine particulate matter formation can refer to the absorption of primary or secondary particles, inorganic or organic, of various sizes (PM10, PM2,5, total suspended particulate matter) and is expressed in kg of primary $PM2,5_{eq}$ or disease incidence (Huijbregts et al., 2016; Zampori et al., 2016) The ionization radiation potential refers to the release of radionuclides, mainly from the nuclear power generation process, and is expressed in kilobecquerels (kBq) of cobalt-60eq, kBq of uranium-235eq, or Bq of carbon-14eq (Huijbregts et al., 2016; Rybaczewska-Błażejowska & Jezierski, 2024b). General risks are discussed in the Table 3-12.

(Alam & Xu, 2023b) present a cradle-to-gate LCA analysis based on the Canadian energy mix. For the categories Carcinogenic, Non-carcinogenic, Respiratory effects, and Smog, panel production was the main impact contributor, accounting for between 40% and 90% of the overall impact in each category. During the life cycle, chromium VI emissions to groundwater were the main contributor in the Carcinogenic category, while emissions of lead and zinc ions to groundwater were the main contributors in the Non-carcinogenic category. Smog impact was mainly derived from nitrogen oxides. Wings et al. (2022), who assessed production in China and use in America, identified panel production as the main contributor for the following categories: smog (~80%), respiratory effects (80%) and ozone depletion (~90%). Panel production contributed about 50% to both carcinogenic and non-carcinogenic impacts.

Table 3-12. Possible risks to human health and mitigation strategies

Risks	**Citation**
Glare • Momentary vision loss and eye damage • Risks can be mitigated with anti-reflective coatings • In critical areas such as flight routes at airports, you can avoid installing panels or change their orientation	(Bošnjaković et al., 2023; Rose & Wollert, 2015; Sreenath et al., 2020)
Fire • Batteries can catch fire and release smoke	(Wu et al., 2020)
Noise • Manufactured by solar trackers, inverters and transformers • Mitigated with noise-canceling techniques, such as placing noise-producing equipment in the center of the solar system or closer to industrial/non-residential areas	(Bahtiarian, 2020; Bošnjaković et al., 2023)
Leaching • Emissions to water during the production phase can include COD, fluoride, suspended solids, nitrogen, and phosphorus • Aged and/or glass-free panels may have increased leaching of elements, such as lead and aluminum. The lack of the glass panel is rare, but it can occur in landfill conditions. • Concentrations of other elements, such as cadmium, chromium, copper, and silver, may remain below regulatory limits even if the panel is glass-free. • Laboratory tests such as TCLP and SPLP are useful for measuring possible leaching into drinking water and ecosystems.	(A. Robinson & Meindl, 2019; Sharma et al., 2021; Xie et al., 2018)
Atmosphere • Indirect air pollutants from the combustion of coal during electricity generation, such as sulphur dioxides, nitrogen oxides and heavy metals • In panel manufacturing, air emissions can include silicon dust, hydrochloric acid, hydrofluoric acid, chlorine, ammonia, NMVOCs, carbon oxides, methane, nitrogen oxides, sulfur hexafluoride, and perfluorocarbons	(Bošnjaković et al., 2023; Chen et al., 2016; Fan et al., 2021; Xie et al., 2018; Yang et al., 2023)

3.4.6 Water Footprint

Water is consumed at different stages of the life cycle, and this consumption is commonly referred to as water consumption or water footprint. Water is used indirectly during the production phase, as it is consumed in some electricity production processes, such as coal combustion or nuclear energy (Bošnjaković et al., 2023). (Stolz et al., 2017b) estimates that 82% of the life-cycle water stress of a PV system comes from the production phase, and that rooftop plants use 83,0-99,6% less water in the life cycle than utility-scale plants. A concrete base and a pile base require 260 and 6 times more water respectively than a roof-mounted structure(Roy & Pearce, 2024).

In contrast, solar panels require less water during the construction and operation phase. Water is used for dust control during the construction phase. During operation, water is used to remove dust, pollen, bird droppings and other particles from the panels, but this depends on the environment. Dustier places, such as deserts, will likely require more frequent cleaning (Bukhary et al., 2018; Rabaia et al., 2021). Water is also used as a cooling agent to reduce the temperature of the panels, as efficiency decreases at high temperatures, with a drop of about 0,5% for every 1°C increase, based on standard temperature conditions (Bamisile et al., 2025; Shalaby et al., 2022).

A purification infrastructure may be required for the water used for cleaning. Due to the risk of salt or other particles (total solids) accumulating on the panels, water can be treated in a desalination plant or wastewater treatment plant. Solar panels can be used as a tool to collect rainwater, which can then be reused for cleaning (Elamri et al., 2018b).

There are various methods for calculating water consumption. The norm ISO 14046:2014 Provides guidance on water footprint measurements and assessments (International Organization for Standardization, 2014). (Roy & Pearce, 2024) calculated the water footprint in m^3/kWp, considering groundwater and surface water, measuring the water used in the supply chain and then weighting it according to the water scarcity of the river basin. (Stolz et al., 2017b) calculated water consumption (water incorporated into the product or evaporated) and water withdrawn (water withdrawn and returned to the same catchment area) in m^3/kWh and water stress (water available in a catchment area after subtracting human and ecosystem demand) in m^3 $water_{eq}$/kWh with the AWARE method. The life cycle of water consumption and withdrawals is measured and then weighted according to country-specific water scarcity values. The LCIA ReCiPe method measures water consumption in m^3 (Huijbregts et al., 2016). Table 3-13 reports the water use values for photovoltaic panels.

Table 3-13. Water consumption due to solar panels

Impact	Citation
Water footprint: 1,7 x10^4 – 1,9 x10^4 m^3/kWp Water footprint of the mounting structure: • Mounting on roof: 22 m^3/kWp • Basis in concrete, mounting a ground: 57 m^3/kWp • Poles fixtures, mounting a ground: 1,30 m^3/kWp	(Roy & Pearce, 2024)
Water footprint: 8,7 x10^{-3} m^3/kWh of which: • 1,5 x10^{-3} m^3/kWh is consume water • 7,2 x10^{-3} m^3/kWh is withdrawal water Water stress: • 3,2 x10^{-2} m^3 watereq/kWh in basis to the consumption • 1,5 x10^{-1} m^3 $water_{eq}$/kWh in basis to the withdrawal	(Stolz et al., 2017b)
Withdrawal water + consumption • Construction: 3,6 x10^{-5} m^3/kWh • Operation: 6,5 x10^{-5} m^3/kWh • Dismantling of the plant: 20 x10^{-5} m^3/kWh	(Bukhary et al., 2018)

3.4.7 Terrestrial and Aquatic Ecosystems

As already mentioned in the section Human Health, chemical emissions to water and soil (directly or indirectly) can occur during the life cycle of solar panels, which also pose a risk to soil and aquatic fauna. Some impact categories related to ecosystems include potential for acidification, the potential for eutrophication and ecotoxicity (marine and freshwater). Acidification, also known as land-based acidification, assesses the release of pollutants, such as ammonia, nitrogen oxides (NO_x) and sulphur oxides, into the air, which can acidify soil and water. Units of measurement are usually expressed in kg SO_{2eq} or mol $H+_{eq}$ (European Commission et al., 2012; PRé, 2020; Zampori et al., 2016). Eutrophication is a measure of emissions into air and water that contain nitrogen or phosphorus and can lead to algae blooms in water bodies; it is sometimes divided into marine eutrophication (Kg N_{eq}) and freshwater eutrophication (kg $PO_4^{-3}{}_{eq}$). Ecotoxicity, also referred to as marine, freshwater, or terrestrial ecotoxicity, is the ecological toxicity (fate and effect on species) of a substance compared to 1,4-dichlorobenzene (referred to as 1,4-DCB or 1,4-DB) in natural soils, freshwater, or marine waters. Units can be expressed in (kg 1.4-DCBeq), (kg1.4-DBeq) or (comparative toxicity units for ecosystems, CTU_e) (European Commission. Joint Research Centre. Institute for Environment and Sustainability, 2010; Huijbregts et al., 2016; Rybaczewska-Błażejowska & Jezierski, 2024b).

Regarding the categories of eutrophication and acidification, according to the results of (Alam & Xu, 2023b), the production of panels contributed between 60 and 68% to the overall impact of these categories, while for the Ecotoxicity category, the production of electrical installation equipment accounted for around 60% of the impact. (Shah et al., 2023) conducted an LCA in Pakistan and observed that panel assembly accounted for 50% of aquatic ecotoxicity in freshwater considering only the panel manufacturing stage. Solar-grade silicon production accounted for 40-50% of the impact for eutrophication and acidification, respectively, and 45% of terrestrial ecotoxicity. (Ali et al., 2022) They observed that panel production contributes about 70% to acidification and eutrophication and about 80% to ecotoxicity.

Another potential impact is the reflection of horizontally polarized light onto water bodies by panels. Some aquatic insects use polarized light as a guide to reach bodies of water where they lay their eggs. (Száz et al., 2016) compared panel surfaces with anti-reflective coatings (ARC) with uncoated ones in terms of the amount of reflected light and attractiveness to horseflies, ephemerals and midges. The study found that i) the ARC surface still reflects horizontally polarized light when sunlight comes from the front or back, while the uncoated surfaces reflected light at all angles tested, and ii) the ARC reduced the attraction for some species in sunny conditions, but in cloudy conditions it increased the attraction or remained the same as that of the uncoated surfaces for some species.

3.4.8 End of Life

EoL options for solar panels are underdeveloped and are not yet widely deployed commercially. It is estimated that 60–78 million tons of photovoltaic waste will reach in 2050 (Chowdhury et al., 2020). This figure can be reduced if the solar panels are managed according to a circular economy approach (Besiou and Van Wassenhove, 2016; Salim et al., 2019). The recovery and recycling of components or the entire solar panel brings numerous benefits, such as reducing the need to extract raw materials, creating jobs in the areas of collection, repair, recycling, processing and transport, as well as promoting research opportunities (IRENA & IEA-PVPS, 2016).

Although many countries do not currently have legislation regarding the end of life of solar panels, there is some momentum being created (Majewski et al., 2021; Ngagoum Ndalloka et al., 2024). EU Directive 2012/19/EU, called the Waste Electrical and Electronic Equipment (WEEE) Directive, entered into force in 2014 and covers the separate collection of WEEE products, illegal exports of waste and the harmonisation of databases and reporting. The directive also requires EU member states to verify that treatment plants are authorised, to indicate and communicate collection points to the public, to comply with minimum collection rates and to require producers to finance end-of-life collection and management (European

Commission, s.d.). Globally, there are several organizations that provide advice and assistance in operations related to end-of-life management, such as PV Cycle.

There are three main options for the end-of-life phase: reuse, recycling, and landfilling. Research globally is evaluating and optimizing end-of-life strategies, but many techniques are still being tested at laboratory scale.

3.4.8.1 Reuse

Reuse includes the reconditioning and subsequent use of the panel for energy production on the second-hand market. The panels can be reused for the production of energy not connected to the grid (remote locations, road signs).

3.4.8.2 Recycling

Recycling occurs when a specific component or material is identified and separated physically, thermally and/or chemically from the rest of the product. The general options are described in the Table 3-14. The component is then brought to an acceptable level of purity, after which it can be recycled in a closed-loop or open-loop recycling process. Closed-loop recycling is when a component/material is used in a new panel for the same purpose it had in the original solar panel. Open-loop recycling occurs when the material is used for a purpose other than the original one (Farrell et al., 2020). For example, the shattered glass from the glass layer, called "glass cutlet", can be used in fiberglass products for thermal insulation (IRENA & IEA-PVPS, 2016).

Every treatment process, whether physical, thermal, or chemical, has advantages and disadvantages. A process may succeed in separating the desired component from the panel, but it may generate potentially hazardous by-products or render the remaining components unmarketable (Chowdhury et al., 2020). Once separated, the materials can be sent to specific recyclers. 85% of the panel, consisting of aluminum, glass and copper, can be recovered with physical separation and, overall, 97% of the copper used in the panel can be recovered. Alternatively, some components are difficult to separate, such as silicon and EVA layers, and purity can decrease. Components such as glass are easier to remove, but can be mixed with metals, screws, polymers and therefore may require additional steps to remove impurities (Bošnjaković et al., 2023; IRENA & IEA-PVPS, 2016).

If a component is considered hazardous, recycling may be more difficult to achieve. Definitions of hazard vary from country to country, as countries may use similar tests, such as the leaching test, but with different parameters (Yasutaka et al., 2017). The literature offers a multitude of innovative recycling methods that are tested on a laboratory scale, but recycling is not widely implemented, often due to a lack of enforcement and financial incentives globally (Majewski et al., 2021)

3.4.8.3 Landfilling

Landfill disposal consists of sending the panels or components, without any prior treatment, to a landfill. The panels could be mixed with other electronic and non-electronic waste. Metals and polymers could leach and contribute to the formation of landfill leachate; therefore, landfill disposal should be avoided.

Table 3-14. End-of-life management options for solar panels

Recycling Options	Citation
• Physical treatment: Separation of layers, manual or mechanical, to remove the aluminum frame, cables and junction box; shredding, crushing, eddy current separation, screening, optical sorting, sonification, electro-hydraulic fragmentation • Heat treatment: Incineration and pyrolysis, used for polymer layers • Chemical treatment: Acid baths and etching (used to separate silicon wafers, EVA layer and metals - copper, lead, silver, aluminum and tin) and electrostatic separation (used for silicon and metals - silver, copper, aluminum)	Physical: (Azeumo et al., 2019; Chowdhury et al., 2020; P. R. Dias et al., 2022; ImpulsTec GmbH, n.d.; IRENA & IEA-PVPS, 2016) Thermal: (Aryan et al., 2018b; Farrell et al., 2020) Chemical: (An & Sun, 2024; Azeumo et al., 2019; Chowdhury et al., 2020; De Souza & Veit, 2023; P. Dias et al., 2016; P. R. Dias et al., 2022; Farrell et al., 2020; Park & Park, 2014)

3.4.9 Environmental Product Declarations

An EPD is a document that presents the LCA of a product or series of products, if they have the same life cycle stages and function. The EPD is financed by the manufacturer of the product (who becomes the owner) and is certified by a third party. The EPD follows the analysis and documentation protocols established by the operator (the company that authorizes the EPD) and international standards. Such protocols are found, but are not limited to, in the product category rules (PCR), ISO 14040, ISO 14044, ISO 14025:2006 e EN 15804:2012 (International EPD System, 2025). The current PCR for solar panels from a leading operator, International EPD System, is named "PV Modules and Parts thereof", registration number 2019:14-c-PCR-016 (International EPD System, 2022). The information included is: manufacturer background, product identification, functional unit, geographical coverage and components of the LCA (inventory, boundaries, results, interpretation). Table 3-15 through Table 3-18Table 3-18 offer examples of intermediate results of LCA analysis for EPDs.

Table 3-15. EPD example n.1 (QingHai Huanghe Hydropower Development CO.,Ltd., 2023)

Category	Value	Unit
Climate change potential (fossil fuels + land use and land use change)	1,6 x10^{2}	kg CO_{2eq}/kW_p
Climate change potential (biogenic)	-0,2	kg CO_{2eq}/kW_p
Potential for depletion of the stratospheric ozone layer	4,9 x10^{-5}	kg $CFC11_{eq}/kW_p$
Acidification potential, accumulated exceedance	1,6	mol H^+_{eq}/kW_p
Eutrophication potential, fraction of nutrients reaching the final freshwater compartment	7,2 x10^{-3}	kg P_{eq}/kW_p
Eutrophication potential, fraction of nutrients reaching the marine final compartment	3,5 x10^{-1}	kg N_{eq}/kW_p
Potential for eutrophication, accumulated overshoot	3,6	mol N_{eq}/kW_p
Potential for tropospheric ozone formation	1,1	kg $NMVOC_{eq}/kW_p$
Abiotic depletion potential for non-fossil resources	1,9 x10^{-2}	kg Sb_{eq}/kW_p
Abiotic depletion potential for fossil resources	1,7 x10^{3}	MJ/kW_p
Potential for water deprivation	-2,7 x10^{1}	m^3/kW_p

Table 3-16. Example EPD n.2 (Viridian Solar Ltd., 2023)

Category	Value	Unit
Global warming potential (fossil fuels + land use and land use change)	1,4 x10^3	kg CO_{2eq}/kW_p
Global warming potential (biogenic)	7,2	kg CO_{2eq}/kW_p
Ozone depletion	1,2 x10^{-4}	kg CFC-11_{eq}/kW_p
Terrestrial and freshwater acidification	8,7	mol $H+_{eq}$/kW_p
Eutrophication of freshwater	3,4 x10^{-1}	kg P_{eq}/kW_p
Marine eutrophication	1,7	kg N_{eq}/kW_p
Terrestrial eutrophication	1,8 x10^1	mol N_{eq}/kW_p
Photochemical oxidation	5,2	kg NMVOC/kW_p
Abiotic Exhaustion – Elements	3,2 x10^{-2}	kg Sb_{eq}/kW_p
Abiotic depletion – fossil resources	1,3 x10^4	MJ/kW_p
Water scarcity	4,2 x10^2	m^3 depriv./kW_p
Respiratory inorganics – particulate matter	1,1 x10^{-4}	disease inc./kW_p
Ionizing radiation	2,9 x10^1	kBq U-235_{eq}/kW_p
Ecotoxicity of freshwater	4,2 x10^4	CTUe/kW_p
Carcinogenic effects on human health	8,4 x10^{-7}	CTUh/kW_p
Non-carcinogenic effects on human health	3,5 x10^{-5}	CTUh/kW_p
Land use impacts, soil quality	4,0 x10^3	Pt/kW_p

Table 3-17. Example EPD n. 3 (Sunova Solar Technology Co.,Ltd., n.d.)

Category	Value	Unit/kWh	Value	Unit/kWp
Global warming potential (fossil fuels + land use and land use change)	2,2 x10^{-2}	kg CO_2 eq./kWh	1,1 x10^3	kg CO_{2eq}/kW_p
Global warming potential (biogenic)	-8,8 x10^{-8}	kg CO_2 eq./kWh	-4,5 x10^{-3}	kg CO_{2eq}/kW_p
Potential for depletion of the stratospheric ozone layer	1,1 x10^{-9}	kg $CFC_{11\ eq.}$/kWh	5,7 x10^{-5}	kg $CFC11_{eq}$/kW_p
Potential for acidification	1,6 x10^{-4}	mol H+eq./kWh	8,3	mol $H+_{eq}$/kW_p
Potential for eutrophication	9,0 x10^{-7}	kg Peq./kWh	4,6 x10^{-2}	kg P_{eq}/kW_p
Potential for tropospheric ozone formation	9,4 x10^{-5}	kg NMVOC eq./kWh	4,9	kg $NMVOC_{eq}$/kW_p
Abiotic depletion potential for non-fossil resources	7,6 x10^{-7}	kg Sb eq./kWh	3,9 x10^{-2}	kg Sb_{eq}/kW_p
Abiotic depletion potential for fossil resources	2,5 x10^{-1}	MJ/kWh	1,3 x10^4	MJ/kW_p
Potential for water deprivation	6,7 x10^{-3}	m^3 depriv./kW,h	3,5 x10^2	m^3 depriv./kW_p

Table 3-18. Example EPD n. 4 (DAS SOLAR CO., LTD, 2023)

Category	**Value**	**Unit**
Global warming potential (fossil fuels + land use and land use change)	$1{,}8 \times 10^{-2}$	kg CO_{2eq}/kWh
Global warming potential (biogenic)	$1{,}3 \times 10^{-4}$	kg CO_{2eq}/kWh
Potential for depletion of the stratospheric ozone layer	$1{,}5 \times 10^{-9}$	kg CFC-11_{eq}/kWh
Acidification potential, accumulated exceedance	$1{,}0 \times 10^{-4}$	mol $H+_{eq}$/kWh
Eutrophication potential, fraction of nutrients reaching the final freshwater compartment	$7{,}3 \times 10^{-7}$	kg P_{eq}/kWh
Potential for tropospheric ozone formation	$5{,}5 \times 10^{-5}$	kg $NMVOC_{eq}$/kWh
Abiotic depletion potential for non-fossil resources	$4{,}6 \times 10^{3}$	kg Sb_{eq}/kWh
Abiotic depletion potential for fossil resources	$2{,}1 \times 10^{-1}$	MJ/kWh
Water deprivation potential, deprivation weighted water consumption	$1{,}2 \times 10^{-2}$	m^3 depriv./kWh

4 WIND TURBINES

4.1 Potential for Integration into a Renewable Energy Community

Including wind energy production within a REC markedly improves the community's self-consumption, since wind generation is very often better distributed over the 24-hour cycle than solar generation. During the hours in which photovoltaic panels do not produce energy, wind can therefore cover part of the demand. On average, in Europe, a REC using 100% solar production reaches a self-consumption of 39.4%, whereas with a hybrid system of 50% solar and 50% wind generation, self-consumption rises to 66% (Papapietro, 2024). Challenges of installing wind turbines include funding and choosing the right location, as the energy production potential is often considered more important than the efficiency of the turbine and generator itself (Bianchini et al., 2022).

4.2 Technical Information

4.2.1 Flow of Energy

Figure 4-1 illustrates the wind energy production process, which starts with the wind as input and involves the conversion of kinetic energy into mechanical energy through the rotor of the turbine blades and, subsequently, into electrical energy through the generator. Depending on the type of generator inside the nacelle and on the point at which the turbine output is fed into the grid, a converter and/or a transformer may be required before injection into the grid.

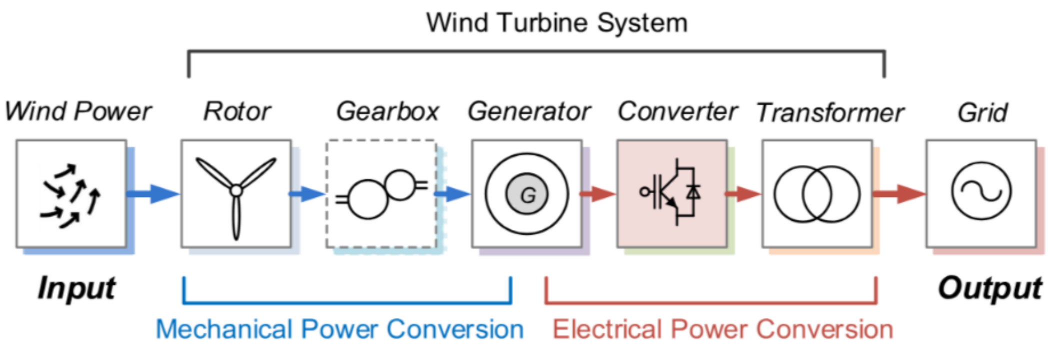


Figure 4-1. Mechanical and electrical conversion of the power in a turbine (Blaabjerg & Ma, 2017)

The turbines considered in the following chapter almost all have a permanent-magnet synchronous/asynchronous AC generator and a 400 V output voltage (low-voltage electricity grid).

4.2.2 Components and Schematics

There are two main types of wind turbines, the horizontal axis wind turbine (HAWT), of which shown in Figure 4-2 on the left and vertical axis wind turbines (VAWT), of which is shown on the right. In both cases, a wind turbine is composed mainly of three components: land blades, the nacelle, and the support tower.

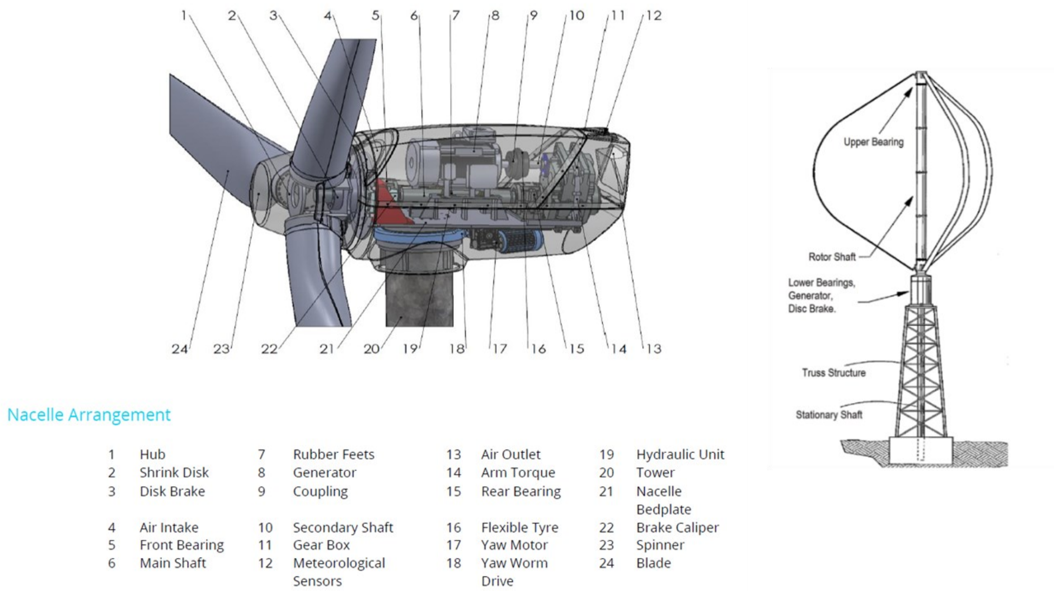


Figure 4-2. a) Diagram of a horizontal axis wind turbine (HAWT) (Zenia Energy, n.d.) on the left and b) a vertical axis wind (VAWT) (Tjiu et al., 2015) on the right

The blades are connected to the hub and by rotating drive the main shaft, which is supported by bearings inside the nacelle. If the shaft speed is low, the shaft is connected to the electric generator through a gearbox (rotational-speed multiplier). The permanent-magnet electric generator converts mechanical power into electrical power which is then fed into the grid. Unlike a VAWT, in which wind direction is irrelevant, HAWTs require a yaw system which allows the entire upper structure of the turbine (rotor and nacelle) to be rotated so that it is aligned with the direction of the prevailing wind at that time.

Table 4-1 provides the materials with the relative percentages of which a wind turbine is composed. The nacelle rotor can be connected to the generator (permanent magnet synchronous generator, PMSG) via the speed multiplier (gearbox, GB) or by direct transmission (direct drive, DD). The tower is the vertical metal structure that supports the nacelle. The foundation is the structure that anchors the tower to the ground, transfers static and dynamic loads to the ground and guarantees the stability of the system in the long term.

Table 4-1. Material compositions of the technologies and components considered (C. Li et al., 2022)

Material	**Rotor, Hub and Blades**	**Nacelle with PMSG - GB**	**Nacelle with PMSG – DD**	**Tower**	**Foundation**
Iron	25,8%	41,5%	52,6%	-	-
High alloy steel	9,4%	39,3%	29,8%	-	-
Low alloy steel	9,8%	10,3%	8,9%	97,1%	✓
Concrete	-	-	-	-	✓
Fiberglass	37,3%	-	-	-	-
Copper	0,1%	2,2%	2,2%	0,9%	-
Aluminum	0,1%	0,9%	0,9%	1,0%	-
Resin	17,5%	-	-	-	-
Polymer	4,6 kg/kW	-	-	-	-
Electrical and Electronic Components (EE)	-	0,4%	z	1,0%	-

Table 4-1. Material compositions of the technologies and components considered (C. Li et al., 2022) (continued)

Material	**Rotor, Hub and Blades**	**Nacelle with PMSG - GB**	**Nacelle with PMSG – DD**	**Tower**	**Foundation**
Chromium	-	0,6 kg/kW	0,5 kg/kW	-	-
Manganese	-	0,8 kg/kW	0,8 kg/kW	-	-
Molybdenum	-	0,1 kg/kW	0,1 kg/kW	-	-
Nickel	-	0,4 kg/kW	0,2 kg/kW	-	-
Neodymium	-	39,0 g/kW	168,0 g/kW	12,0 g/kW	-
Dysprosium	-	4,0 g/kW	15,0 g/kW	2,0 g/kW	-
Praseodimio	-	4,0 g/kW	35,0 g/kW	-	-
Terbium	-	4,0 g/kW	7,0 g/kW	-	-
Boron	-	1,0 g/kW	6,0 g/kW	-	-

4.2.3 Reference Parameters

The main parameters of turbines with rated powers of 1, 5, 10, 30, 50, 100, 200, 300, 400 and 500 kW are summarized in The cut-in speed is the speed of the starting wind of the blades, which is the minimum operating speed, while the cut-off speed is the stopping speed of the blades. The safety wind speed is a structural design limit beyond which the turbine does not operate. The swept area is the surface intercepted by the wind.

Table 4-1 and in

Table 4-2. Data sources mainly focus on HAWTs. The literature and data sheets (provided by manufacturers and retailers) have been consulted, and the main sources are (Aeolos wind turbines, n.d.; Engelec Energy, n.d.; Ergowind, 2016; GHREPOWER, 2020; Leitner S.p.A, 2025; Northern Power Systems, n.d.; Wind Engineering Spa, 2013; WindUp Srl, 2018; Zenia Energy, n.d.)

The cut-in speed is the speed of the starting wind of the blades, which is the minimum operating speed, while the cut-off speed is the stopping speed of the blades. The safety wind speed is a structural design limit beyond which the turbine does not operate. The swept area is the surface intercepted by the wind.

Table 4-1. Technical parameters for turbines with a rated power from 1 to 50 kW

Rated power [kW]	1	5	10	30	50
Maximum power [kW]	1,1	7	10	30	50
Type	VAWT	HAWT	VAWT	HAWT	HAWT
Cut-in speed [m/s]	3	3	3,8	3-4	3,5
Rated wind speed [m/s]	12	10	13	11-12	10,5
Cut-out speed [m/s]	25	25	25	25	25
Safety wind speed [m/s]	45	50	50	-	52,5
Rotor diameter [m]	1,2	6	6	13	15,95
Swept area [m^2]	6,15	19,62	-	120	200
Head weight (basket + rotor) [kg]	-	310	660	1950	2600
Hub height [m]	2,7	8	10	18	27
Generator Type	Permanent Magnet Synchronous Generator	Permanent magnet generator	Permanent magnet generator	Asynchronous permanent magnet generator	Asynchronous permanent magnet generator
Output voltage, alternating current [VAC]	Three-phase 400	500 (48V_{DC})	220-380	400	400

	Single Phase 230				
Operating temperature [°C]	-20 – 50	-40 – 50	-45 – 60	-	-

Table 4-2. Technical parameters for turbines with a rated power from 95 to 500kW

Rated power [kW]	95	200	300	400	500
Maximum power [kW]	95,3	205	300	400	500
Type	HAWT	HAWT	HAWT	HAWT	HAWT
Cut-in speed [m/s]	3.5	4	3	3	2,5
Rated wind speed [m/s]	12	13,5 - 14	10	9,5	13
Cut-out speed [m/s]	25	25	20	22	20
Safety wind speed [m/s]	52,5	67	52,5	52,5	-
Rotor diameter [m]	24,4	29,8 - 31	42	56	42
Swept area [m^2]	467,6	697,5 – 754,8	1385,4	2460	1416
Head weight (basket + rotor) [kg]	7250	13750	28600	35500	-
Hub height [m]	30 - 37	36 - 46 - 50	39 - 51	51	39
Generator Type	Permanent magnet generator (gearless)	Asynchronous permanent magnet generator	Synchronous with permanent magnets with direct transmission	Synchronous with permanent magnets with direct transmission	Synchronous with permanent magnets with direct transmission
Output voltage, alternating current [VAC]	400	415	400	400	690
Operating temperature [°C]	-20 – 40	-	-20 – 50	-20 – 50	-

4.2.4 Energy Balance and Power Curves

The IEC 61400-12 series of standards defines procedures for the measurement, analysis and reporting of wind turbine power performance tests. In particular, particular attention is paid to the selection of instruments used for wind speed measurement, as this choice can significantly influence the results of performance tests. The procedures for calibration, classification and uncertainty assessment of cup anemometers and ultrasonic anemometers are defined in IEC 61400-50-1, while those for remote sensing devices are set out in IEC 61400-50-2. The application of these procedures allows to obtain as main outputs the measured power curve of the turbine and the annual energy production (AEP) and the values for the turbines selected in the previous paragraph are shown below. Not all data sheets contain both power curves and AEPs, so for some turbines, only one of the two data is available.

The measured power curve, defined as the relationship between wind speed and power delivered by the wind turbine, is determined by collecting simultaneous measurements of weather variables, including wind speed, and turbine operating signals, especially the electrical power produced. These measurements are carried out at the test site over a period of time long enough to allow the construction of a statistically significant database, representative of a wide range of wind speeds and variable atmospheric conditions. The Table 4-3 It reports the resulting power output values of the 9 turbines for which data were available, for wind speeds between 1 and 25 m/s. Figure 4-1 shows the power curves of the 9 turbines, i.e. the relationship between the increase in wind speed and the resulting normalized power

Table 4-3. Values of output power of the turbines selected

	Nominal Power								
	1 kW	5 kW	10 kW	30 kW	50 kW	100 kW	200 kW	400 kW	500 kW
	Outputs power								
Wind Speed [m/s]	[W]					[kW]			
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	300	0	1	0	1,2	0	5,8	0
4	20	600	200	2	1	7,2	7	16,8	14
5	50	1000	1200	5	5	14,5	19	31,5	40
6	100	1700	2600	8	10	24,7	34	50,2	74
7	150	2500	4300	13	15	37,9	56	73	124
8	180	3200	5700	18	25	58,7	78	100,8	188
9	300	4000	7000	23	35	74,8	109	134,1	270
10	400	5000	8300	27	42	85,1	138	171	360
11	550	6000	9800	30	50	90,2	162	213,8	439
12	770	6600	10200	31	50	94,7	184	261,9	483
13	970	7000	10300	31	50	95,3	196	309,3	496
14	1050	6700	10400	31	50	95,1	205	352,4	500
15	1030	6400	10500	31	50	94,2	202	387,2	500
16	1030	6000	10600	30,5	50	92,9	200	400	500
17	1030	5500	10700	30	50	91,2	196	400	500
18	1030	5000	10700	30	50	88,9	196	400	500
19	1030	4500	10700	30	50	87,1	196	400	500
20	1030	4000	10700	30	50	84,1	196	400	500
21	1030	3500	10700	30,5	50	81,3	196	400	0
22	1030	3000	10700	32	50	78,6	196	400	0
23	1030	2500	10700	33	50	76,1	196	0	0
24	1030	2000	10700	35	50	74,3	196	0	0
25	1030	0	0	36	50	71,7	196	0	0

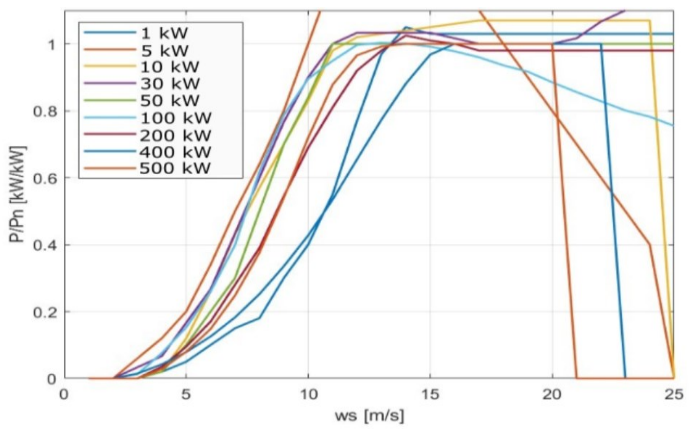


Figure 4-1. Normalised power curves for 9 of the turbines selected, made with Matlab

Once the output power has been measured P_{out}, calculating the available power of the wind flow P_{kin} by (Equation 1), it is possible to calculate the rotor power coefficient C_p, as a function of wind speed, as shown in (Equation 2). The rotor power coefficient is constrained above by the Betz limit, $C_{p,max} = \frac{16}{27} \cong$

0,593. A is the turbine swept area (m^2), v is the wind velocity (m/s^2), and ρ is the air density (kg/m^3) (Al-Bahadly & Peterse, 2011).

$$P_{kin} = \frac{1}{2}\rho v^3 A \quad (1)$$

$$C_p = \frac{P_{out}}{P_{kin}} \quad (2)$$

The AEP provides the estimate of the total energy production of a wind turbine over a period of one year, applying the power curve measured according to the different frequency distributions of the speed of the wind turbine. The reference wind is at hub height, assuming 100% availability (International Electrotechnical Commission, 2022). Table 4-4 provides AEP values for 5 of the selected turbines for annual wind speeds between 4 and 8 m/s.

Table 4-4. Values of annual energy production for 5 of the turbines selected

	Nominal Power [kW]				
	1 kW	100 kW	300 kW	400 kW	500 kW
Wind Speed [m/s]	Annual energy production [MWh/year]				
4	0,264	-	293	567	-
4,5	-	-	416	776	492
5	0,640	196	550	989	622
5,5	-	240	686	1194	750
6	1,17	284	816	1379	872
6,5	-	325	934	1539	985
7	1,76	364	1034	1670	1088
7,5	-	399	1114	1750	1181
8	2,33	-	-	1820	-

4.3 Economic Data

Table 4-6 reports the cost parameters for the turbines selected and analysed in the previous sections. According (Bianchini et al., 2022), the CAPEX of a wind farm is in the range of €3.480 to €9.565/kW. The table refers to the average value of € 6.522 / kW for systems with a power of up to 100 kW. For plants with a power of more than 100 kW, a value of € 4.050/kW is adopted, as reported in (Orrell et al., 2023).

The literature provides several estimates of O&M costs, ranging from 1% to 3% of CAPEX (Bianchini et al., 2022) or they are quantified as a fixed value of 32 €/kW (Orrell et al., 2023). In this work, the cost of OPEX was calculated assuming an average value of 1% of CAPEX.

Table 4-6. Cost parameters for the different models of selected turbines

Rated power [kW]	**CAPEX [€/kW]**	**OPEX [€/year]**
1 kW	6.522	65
5 kW	32.612	326
10 kW	65.225	652
30 kW	195.660	1.957
50 kW	326.100	3.261
95 kW	619.000	6.190
200 kW	810.000	8.100
300 kW	1.215.000	12.150
400 kW	1.620.000	16.200
500 kW	2.025.000	20.250

Figure 4-4 exhibits the CAPEX and of OPEX for a wind farm as a function of nominal power.

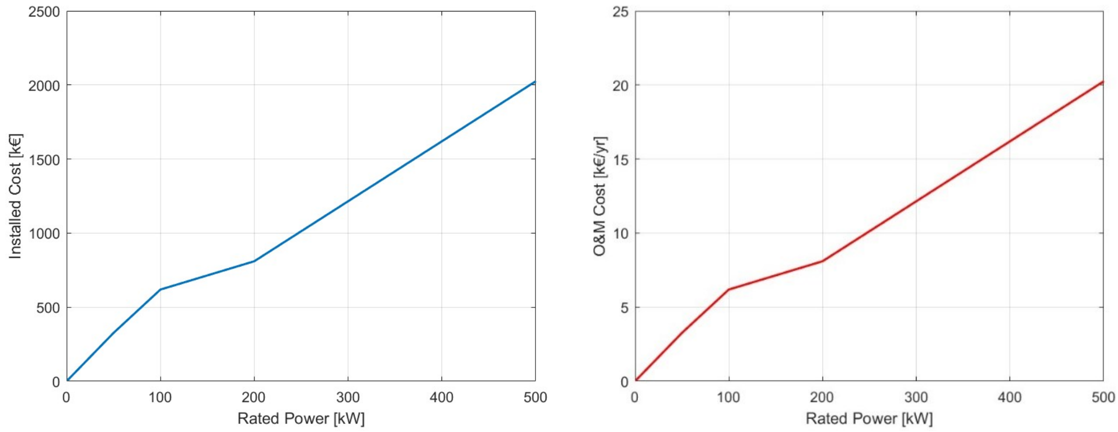


Figure 4-4. The CAPEX (on the left) and costs of OPEX (on the right) in Operate of the rated power

4.4 Environmental Impacts

4.4.1 Impact Results

Table 4-7 reports, for turbines of different sizes, literature LCA values related to the impact categories ED, CCP, Eutrophication potential (EP), and acidification potential (AP). Where possible, turbines with similar power ratings have been considered, and the functional unit is 1 kWh of electricity generated. To calculate the impacts in cases where data were not available in the literature, the simplified LCA model of (Mendecka and Lombardi, 2019) was used. In Matlab, the report authors used the parameters for onshore wind turbines operating at 6 m/s, as illustrated in the Figure 4-2.

Table 4-7. Life cycle indicators for various turbine models based on a functional unit of 1 kWh of generated electricity

Model (kW)	**ED** $(\frac{MJ}{kWh})$	**CCP** $(\frac{gCO_2eq}{kWh})$	**EP** $(\frac{gCO_2eq}{kWh})$	**AP** $(\frac{gSO_2eq}{kWh})$	**Details**	**Citation**
1	1,4	110	0,35	1,1	Actual data referring to 900 W turbines	(Troullaki et al., 2019)
	1,6	109	0,1	0,71	Model of regression not linear with inputs P=1kW	(Mendecka & Lombardi, 2019)
5	1,15	48	0,063	0,31	Actual data referring to turbines with rated power of 6 kW rather than 5 kW	(Greening & Azapagic, 2013)
	0,9	60	0,06	0,38	Model of regression not linear with inputs P=5kW	(Mendecka & Lombardi, 2019)
10	1,3	86	0,004	0,53	Actual data referring to 10 kW turbines installed in Quebec	(Amor et al., 2010)
	0,7	47	0,04	0,3	Model of regression not linear	(Mendecka & Lombardi, 2019)
30	0,61	40	0,0015	0,24	Actual data referring to 30 kW turbines installed in Quebec	(Amor et al., 2010)
	0,46	31,1	0,03	0,19	Model of regression not linear	(Mendecka & Lombardi, 2019)
50	0,38	25,8	0,025	0,16		
100	0,13	17,8	-	0,042	Actual data referring to a turbine from the same company with a diameter of 21 m rather than 24 m	(Kabir et al., 2012)
	0,3	19,9	0,02	0,12	Model of regression not linear	(Mendecka & Lombardi, 2019)
200	0,23	15,4	0,015	0,09		
300	0,2	13,3	0,013	0,078		
400	0,18	11,9	0,012	0,07		
500	0,16	11	0,011	0,064		

```
P = 200% [kW] inserire potenza nominale considerata

% Parametri considerando la classe di vento IEC IV
% velocità media annua v=6 m/s
% FU = 1kWh, Scope = Cradle to grave
c1_GWP = 109.57
c2_GWP = -0.37

c1_AP = 0.71
c2_AP = -0.387

c1_EP = 0.104
c2_EP = -0.361

c1_CED =  1.596
c2_CED = - 0.366

GWP = c1_GWP*P^c2_GWP % [gCO2eq/kWh]
AP = c1_AP*P^c2_AP  % [gSO2eq/kWh]
EP = c1_EP*P^c2_EP  % [gPO4eq/kWh]
CED = c1_CED*P^c2_CED  % [MJ/kWh]
```

Figure 4-2. Models for the calculation of indicators as a function of nominal power extracted from the study (Mendecka & Lombardi, 2019), runs performed on Matlab for nominal powers equal to 1-5-10-30-50-100-200-300-400-500 kW. Note that the dot represents the decimal point.

Figure 4-3 highlights the comparison between the (Mendecka & Lombardi, 2019) and other LCA studies for powers from 1 to 100 kW. It is possible to see how the values of the indicators for the individual studies are in line with the model, finding only a deviation from (Amor, 2010). In this study, the EP indicator (for P = 10 – 30 kW) has a deviation of an order of magnitude. (Mendecka & Lombardi, 2019) also conducted a systematic review of the LCA analyses and found that for onshore wind turbines with power below 20 kW, the CCP values ranged from 79 to 189 g CO_2/kWh, with a decrease as the nominal power increases.

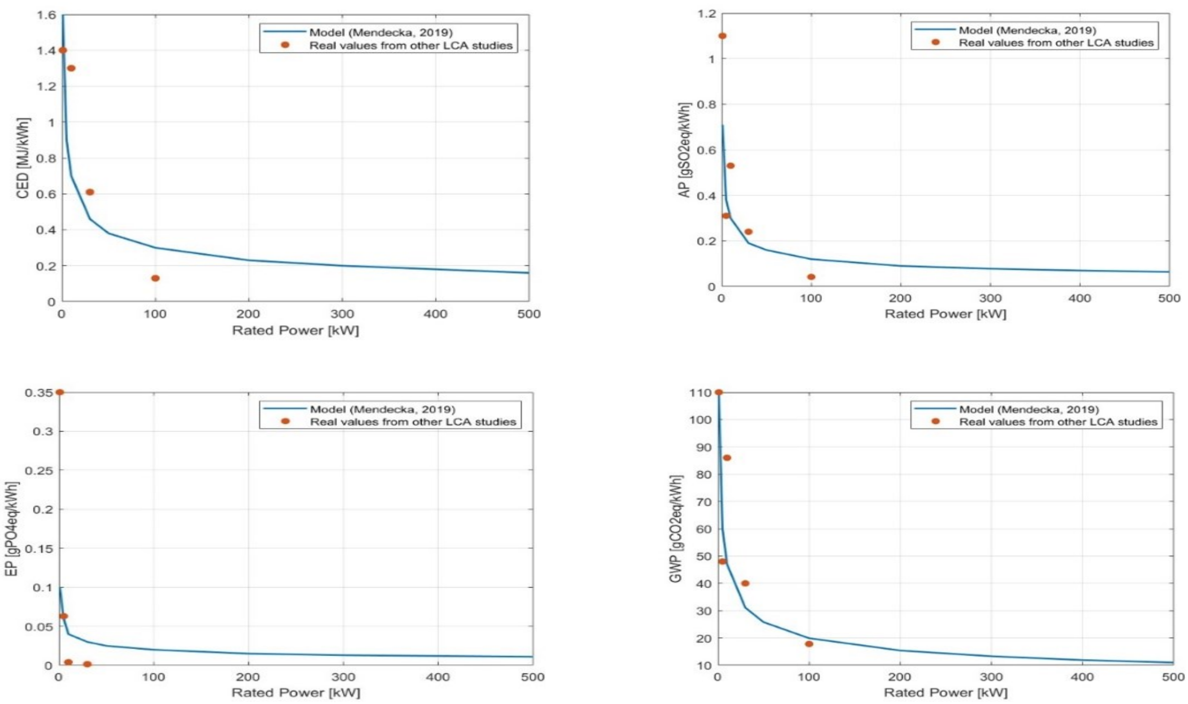


Figure 4-3. Life cycle indicators as a function of nominal power (Matlab processing)

4.4.2 Acoustic Emissions

The European Union does not impose common limits for member states but establishes, through Directive 2002/49/EC, an approach aimed at avoiding, preventing and reducing the harmful effects of environmental noise and establishes common indicators such as Lden (day-evening-night level) and Lnight (night level) (Directive 2002/49/EC, 2002).

In Italy, the Prime Ministerial Decree of 14 November 1997, in implementation of the law of 26 October 1995 n°447 "Framework law on noise pollution", established the emission limit values of the equivalent continuous sound level (Leq) in dB(A). The territory is divided into six usage classes for two reference times as reported in the Figure 4-4, which was extracted from the decree (Determinazione dei valori limite delle sorgenti sonore, 1997). Adaption to the new indicators and standards begins to take shape in Legislative Decree 42/2017 which, however, does not introduce new emission limits (Legislative Decree 42/2017, 2017). Table 4-8. Noise emission levels for each turbine provides noise emission data for different turbine sizes.

classi di destinazione d'uso del territorio		tempi di riferimento	
		diurno (06.00-22.00)	notturno (22.00-06.00)
I	aree particolarmente protette	45	35
II	aree prevalentemente residenziali	50	40
III	aree di tipo misto	55	45
IV	aree di intensa attivita' umana	60	50
V	aree prevalentemente industriali	65	55
VI	aree esclusivamente industriali	65	65

Figure 4-4. Emission limits Leq in dB(A)

Table 4-8. Noise emission levels for each turbine

Model	Acoustic Emissions [dBa]	Measurement Conditions
1 kW	<50	Not specified
5 kW	41,8	15 m away from the turbine with a wind speed of 10 m/s
10 kW	27	10 m away from the turbine with a wind speed of 13 m/s
30 KW	>35 dB 55	- Speed of the wind of 7 m/s
50 kW	58,5	Speed of the wind of 7 m/s
100 kW	50	50 m away from the turbine
200 kW	50	100 m away from the turbines
300 kW	58	25 m away from the turbines
400 kW	58	79 m away from the turbines
500 kW	58	79 m away from the turbines

4.4.3 EoL Management and of the Circularity

Wind turbines have a service life between the 20 - 25 years. It can be extended sometimes up to 30 - 35 years and can undergo repowering to increase its energy generation efficiency (WindEurope, 2020)

Sometimes, however, the service life is shorter than expected due to impacts on the blades or structural stresses due to adverse weather conditions. The components of a wind turbine are largely recyclable, with a recyclability rate of around 85 - 90%. The steel from the tower can be processed as a raw material for steelmaking, while the concrete from the foundation is used for building materials, for road construction or can be recycled to build new wind turbines, encouraging the circularity of concrete within the same sector. In some cases, foundations cannot be removed due to concerns about possible environmental impact.

Regarding the blades, they represent the most complex part to recycle, due to the materials involved in their composition. The main material of which wind turbine blades are made is a Glass Fiber Reinforced Polymer with 60 - 70% reinforcing fibers and 30 - 40% polymer matrix by weight (WindEurope, 2020). According to the waste management hierarchy defined in the EU Directive 2008/98/EC, the following options can be considered for wind turbine blades in order of preference, from the best to the last possible option (Directive 2008/98/EC, 2008; Spini & Bettini, 2024; WindEurope, 2020): 1) Prevention; 2) Reuse and reconversion; 3) Recycling; 4) Recovery (e.g. of material or energy); 5) Disposal. The five options are discussed in depth below.

4.4.3.1 Prevention

To prevent waste generation, you can design the blades in such a way that the failure rate decreases to extend their useful life and reduce the amount of material to be recycled (WindEurope, 2020).

4.4.3.2 Reuse and Repowering

After a proper evaluation and possible repair of the replaced blades, the most advanced countries from the point of view of wind technologies often sell the reconditioned blades to the less developed countries where the power and efficiencies involved are lower. It is also possible to completely change the purpose of use of these components, such as, for example, considering the use of discarded blades to build pedestrian bridges, bus stops and bicycle parking lots, as is already the case in Denmark, for example (Spini & Bettini, 2024).

4.4.3.3 Recycling

Technology readiness levels (TRL) measure the state of development of a technology and range from 1 to 9, where 1 indicates the initial phase of research and 9 indicates full functionality (European Space Agency, 2020). For the blades, mechanical (Mechanical grinding TRL 9), thermal (Pyrolysis TRL 9, Fluidised bed TRL 5/6), thermochemical (Solvolysis TRL 5/6) and electromechanical (High voltage pulse fragmentation TRL 6) recycling methods can be used (WindEurope, 2020).

4.4.3.4 Recovery

The most widely used method nowadays for the recycling of compound waste is that of cement co-processing (TRL 9). The polymer matrix is burned as fuel in the cement production process, while the glass fibers contain three of the main oxides that make up clinker (calcium oxide, silica, aluminum oxide) (Spini & Bettini, 2024). With one ton of waste material from turbine blades, about 490 kg of coal, 110 kg of limestone (CaO), 290 kg of silica, 70 kg of aluminum oxide (Al_2O_3) and iron(III) oxide 9 kg of iron(III) oxide (Fe_2O_3) (Schindler et al., 2024). There is also a reduction of up to 16% in the carbon foot print of cement production. The disadvantage is certainly that of the loss of physical form of the glass fibers (WindEurope, 2020).

4.4.3.5 Disposal

Landfilling or incineration without energy recovery is still a used solution today, but it is the least sustainable method in the hierarchy of waste management. Some countries such as Germany have banned the use of landfills to manage this waste and others impose taxes to make it unviable (Spini & Bettini, 2024).

5 HYDROPOWER

5.1 Potential for Integration into a Renewable Energy Community

Hydropower is a form of renewable energy that harnesses the movement of water to produce electricity. Since water bodies, such as lakes, rivers and reservoirs, can have natural or anthropogenic origin and are constantly fed by the water cycle, they represent a resource that can be used for energy production.

Hydropower can be implemented in combination with other forms of renewable energy, such as solar. In (Mérida García et al., 2021) a pump-as-turbine (PAT) was combined with a PV system, called the PAT-PV system, plus a battery to provide energy to an off-grid irrigation system. The hybrid system replaced a diesel generator and was able to provide power to the fertigation system, compressor, electric valves and filtration station. After one year of operation, the PAT-PV system used only 41% of the energy generated, while the PAT was not operating at full potential. This case study demonstrates the possibility of combining different energy sources to meet energy demand, with or without grid connection. Mixed renewable energy systems can bridge gaps between energy sources in the event of fluctuations. For example, a hydroelectric power plants (HPP) can support the grid during periods of heavy rain or at night, when the sun is not available for the PV system, or during the summer months, when reservoirs are drier, while solar can take advantage of higher levels of solar irradiance (Paraschiv & Paraschiv, 2023) (Ball et al., 2020). Hydropower can also be integrated into existing systems, such as wastewater treatment systems. Turbines can be installed along the path of wastewater, drinking water, irrigation, drainage and cooling canals, thus producing electricity (Ball et al., 2020). The exploitation of these small but numerous water networks for the production of electricity makes this technology interesting for integration into RECs and for a constant contribution.

The compatibility of a hydropower plant in a REC depends largely on the size of the plant, its location in relation to the customer base and its integration into the electricity grid. Due to production regulations in RECs, such as the maintenance of a low to medium voltage in Austria and a maximum power of 1 MW in Italy, free-flowing small hydropower plants (SHPs) are often selected for REC applications (projects are described in Section 5.2). Dam and reservoir projects are also used, while pumping systems by storage are less common due to their size. When evaluating hydropower within a REC, decisions are not made solely based on electricity production, but taking into account the interaction between the built environment, the natural environment, and management constraints to create stable and reliable system dynamics.

A REC can benefit from the integration of hydropower because, in the presence of demand, electricity can be generated quickly, while in the absence of demand the water remains in the basin or simply continues its natural course. In run-of-river systems, production is considered relatively reliable for an estimated period of time, thanks to knowledge of water runoff patterns. In addition, hydropower can compensate for errors in demand forecasts and supports small-scale decentralized grids, which is particularly useful for preventing large-scale blackouts. Finally, the use of hydroelectric energy located close to customers avoids large energy losses due to the transport of electricity on low and medium voltage lines, allowing economic savings and a reduction in environmental impact (Ball et al., 2020). There are various tools that guide hydropower planning, such as HydroHelp (Gordon, 2006), tools that guide CER planning, such as the Renewable Optimization Simulation Environment (ROSE) (Maps Energy S.r.l., 2026), and newly developed tools, such as the one described in (Leva et al., 2025) which assists in the sizing and optimization of small-scale hydropower systems, using regional data from Northern Italy as a basis, to integrate hydropower into RECs.

5.2 Technical Information

Hydroelectric technology converts the potential (gravitational) energy of water into kinetic energy and, subsequently, into electrical energy. The potential energy derives from the difference in height between the entry point and the final height of the system consisting of the turbine and generator, called the hydraulic head. The water passes through the turbine, which transforms kinetic energy into mechanical energy. The turbine is connected to the generator via a drive shaft. Inside the generator, there are two main components: the rotor, made up of moving electromagnetic elements, and the stator, made up of fixed copper windings. The rotation of the rotor relative to the stator generates a variable electromagnetic field, thus inducing an electric current. This electricity is then piped to a transformer and fed into the grid (Corà et al., 2020; U.S. Energy Information Administration, 2023). The discharge channel conveys the flow of water leaving the turbine, allowing it to rejoin the main watercourse. The lifespan of a hydroelectric plant can range from 50 to 85 years, with some internal components that may have a shorter lifespan (Ball et al., 2020).

5.2.1 Types of Plants

There are two main types of hydroelectric plants: Dam with reservoir and Run-of-river systems.

The dam with reservoir system consists of an intake dam, an intake, a penstock, a power plant, and a drain. As can be seen in the Figure 5-1. Diagram of a dam with reservoir hydropower plant (Kumar et al., 2011a), the water is stored in a basin. When electricity is needed, the inlet gates open and water flows down by gravity through pipelines, called penstocks, which can withstand high pressure. Along the penstock there is a compensation tank or a piezometric well to allow pressure relief in case of water peaks. The water then arrives at the power plant, where the turbine and generator are located. There may be a protective grille in front of the turbine to prevent large objects, such as branches and stones, from entering the blades. Water passes through the turbine, which drives the generator and produces electricity that is sent to the grid or other electrical connections, while the water is released into a basin or continues to flow (Corà et al., 2020).

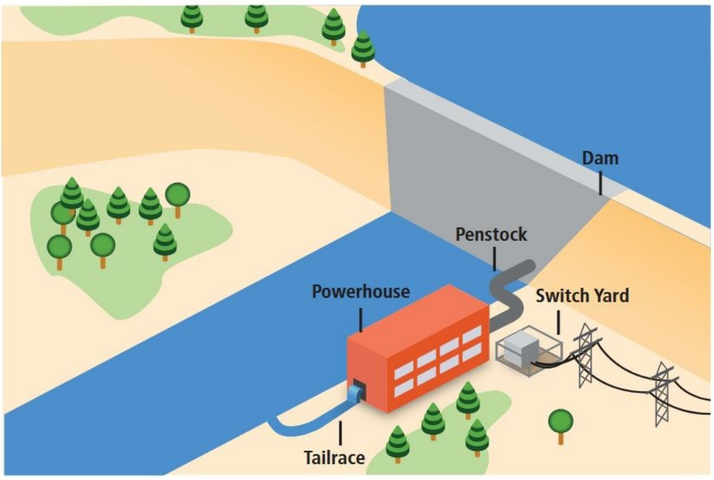


Figure 5-1. Diagram of a dam with reservoir hydropower plant (Kumar et al., 2011a)

Pumped storage is a type of dam with a storage basin and is illustrated in the Figure 5-2. Diagram of a pumped storage hydropower plant (Kumar et al., 2011a). The water is initially released from the upper basin and descends through penstocks. After passing through the turbine, the water is channeled into a lower basin, which serves as an energy storage system. When the energy demand is low, the water is pumped upwards, along the same route as the descent, and reaches the initial basin. The upper pelvis is thus filled. When there is demand for electricity, the water follows the normal process of the dam with storage basin (Kumar et al., 2011b). The system includes a pump and a turbine or a combined component, such as a fixed-speed turbine that performs both roles (Corà et al., 2020).

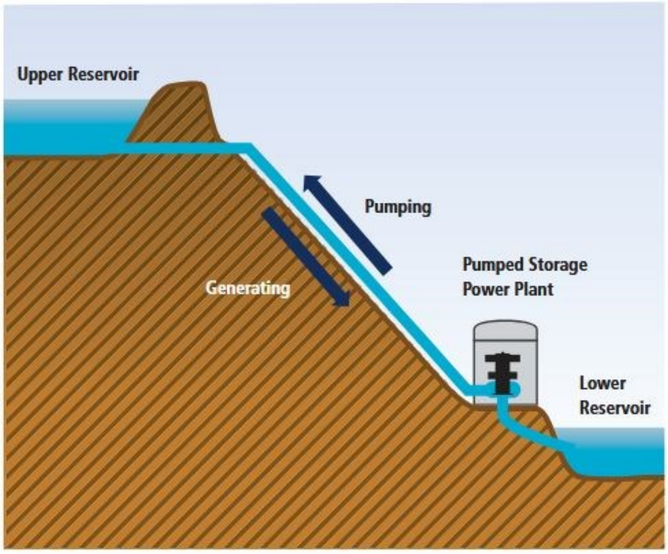


Figure 5-2. Diagram of a pumped storage hydropower plant (Kumar et al., 2011a)

The run-of-river system is based on the diversion of the natural course of the water. The water is diverted from the normal course of the river via dams, weirs or sluice gates and flows through canals or penstocks until it reaches a system consisting of a turbine and generator. After the diversion, there may be a small accumulation area with short water residence times, from a couple of hours to a day (Kumar et al., 2011b) (Tsuanyo et al., 2023). Other projects involve water passing directly from the diversion point to the turbine. After passing through the turbine and generator, the water rejoins the original flow. Figure 5-3. Diagram of a run-of-river hydropower plant (Kumar et al., 2011a) shows the system and the Figure 5-4. Different types of run-of-river systems (Tsuanyo et al., 2023) illustrates the various deviation strategies used.

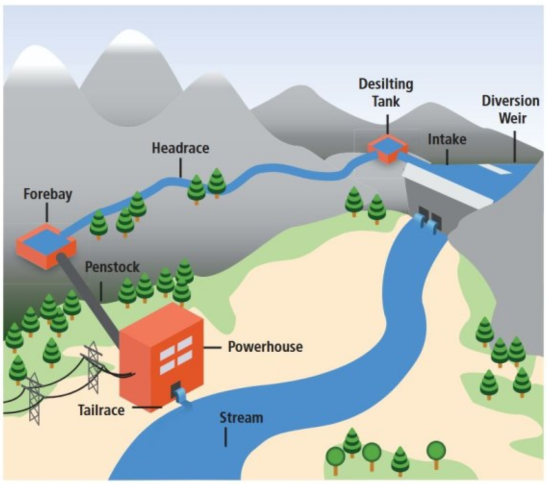


Figure 5-3. Diagram of a run-of-river hydropower plant (Kumar et al., 2011a)

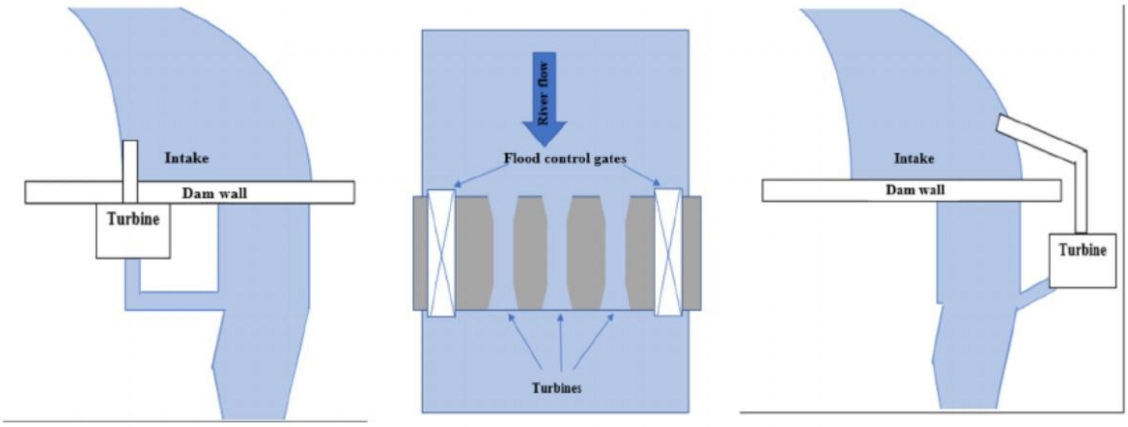


Figure 5-4. Different types of run-of-river systems (Tsuanyo et al., 2023)

The dam system with a reservoir is more predictable than the run-of-river system, as it has a large reservoir. The run-of-river system is more sensitive to seasonal variations and is therefore generally used in smaller plants to provide basic energy; However, thanks to hydrological forecasts, it is still able to supply the energy market.

Hydropower can be classified into different categories based on size, and definitions vary from country to country. The general size categories of hydropower are: pico <5 kW, micro 5 – 100 kW, small 100 kW < 1 – 10 MW, and large >1-30 MW (British Hydropower Association, 2026) (Corà et al., 2020).

5.2.2 Technical Parameters and Turbine Types

The potential energy (PE) of the system in J is calculated using equation 3. The variables are the mass of water (m) in kg, the acceleration of gravity (g) in m/s², and the gross head (H_{gross}), i.e. the distance between the starting point of the water and the turbine, expressed in meters.

$$PE = m * g * H_{gross} \qquad (3)$$

The power (P) delivered by a HPP, expressed in J/s or W, is calculated using equation 4. Variables not mentioned include: water density (ρ) in kg/m³, volume flow (Q) in m³/s, net height (H_{net}) in m and turbine efficiency (η). H_{net} is calculated in Equation 5, which includes the following variables: H_{gross} and H_f, which represent the pressure drop due to friction.

$$P = \rho * g * Q * H_{net} * \eta \qquad (4)$$

$$H_{net} = H_{gross} - H_f \qquad (5)$$

The system is subject to various energy losses due to hydraulic, mechanical and electrical performance factors of the structure and equipment. Hydraulic leaks can occur when water is in the pipes or passing through the turbine, due to leaks, friction, and changes in speed; mechanical losses can occur inside the turbine and generator, as some of the water escapes from the turbine blades, and due to friction, the energy is dispersed in the form of heat; Finally, electrical losses can occur in the generator and transformers (Muljadi et al., 2021).

The energy produced by a micro-hydroelectric power plant would be fed into the low or medium voltage grid, while that coming from a small hydroelectric power plant would require a high voltage network (Muljadi et al., 2021). Micro-hydropower plants generally handle small water heads, between 15 and 30 m or less, which can be further divided into small (<5 m) and very small (<2.5 m) jumps. Large hydroelectric power plants are usually associated with water jumps of 50-70 m or more (Ball et al., 2020).

There are numerous turbine options, which can be classified into three groups: reaction, impulse and gravity; The choice for a given project should be based on flow rate and hydraulic head, while also taking into account secondary factors such as cost and desired efficiency. Jet turbines are typically used in systems with high flow and low hydraulic head. Examples of models are the propeller turbine, which includes the Bulb, Staflo, Tube and Kaplan turbines, as well as the Francis and Kinetic turbines. Impulse turbines are generally suitable for systems with low flow but high hydraulic head. The most common models are the Pelton, the Turgo and the Cross-Flow. Gravity turbines are used for low hydraulic charges and run very slowly (U.S. Department of Energy, s.d.-c). Examples are the water wheel and the Archimedes screw. (Corà et al., 2020) offers an in-depth description of the turbine models presented.

5.3 Economic Data

As with other renewable technologies, the terms CAPEX and OPEX are often used as economic indicators of hydropower. CAPEX estimates generally include (i) site preparation, such as site assessments, permitting, risk assessments and land clearance, and (ii) the production and construction of the components for water transport, power plant structure, electromechanical system and grid connection. OPEX includes the average annual fixed costs for the operation and maintenance of the hydropower plant. One method for calculating OPEX is 2,5% of CAPEX (National Laboratory of the Rockies, 2024). As for site-related authorizations, it can take about 2-6 months for micro hydropower plants, while for medium and large plants it can take 9-18 months (Fichtner Management Consulting AG, 2021). Within OPEX, a distinction is made between: (i) fixed OPEX (FPOEX), in which costs are annual and scheduled, and (ii) variable OPEX, in which costs are unexpected. The Table 5-1. Hydropower plant CAPEX and OPEX reports the CAPEX and OPEX values taken from the literature.

HPPs have a high CAPEX due to the considerable infrastructure costs, as can be seen from the average breakdown of the CAPEX: project development (9,2%), civil works (54,3%), electrical and mechanical equipment (30,3%), other (1,3%) and contingencies in the feasibility phase and other (10,4%). HPPs with dams usually have a higher CAPEX. The costs of a hydroelectric power plant depend on the specificity of the location in terms of hydrology, geography, size and local policies. Financing hydropower plants can be difficult due to the hydrological unpredictability of some locations and the long lifespan (Fichtner Management Consulting AG, 2021). The European Union-funded project 'Hydropower Extending Power System Flexibility' (XFLEX HYDRO) provided a methodology for assessing the economic parameters of hydropower, as well as cost-cutting technologies tested in pilot areas (Boucher et al., 2020).

Table 5-1. Hydropower plant CAPEX and OPEX values

Citation and Notes	Details HPP and Year	Size HPP (MW)	CAPEX ($/kW)	OPEX ($/kW-year)
(National Laboratory of the Rockies, 2024) - Using 2022$, FMOEX, a 30-year payback period and a conservative estimate.	Dam with reservoir plant, NPD, 2025	~10	3.241 (estimate low)	92
		~6	6.488 (estimate average)	113
		~2	14.240 (estimate very high)	188
	Run-of-river plant, NPD, 2025	~86	5.220 (estimate low)	34
		~67	7.859 (estimate average)	39
		~2	21.498 (estimate very high)	204
	NSD, <30 ft head, 2025	~4	9.165	155
		~44	8.182	50
	NSD, >30 ft head, 2025	~4	8.013	145
		~94	7.214	35
	Values collected from the literature, 2025	-	1.215 – 7.125	-
(International Renewable Energy Agency (IRENA) & IEA Energy Technology Systems Analysis Programme (IEA-ETSAP), 2015) Using the values of the 2010$	-	<1	3.400 – 10.000	1%–4% of the costs annual of investment
		1< x <10	1.000 – 4.000	
		>10	1.050 – 7.650	
(Bor & Üçtuğ, 2022) - Using 2010$	Run-of-river plant, 50 years	4	2.548	37,0
(A. Raimondi et al., 2021)	-	0,1 – 0,5	4.000 – 7.000 €/kW	125 €/kW for,1 MW
				115 €/kW for 0,250 - 0,5 MW
		1	3.000 – 6.000 €/kW	-

NPD = Powering of non-powered dams, i.e. the integration of hydroelectric production systems into existing dams that are not currently equipped with hydroelectric power generation plants (Hadjerioua et al., 2013).
NSD = New stream-reach development, i.e. the development of new hydroelectric plants along stretches of watercourses not yet exploited for the production of hydroelectric energy (Hadjerioua et al., 2013).

5.4 Social and Environmental Aspects

Hydropower has several positive and negative aspects. Among the advantages is the fact that reservoirs act as water reservoirs and can provide water in the event of drought. In the event of heavy rainfall, the reservoir can serve as a flood control system. In addition, reservoirs can be a source of water for irrigation, tourism and fishing.

The creation of reservoirs and dams can have an impact on human society, as populations may need to be relocated to make room for infrastructure. If the dam breaks, the surrounding area is in danger as unregulated water flow can flood nearby communities, uproot vegetation, and ultimately cause damage and death. Additional noise and vibration may occur during operation, e.g. when turbines are overloaded (Muljadi et al., 2021).

Water storage, particularly in systems with dams and reservoirs, can have several negative impacts on the ecosystem. Methane can be formed within basins due to the decomposition of organic matter, a phenomenon that can also occur in basins not intended for hydroelectric energy production. Thermal stratification can occur in stagnant waters. When cold water at the bottom of the basin is released and returned to the ecosystem, the temperature of the water can cause a shock to aquatic wildlife. In addition, sediment flow, gas exchange between water and air, and control of river erosion are altered (Kumar et al., 2011b).

Aquatic species, mammals, and birds may experience disturbances due to changes in daily and seasonal flood patterns and water levels, as nests or other habitats may flooded. Flooding may occur during hydropeaking, i.e. the increase in production to meet the demand for electricity, which can be sudden for the ecosystem (Smokorowski, 2022). In addition, aquatic animals, such as fish and eels (generally referred to as fish), can become trapped in the current and be pulled into the turbine. Contact with the turbine and sudden changes in pressure can cause injury or death. There are various projects that aim to improve the compatibility between hydropower and fish populations, such as the EU-funded FIThydro project, which ran between 2016 and 2021. This project assessed fish migration patterns, created risk assessments and decision-making tools such as the Fish Population Risk Index, and tested various fish diversion strategies. Some options for limiting the danger to fish include creating fish bridges (also called fish passages or ladders), where a separate water stream is designated to allow fish to bypass the turbine-generator system. Other options include the choice of low-impact turbines on fish, such as Kaplan or Archimedes screw turbines, vertical and horizontal grids to prevent entry, electrical stimulation to redirect movement, and pressure control as it passes through the turbine (FIThydrowiki contributors, 2023) (Dewitte, 2018).

LCAs have been applied to hydroelectric plants. Results vary greatly depending on the design of the plant, its location, and the inclusion of emissions from the reservoir. The functional unit is often 1 kWh of electricity produced by the system. The main life cycle stages taken into account are production, which includes the manufacture of the various components, the transport of the components to the site, the construction of the hydropower plant and direct emissions from the reservoir, operation, end of life and transmission of electricity. Alternatively, in HPP LCAs, construction is a life cycle stage that includes production, transportation, and construction. Transportation can play an important role when a hydroelectric power plant is installed in remote locations, so the distance between the place of production and the place of installation could be considerable (United Nations Economic Commission for Europe, 2021). Since many hydropower plants have not yet been decommissioned, the end-of-life phase is often not included in the LCA (Simon et al., 2023), although waste management during construction is sometimes included. The literature on waste management commonly applies LCA considering the production and operation phases, often over a time horizon of 80 to 100 years, and as a result, the results are spread over a very long period.

In the production phase, concrete fabrication is often the main contributing factor to CCP. Hydropower plants have CCP values that are consistently lower than the grid electricity mix of the respective study location. For example, in the study of (Bor & Üçtuğ, 2022), focused on a run-of-river SHP in Turkey, the CCP is 30,6 kg CO_{2eq}/MWh compared to the average electricity grid CCP of 520,2 kg CO_{2eq}/MWh, where the grid mix in 2020 was made up of 83,3% solid fuels, gas and oil (Republic of Turkey Ministry of Energy and Natural Resources, 2022).

In (Kjeld et al., 2025a), production and construction were the main emission factor for three of the four HHPs examined during the life cycle assessment, from the construction phase to the operation phase, mainly due to the energy required for concrete production and for the operation of the plant itself. For the remaining HPP studied, reservoir emissions were the predominant factor, accounting for around

95%, demonstrating the variability of LCA results. The presence of organic matter can be influenced by various factors, such as soil type, water temperature, previous soil type, and the presence of pollution (e.g., wastewater) (Kjeld et al., 2025b, 2025a; Kumar et al., 2011b). LCAs related to hydropower are lacking in the literature, in particular those focused on SHPs. The EU-funded ReHydrate project is currently conducting an LCA analysis related to the renovation of HHPs. The Table 5-1 provides a brief collection of CCP values from the literature. (Gemechu & Kumar, 2022) and (Luangphon et al., 2025) offer further summaries of CCP values taken from the literature.

Table 5-1. Hydropower plant climate change potential values obtained from the literature

Citation	**Type of Plant**	**Plant Size**	**System Boundary**	**Operational Period (years)**	**CCP Value (g CO_{2eq}/kWh)**
(Bor & Üçtuğ, 2022)	Run-of-river plant	4 MW	Production – Construction	49	30,6
(Tang et al., 2024)	Dam with reservoir plant	1,3 MW	Preparation – Dismantling Production – Construction	30	417,6 280,1
(Geller & Meneses, 2016)	Dam with reservoir plant	30,3	-	100	5,5
(United Nations Economic Commission for Europe, 2021)	Dam with reservoir plant	360 MW	Construction – Dismantling	80	10,7
(Kjeld et al., 2025a)	Dam with reservoir plant	95 – 690 MW	Production – Operation Production – Construction	100	0,5 – 21,1 0,4 – 1,1
(Merida García et al., 2021)	Pump-As-Turbines	4 kW	Production – Operation of the turbine	20	111,8
(Simon et al., 2023)	Pumped storage plant	835 MW	Construction – Dismantling	80	86

6 LITHIUM-ION BATTERIES

6.1 Potential for Integration into a Renewable Energy Community

4.1.1 Description

With the introduction of distributed and renewable energy resources, EES systems play a key role in providing flexibility, controlling the intermittency of generation, and ensuring a continuous supply of energy to the consumer and the grid. As described above, an EES system is defined as the process by which electrical energy from one source is converted, via a conversion module, into another form or storage medium, which can be chemical, mechanical, thermal, or magnetic, and then converted back into electrical energy. This process occurs when there is a surplus of energy, such as during peak solar production hours. The converted energy is stored for a limited period and then converted back into electricity when needed (Medina et al., 2014). The use of EES systems often occurs when energy production is insufficient compared to demand.

A chemical storage that stores electrical energy in rechargeable batteries is defined as battery energy storage system (BESS). BESSs offer a number of strengths that make them popular solutions in the energy storage landscape, such as near-instantaneous response, on the order of a few milliseconds; low initial investment costs; modularity, which allows for easy capacity adjustment based on needs; and high scalability and portability, which facilitate integration into various applications (Medina et al., 2014).

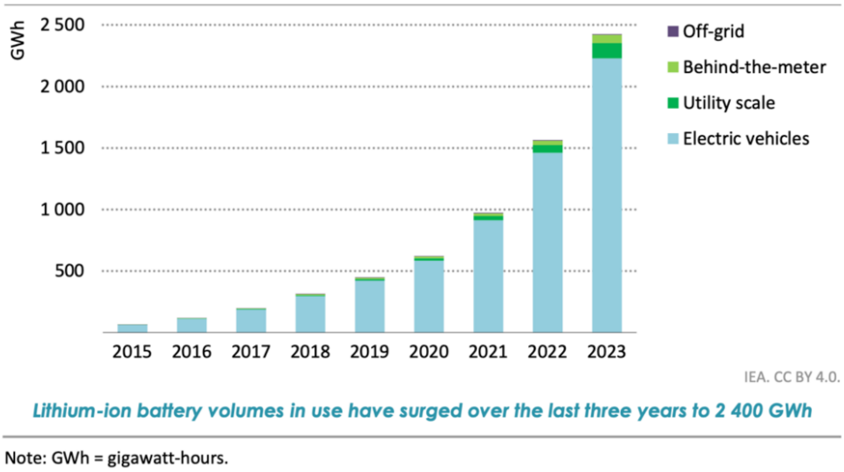
BESSs are an important element for a storage system of a REC. They can provide electricity when energy production is insufficient, such as at night when there is no solar production or during periods of low wind production. A BESS reduces energy waste, as excess energy is stored for later use and not discarded. In addition, this technology can contribute to "peak demand reduction", where during peak consumption the consumer draws energy from the battery to reduce pressure on the grid and avoid rising electricity prices. Finally, a BESS ensures safety in the event of a network failure (Bielewski et al., 2022; Šimić et al., 2021a).

4.1.2 Presence of Lithium-ion Batteries in the Market Global

There are different types of batteries, each with specific characteristics: advanced lead-acid and lead-acid, nickel-cadmium, nickel-metal hydride, lithium-ion, sodium-sulfur, and sodium-nickel chloride. This diversity allows BESSs to cover a wide range of applications, from small home installations to complex grid-connected systems (Medina et al., 2014). Among these, lithium-ion batteries are currently the most widespread and include the following chemical types: lithium nickel manganese cobalt (NMC), nickel cobalt aluminum oxide (NCA), LFP, and lithium cobalt oxide (LCO).

As seen in Figures 6-1, the presence of lithium-ion batteries has increased due to the popularity of electric vehicles (EV), which resulted in an approximately 90% increase in lithium-ion battery capacity in the global energy sector between 2015 and 2023. In 2023, capacity exceeded 2,400 GWh, four times the value of 2020. NMC batteries remained the leading technology for EV batteries from 2018 to 2023, but the presence of LFP batteries increased from about 10% to 40%. Despite having a lower energy density than NMCs, LFP batteries are on the rise because they do not contain nickel or cobalt, are more thermally stable and therefore less flammable than NMCs, and are cheaper (IEA, 2024).

Lithium-ion batteries are also crucial within the power grid as stationary energy storage systems. The amount of stationary batteries exceeded 190 GWh in 2023, thanks to large-scale deployment and later "behind the meter" deployment (installed at the consumer's premises). The presence of LFP batteries increased from 65% to 85% respectively between 2022 and 2023 (IEA, 2024). Compared to lithium-ion batteries in the mobile sector, stationary batteries have a longer lifespan with shallower charge/discharge cycles and therefore a greater number of cycles, resulting in a higher overall amount of energy delivered during their useful life (Bielewski et al., 2022).



Figures 6-1. Global volumes of lithium-ion batteries within the energy sector (IEA, 2024)

6.2 Technical Information

6.2.1 Chemical Composition

The following section will be devoted to the chemistries of lithium-ion batteries, many of which are classified as TLR 9, demonstrating a mature technology (Bielewski et al., 2022). These batteries are classified and named according to the composition of the cathode.

A lithium-ion battery consists of thin layers consisting of cathode, anode, electrolyte, separator, and current collectors. The cathode (positive electrode) is made of a lithium metal oxide, usually cobalt, nickel or manganese, or lithium phosphate. Some batteries use a combination of chemistries (such as the LCO NMC battery) to achieve the desired qualities. The anode (negative electrode) is commonly made of graphite, but another option is lithium titanate. The two electrodes are immersed in an electrolyte that allows the accumulation and movement of lithium ions. The electrolyte is typically composed of lithium salts, such as lithium hexafluorophosphate ($LiPF_6$) and a mixture of organic solvents. The separator allows passage between the two electrodes, prevents the latter from touching each other, and finally, prevents electrons from entering the battery due to its lack of conductivity. The separator is normally made of polyolefin, a mixture of polyethylene or polypropylene, and electrolyte. Current collectors allow the movement of electrons. The positive current collector, made of aluminum, is fixed to the cathode. The negative current collector, made of copper, is fixed to the anode (Cutaia et al., 2014) (Buchmann, 2023b).

As shown in the Figure 6-2, during redox reactions that take place during charging and discharging, lithium ions migrate reversibly from one electrode to another due to the potential difference. During discharge, the lithium in the anode is oxidized and the free electrons move along the external circuit, through the charging device, until they reach the cathode, where they reduce the transition metal present. In addition, the lithium ions de-intercalate from the anode and move to the cathode where they intercalate, passing through the separator. During battery charging, electrons and lithium move from the cathode to the anode following the same paths as discharge. The oxidation reaction takes place in the cathode and the reduction reaction in the anode (Preger et al., s.d.) (Stallard et al., 2022).

During the first cycles of charge and discharge, in addition to the transfer of lithium ions, a passivating layer is also formed on the negative electrode, called the electrolyte-solid interface, composed of oxides, hydroxides, carbonates and fluorides. This layer is important for battery performance as it reduces electrolyte degradation over life cycles, ultimately affecting battery capacity and safety(Cutaia et al., 2014) (Stallard et al., 2022).

A group of cells is then brought together into a battery module (also called a battery pack or simply battery). There is also a battery management system (BMS) inside the battery. The BMS measures and regulates the voltage between the cells, as well as measures temperature and state of charge (SoC). The system also alerts you when capacity is below the set threshold, alerts you to system faults, and disconnects the battery from the charging device if operating parameters are out of bounds (Stallard et al., 2022) (Buchmann, 2021).

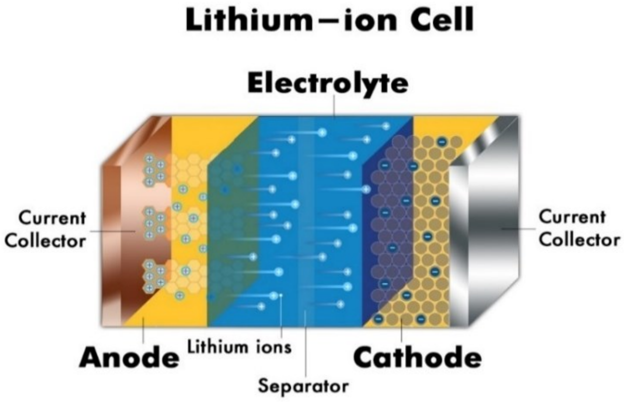


Figure 6-2. Schematic of a lithium-ion battery cell (Richye, 2024)

6.2.2 Material Composition

An average composition of LFP battery cells is provided in Table 6-1, with most of the weight consisting of LFP. Table 6-2. Average composition of battery pack (Carvalho et al., 2021; Krebs et al., 2020) shows the average composition of the battery components. Cells account for approximately 60–85% of the total battery weight (Carvalho et al., 2021) (European Union, 2025a).

Table 6-1. Average material composition of lithium-iron phosphate cells (Contemporary Amperex Technology Co., Limited, 2024; Sunwoda Mobility Energy Technology Co., Ltd., 2025)

Material	% of Battery Cell Weight	Material	% of Battery Cell Weight
LFP	40,7	PP	1,7
Aluminium	9,1	PC	1,7
Graphite	18,4	PET	1,7
Copper	8,2	Electrolyte	20,3
Separator	2,5	Other products chemical	2,0

Table 6-2. Average composition of battery pack (Carvalho et al., 2021; Krebs et al., 2020)

Component	% of Battery Pack Weight
Cells	60,2
System of cooling	4,0
Battery shell	32,0
BMS	3,9

6.2.3 Energy Density and Temperature Ranges

Lithium-ion battery cells have specific energy values between 80 and 250 Wh/kg, energy density values between 95 and 500 kWh/m³ and specific powers between 200 and 2000 W/kg. Energy efficiency is very high, with values that even exceed 95% depending on operating conditions, especially when compared to other technologies (Šimić et al., 2021b).

The recommended storage temperature range is 5 to 20 °C (Environment Health & Safety, 2025a). The suggested temperature range when charging is 0 to 45 °C and when discharging between -20 and 60 °C

(Buchmann, 2022). The batteries were used in more extreme temperature conditions, but with reduced long-term functionality.

4.2.2 Charge and Discharge

The voltage rating is usually between 3,6 and 3,7 V, which is the midpoint between the fully charged voltage (4,2 V) and the voltage below which it should not fall (3,0–3,2 V) (Buchmann, 2023a). When charging, the batteries use a system called 'constant current/constant voltage'. Initially, the battery receives a constant current as the voltage increases, until it reaches 4,2 V, after which the current decreases to zero while the voltage remains at 4,2 V (Z. Wang et al., 2019). The charging time depends on the battery capacity and the input current, which should not exceed 1/10 of the battery's peak current to avoid damage and overheating.

During discharge, the maximum current that a lithium-ion battery can deliver continuously depends on both the capacity of the battery itself and the nature of the load to which it is connected. A cell can be an energy cell, which provides maximum capacity and a long lifetime, or a power cell, which allows for a high load with a lower capacity than the energy cell (Buchmann, 2023a). If the cell is over-discharged, there can be a risk of uncontrolled overheating, although that risk is reduced with lithium-ion chemical compositions, especially LFP (Environment Health & Safety, 2025b) (IEA, 2024).

The lifespan of a lithium-ion battery is typically measured by the number of full charge-discharge cycles performed until a certain degradation threshold is reached, which is usually 80% of the rated capacity. The lifespan of a cell can range from 100 to 10,000 cycles (Šimić et al., 2021b), but can go up to 20,000 (Bielewski et al., 2022). The SoC is the currently available capacity of a battery, while the depth of discharge (DoD) measures the amount of charge released in a single discharge. The relationship between the two is DoD = 1 - SoC. For example, a DoD of 80% indicates that up to 80% of the stored energy can be used, leaving the remaining 20% of the SoC as a reserve to prevent battery damage. It is critical to manage DoD carefully, as excessive use can significantly reduce the lifespan of the accumulator, and in practical applications, batteries are never fully charged or discharged.

Additionally, the battery undergoes progressive degradation even when not in use, a phenomenon known as "self-discharge". The passive storage period is often taken into account when defining the average shelf life of the product. Degradation during storage is influenced by factors such as temperature, SoC and battery age: a fully charged battery (100% SoC) stored at high temperatures (above 50°C) can experience a rapid drop in capacity and produce gas. The self-discharge rate is declared by manufacturers and is typically 1,5-2% per month, plus an additional 3% due to the consumption of safety circuits (Cutaia et al., 2014).

6.2.4 Energy Balance

In general, properly sizing a battery relative to a system is critical to avoid system overload or inefficiencies. The charging capacity of an energy storage system is the rate at which the system is able to absorb and store energy. When evaluating sizing, it is also possible to evaluate the charge and discharge efficiencies of a storage system. During charging and discharging, some energy is inevitably lost, for example in the form of heat. An efficiency of 90% implies that 10% of the energy is lost in the conversion processes.

6.2.5 Reference Values

In the Table 6-2 are reported the technical data of some batteries to the lithium and batteries LFP, collected from the literature and by the data sheets of different companies operating in the market of the BESS.

Table 6-2. Technical data from the literature and data sheets

Citation	Technology/ Model	Voltage Rated/Capacity Rated	Useful Energy	Specific Energy (Wh/kg) --------- Energy Density (kWh/m^3)	Depth of Discharge	Self-discharge	Operational Temperature	Round-trip efficiency	Service Life	Weight
(Šimić et al., 2021b)	Li-ion	2,5 – 5 V	-	80 – 250 Wh/kg 95 – 500 kWh/m^3	100%	0.1 – 0.3 %/day	20 – 65°C	75 - 97%	100 – 10.000 cycles/ 5 - 15 years	-
(Borerwe & Longe, 2025)	LFP	-	-	90 - 120 Wh/kg	80 - 100%	<2%/month	-	~95%	>2.000 cycles/ 10 - 20 years	-
(Jaiswal, 2017)	LFP	13,2 V/2 Ah	-	-	-	- -	-	95%	4.400 cycles	-
(Kebede et al., 2021)	Li-ion	-	-	151 Wh/kg 311,7 kWh/m^3	-	0,17%/day	-	87,4%	12,7 years	-
(Khosravani et al., 2026)	Li-ion	-	-	-	-	0.1 %/day	-	95%	25 years	-
(Laksahapsoro et al., 2025)	LFP	-	466 kWh	105,9 kWh/m^3	-	-	-	85%	15 years (2,67%/year degradation)	-
(Tsai et al., 2020a)	LFP	Cell: 3,2 V/280 Ah Module: 44,8V/280 Ah Battery pack: 761,6 V/280 Ah	- - 213,2 kWh	-	-	-	-	- - 92%	- - 967.765 kWh	-
(Senmei Technology Co., n.d.)/CATL	LFP	3,22 V/302 Ah	-	-	-	-	Charge: 0 – 60 °C Landfill: -30 – 60°C	-	≥4,000 cycles	≤5.5 kg
(Energy Srl, n.d.)/Pylontech	LFP/US3000C	48 V (45 – 53,5 V)/74 Ah	3,55 kWh	-	95%	-	Charge: 0 – 50 °C Discharge: -10 – 50°C	-	15+ years>6000 cycles	32 kg

Table 6-3. Technical data from the literature and from lithium-battery data sheets (continued)

Citation	Technology/ Model	Voltage Rated/Capacity Rated	Useful Energy	Specific Energy (Wh/kg) --------- Energy Density (kWh/m³)	Depth of Discharge	Self-discharge	Operational Temperature	Round-trip Efficiency	Service Life	Weight
(Huawei, n.d.)/ HUAWEI	LFP/LUNA 2000-5-AND0	360 V (350 – 560 V)	5 kWh	-	-	-	-20 – 55°C	-	15 years	50 kg
(SolarEdge Technologies, Inc., 2024)/ SolarEdge	LFP/BAT-05K48, BT	48 V (44,8 – 56,5 V)	4,6 kWh	-	-	-	-10 – 50°C	>95.4	10 years of guarantee	54,7 kg
(Jinko Solar Co., Ltd., n.d.)/Jinko Solar	LFP/JKS 215KLAA-100PLAA	768 V (672 – 864 V)	215 kWh	-	95%	-	-20 – 50°C	-	6.000 cycles	2800 kg
(SMA Solar Technology AG, n.d.)/SMA	LFP/HS-BM-3.28-10	96 V (90 – 108 V)/36 A	3,28 kWh	-	-	-	Charge: 0 – 50 °C Discharge: -10 – 50°C	94,5%	8.000 cycles, 10 years of guarantee	38 kg
(Fronius International GmbH, 2025)/Fronius	LFP/Reserva 6.3	102,4 V	3,15 kWh	-	-	-	-20 – 55°C	95%	6.000 cycles, 10 years of guarantee	33,5 kg
(LG Energy Solution, 2021)/LG	Li-ion/RESU6.5, BT	51,8 V (42,0 – 58,8 V)/126 Ah	6,5 kWh	-	90%	-	-10 – 50°C	>95%	10 years of guarantee	52 kg

6.3 Economic Data

Battery production costs have decreased, mainly due to technological advancements, application versatility, and economies of scale. Currently, the price of batteries is largely determined by the cost of raw materials, which accounts for around 50–70%, making prices more sensitive to fluctuations in the prices of critical minerals (European Union, 2025a). Lithium-ion battery prices (including cell and pack costs) decreased from around USD 800/kWh to less than USD 140/kWh between 2013 and 2023. Prices fell significantly in 2023 due to an increase in mineral supply and production capacity, while demand declined. In addition, in 2023, LFP batteries recorded the lowest global average prices among all lithium-ion batteries, falling below USD 100/kWh for the first time in history (EUR 86,65/kWh, conversion rate EUR 1 = USD 1,1544) and continuing to decline in 2024 (European Central Bank, 2023) (IEA, 2024).

LFP battery prices are lowest in China and about 10-20% higher in the U.S. and Europe, though they seem to converge over time (IEA, 2024). Since much of the battery production takes place in China, scaling up production in Europe presents some challenges. Obstacles include the high investment required for plant construction, rising labor costs, and access to raw materials. For example, about 90% of graphite is mined in China and about 50% of lithium in Australia, while Europe accounts for about 1%. Important strategic action plans, industry-government cooperation plans and European Union research projects over the past 20 years have increased investment and local battery production (European Union, 2025b).

In

Table 6-3 economic data from literature relating to lithium batteries is reported. Conversion values were derived from (European Central Bank, 2026). In Table 6-4 technical and economic data of different models of LFP batteries of the BYD brand are reported. In Table 6-6. Technical and economic data for lithium-iron phosphate battery models LFP from the brand EPever technical and economic data of various LFP battery models of the EPever brand are reported.

Table 6-3. Economic data of different battery models

Economic Parameter	**(Borerwe & Longe, 2025)***	**(Jaiswal, 2017)**	**(Kebede et al., 2021)**	**(Khosravani et al., 2026)**	**(Laksahapsoro et al., 2025)⁺**	**(Tsai et al., 2020b)#**
Cost of investment/CAPEX	336,5 €/kWh	269,6 €/kWh	Cost: 463,22 €/kWh Installation and other costs: 16,8 €/kW	-	99,9 €/kWh	243,5 – 295,7 €/kWh
OPEX	9,5 €/kWh	-	Replacement: 412,7 €/kWh	-	Sostituzion: 99,9 €/kWh (6,7 €/kWh-year)	3,7 €/kWh-year
COE/LCOE/LCOS	LCOE: 0,2 €/kWh	COE: 0,4 €/kWh	LCOE: 0,3 €/kWh	LCOE: ~0,07 - 0,3 €/kWh LCOS: 17,2€/kWh	-	LCOE: 0,08€/kWh
ROI	3,4 – 14,6%	-	-	-	-	2,16%
IRR	5,3 – 19,6%	-	-	-	-	3,7%
Discounted payback period	4,6 – 9,4 years	-	-	-	-	8,4 years

*Converted using the ZAR to Euro conversion rate: 1 Euro = 19,6271 ZAR, date of calculation 31 March 2026
⁺Converted using the GBP to Euro conversion rate: 1 Euro = 0,8683 GBP, date of calculation 31 March 2026
#Converted using the USD to Euro conversion rate: 1 Euro = 1,1498 USD, date of calculation 31 March 2026
COE = cost of energy
LCOE = levelized cost of energy
LCOS = levelized cost of storage
ROI = return on investment
IRR = internal rate of return

Table 6-4. Technical and economic data for lithium-iron phosphate models from the brand BYD

Company - Product	BYD - Box Premium LVS (Low Voltage Series)					
LVS module	4 kWh; 51,2 V; 45 kg					
Number of modules	1	2	3	4	5	6
Available Energy (kWh)	4	8	12	16	20	24
Maximum Current (A)	65	130	195	250	250	250
Weight (kg)	64	109	154	199	244	289
Rated Voltage (V)	51,2					
Operating Voltage (V)	40 – 57,6					
Working temperature (°C)	-10 – 50					
Efficiency (%)	>95					
Module price (€)	1145,4					
Module price (€/kWh)	286,4					
Quote	(VPSolar, 2023)					

Table 6-6. Technical and economic data for lithium-iron phosphate battery models LFP from the brand EPever

Company	**EPever**			
Model	LFP5012EP	LFP10012EP	LFP10024EP	LFP20012EP
Cell configuration	4 in series and 1 in parallel	4 in series and 1 in parallel	8 in series and 1 in parallel	4 in series and 1 in parallel
Rated capacity [Ah]	50	100	100	205
Rated voltage [V]	12,8	12,8	25,6	12,8
Energy Available [kWh]	0,640	1,280	2,560	2,624
Working temperature [°C]	-20 – 60	-20 – 60	-20 – 60	-20 – 60
Life cycle [cycles] @ 80% DoD and 25°C	>4000	>5000	>5000	>4000
Weight [kg]	7,6	12,2	22,6	54,7
Price [€]	215,62	334,41	532,01	589,46
Price [€/kWh]	336,01	261,26	207,82	224,64
Citation	(Beijing Epsolar Technology Co. LTD, n.d.)			

6.4 Environmental Impacts

Since batteries are often installed alongside solar panels, it is important to also assess the environmental impact of these products. This section covers LFP batteries, but some of the information related to EoL refers to lithium-ion batteries, as no specific data was available for LFP batteries. The environmental impacts described in this report relate to LFP batteries used in a variety of applications, including photovoltaic systems, EVs and communication base stations.

Information and data were collected from the literature (LCA and non-LCA studies), from reports, and from government and educational websites. As described in the previous chapters, LCA impact values will depend on various elements: 1) the FU, 2) the boundaries, 3) the years in which the inventory was collected, 4) the location of each life cycle process, 5) the LCIA method, and 6) the interpretation of the data (raw, normalized and/or weighted) (Porzio & Scown, 2021). Similar discrepancies can also occur among non-LCA data. In addition, the shape of the battery or the conditions of use may result in different impact values, perhaps due to variation in the size and shape of the components (Botejara-Antúnez et al., 2024; Carvalho et al., 2021). Numerical data is only provided for the production phase of the life cycle, as studies evaluate a mix of single use or multiple uses and therefore are not comparable (Yudhistira et al., 2022). The authors suggest that the reader should further explore the resources included and harmonize the data if comparing data points from differing methodologies. This resource should be used as a synthesis and starting point to explore the environmental impact of LFP batteries.

Note that most of the literature is based on production and use in countries with fossil fuel-powered power grids. The included literature features some batteries produced or recharged during their use phase with electricity coming, in whole or in part, from renewable sources, such as (Carvalho et al., 2021; Jasper et al., 2022), offering an interesting perspective. Environmental impacts, such as CCP, can be significantly affected (usually reduced) by the use of renewable energy sources compared to fossil fuel-based power grids (Han et al., 2023).

6.4.1 Life Stages

The LFP battery life cycle stages are manufacturing, usage, and EoL. Within the production stage, there are material collection, electrode preparation, cell production, battery management system production, and battery assembly. The use phase may be of a single intended use (such as use in an EV or PV system) or it may include a secondary use (e.g., an EV battery that is reconditioned and then used for energy storage in a PV system). This phase often includes installation. Finally, the EoL phase, in which the product or parts of the battery are reused, recycled or disposed of in landfills (Zhu & Chen, 2020). The transport of materials and products takes place throughout the life cycle.

EoL of LFP batteries occurs when the battery no longer meets operational requirements. The battery can enter the EoL phase immediately after its intended use, or it can be reconditioned for reuse. EV batteries are usually withdrawn from the market when they reach 80% capacity, but refurbished lithium-ion batteries can be used for other purposes up to 50-60% capacity (Torabian et al., 2022). (Ma et al., 2024) found that as the percentage of LFP batteries decreases, the profit from recycling decreases; Therefore, it is advantageous to extend their useful life before recycling.

6.4.2 Production Stage Energy Consumption

Energy consumption is the electrical energy required during the manufacturing process for the processing of materials and components, the assembly of parts, and the operation of equipment. The units of measurement may vary in the literature, but here in the Table 6-5, the data shown are expressed in kWh/kWh, i.e. the kWh consumed during the production process divided by the kWh capacity of the battery. Studies may only consider electricity consumption, or natural gas, or include other fossil fuels. (Degen et al., 2023) states that cell production, excluding material extraction, coating, drying, forming and cleanroom maintenance, is the most energy-intensive phase.

Table 6-5. Energy consumption during the production

Functional Unit	Value and Unit	Citation
Capacity of the battery in kWh	Electricity: 3,8 kWh/ kWhnominal_capacity Natural gas: 1,8 kg/kWh$_{nominal_capacity}$	(Feng et al., 2022b)
	Electricity: 12,2 kWh/kWhlifetime_capacity Natural gas: 5,7 x10^{-1} N-m^3/kwh$_{lifetime_capacity}$	(Han et al., 2023)

6.4.3 Production Stage Waste

During the production process, various emissions can be released, as listed in **Error! Not a valid bookmark self-reference.**.

Table 6-6. Examples of emissions released during the production of batteries

Pollution		Citation
Air		
Dust	Sulphur dioxide (SO_2)	(Han et al., 2023; Quan et al., 2022)
Hydrochloric acid (HCl)	NMVOC	
Carbon monoxide (CO)	Nitrogen oxide (NOx)	
Nitrogen (N_2)	Carbon dioxide (CO_2)	
Water		
Wastewater	Phosphorus (total)	(Feng et al., 2022b; Han et al., 2023)
COD	Volatile organic compounds	
Suspended solids	Ammonia (N)	
Solid waste		
Scrap metal	Waste plastic	(Carvalho et al., 2021; Feng et al., 2022b)

6.4.4 Impact Results

This section presents the results of various LCA studies. Table 6-9. LCIA methods, their respective impact categories, and various literature which used these methods. “NA” indicates that the LCIA method does not include that category. For each study, the "X" indicates that the category is assessed, while the "-" indicates that the topic is not assessed. illustrates the LCIA methods and impact categories assessed in the various LCA studies. Some LCIA methods have multiple impact categories for each impact theme. For example, the EF method has three categories of eutrophication: terrestrial, freshwater aquatic, and marine aquatic. Table 6-7 provides details and impact values related to CCP, water consumption and LU in the production phase for 11 studies. Terminology is often unclear on whether the results reflect a battery cell, module, or pack.

It is important to note that two functional unit approaches are commonly used in the battery literature, as shown in Table 6-7. One approach is to define the functional unit based on the rated capacity of the battery and it is referred to in this report as kWh$_{nominal}$. The other approach is to define the functional unit as the cumulative energy stored or released during the useful life of the battery and is referred to in this report as kWh$_{lifetime}$. The first approach makes it easier for the reader to compare batteries when the expected service life is not known. The second approach may be more accurate, but it is mainly useful if the useful life is known and if the batteries being compared have similar useful lives.

Table 6-9. LCIA methods, their respective impact categories, and various literature which used these methods. "NA" indicates that the LCIA method does not include that category. For each study, the "X" indicates that the category is assessed, while the "-" indicates that the topic is not assessed.

LCIA Method	**RECIPIE**				**CML/CML-IA**		**ILCD**		**EF**
Category	(Botejara-Antúnez et al., 2024)	(Feng et al., 2022b)	(Han et al., 2023)	(Guo et al., 2023a)	(Quan et al., 2022)	(Shu et al., 2021b)	(Jasper et al., 2022)	(Carvalho et al., 2021)	(Yudhistira et al., 2022)
Climate change	X	X	X	X	X	X	X	X	X
Depletion of ozone stratospheric	X	X	X	X	X	X	-	-	-
Human toxicity	X	X	X	X	-	X	-	-	-
particulate matter/material respiratoria/inorganic	X	X	X	X	NA		-	-	X
Ionising radiation	X	X	X	X	NA		-	-	-
Formation of ozone photochemical	X	X	X	X	X	X	-	-	-
Acidification	X	X	X	X	X	X	-	X	X
Eutrophication	X	X	X	X	X	X	-	X	-
Ecotoxicity	X	X	X	X	-	X	X	-	-
Land use	X	X	X	X	NA		-	-	-
Water use	X	X	X	X	NA		NA		-
Depletion of abiotic resources	X	X	X	X	-	X	X	X	X

Note: A study may have multiple impact categories for certain themes, and that the names of the themes used may not exactly match the wording in the study. NA indicates that the LCIA method does not assess that environmental issue. The "X" indicates that the study evaluates the theme, while the "-" indicates that the essay is not evaluated.

Table 6-7. Functional units, boundaries, and impact results for various studies

Citation	Application	Functional Unit	Study Boundary	Phases Included in Cradle-to-Gate	Production Impact		
					Climate Change Potential	Water Use	Land Use
(Botejara-Antúnez et al., 2024)	-	$kWh_{nominal}$	Cradle to gate	Raw material extraction and lithium-ion battery production	281,1 kg CO_{2eq}/kWh	9,4 m^3/kWh	9,4 m^2a $crop_{eq}$/kWh
(Feng et al., 2022b)	EV	$kWh_{nominal}$	Cradle to grave	Part machining and combined assembly	97,3 kg CO_{2eq}/kWh	~2 m^3/kWh	~3 m^2a $crop_{eq}$/kWh
(Guo et al., 2023b)	EV, then communication base station	$kWh_{nominal}$	Cradle to grave	Raw material extraction, component manufacturing, battery assembly and molding	110 kg CO_{2eq}/kWh	~2,2 m^3/kWh	~3,4 m^2a $crop_{eq}$/kWh
(Quan et al., 2022)	EV, then energy storage system	$kWh_{nominal}$	Cradle to grave	Electrode preparation, cell manufacturing, and battery assembly	76,7 kg CO_{2eq}/kWh	-	-
(Shu et al., 2021a)	EV	$kWh_{nominal}$	Cradle to grave	Component manufacturing, battery cell manufacturing, battery system assembly	46,4 kg CO_{2eq}/kWh	-	-
(Carvalho et al., 2021)	Grid energy storage	kWhnominal and kWhlifetime	Cradle to grave	Raw material extraction and processing, cell production, packaging, cooling system production, BMS production, battery assembly	Cell: 61,9 kg CO_{2eq}/kWh (Nominal)Battery: 114 kg CO_{2eq}/kWh (Nominal)	-	-

Table 6-10. Functional units, boundaries, and impact results for various studies (continued)

Citation	Application	Functional Unit	Study Boundary	Phases Included in Cradle-to-Gate	Production Impact		
					Climate Change Potential	Water Use	Land Use
(Jasper et al., 2022)	Storage energy of grid	$kWh_{nominal}$ and $kWh_{lifetime}$	Cradle to gate and cradle to grave	Primary extraction of raw materials, secondary production of materials, production of cells	63,7 kg CO_{2eq}/kWh (Nominal) 0,012 kg CO_{2eq}/kWh (Lifetime)	-	-
(Yudhistira et al., 2022)	Storage energy of grid	$kWh_{lifetime}$	Cradle to grave	Raw material extraction, battery cell production, battery pack assembly	Cell: 0,3 kg CO_{2eq}/kWh Battery: 1,0 kg CO_{2eq}/kWh	-	-
(Han et al., 2023)	Storage energy of grid	$kWh_{lifetime}$	Cradle to grave	Extraction and processing of cell raw materials and battery pack components, cell component manufacturing, cell assembly, battery pack manufacturing, battery pack assembly	~25 $x10^{-3}$ kg CO_{2eq}/kWh	1,9 $x10^{-3}$ m^3/kWh	4,5 $x10^{-3}$ m^2a-$crop_{eq}$/kWh
(GreenDelta , 2020)*	-	$kWh_{nominal}$	Cradle to gate	Battery production	130,6 kg CO_{2eq}/kWh	-	-
(Contemporary Amperex Technology Co., Limited, 2024)	-	$kWh_{nominal}$	Cradle to grave	Component manufacturing, semi-finished product processing, cell assembly, cell performance testing	64,4 kg CO_{2eq}/kWh	-	-

*Average of OpenLCA "Battery production, Li-ion, LFP, rechargeable | battery, Li-ion, LFP, rechargeable | Cutoff, U-CN and U-RoW" values.

The average CCP of a battery is 109,4 kg CO2eq/$kWh_{nominal}$ (Botejara-Antúnez et al., 2024; Contemporary Amperex Technology Co., Limited, 2024; Feng et al., 2022a; GreenDelta, 2020; Guo et al., 2023a; Quan et al., 2022; Shu et al., 2021a). The literature does not agree that production or use has a greater potential for impact on the CCP. During the manufacturing phase of the life cycle, the manufacture of electrodes (in particular the cathode) and electricity (for production equipment) are often the major contributors, although in particular the (Carvalho et al., 2021), electricity consumption and battery packaging (module packaging, battery containment and battery tray) were the biggest contributing factors.

In terms of the use phase, the production of additional energy to compensate for losses during charging and discharging has often been a determining factor, as has battery charging, both of which are largely influenced by the power grid. Many studies focus their analysis on China, since that is where the vast majority of production is concentrated. Because China has coal-based energy grids, the potential climate change values are expected to be higher than for an energy grid that uses renewable energy, as can be seen from (Guo et al., 2023b; Han et al., 2023). (Carvalho et al., 2021) used the Italian medium-voltage grid in 2018, with a composition consisting mainly of natural gas at 42,3% and renewable energy and biofuels at 31.3% (Gargiulo et al., 2020). During the use phase of (Carvalho et al., 2021), the overall CCP was lower than in the other studies.

The average value of water consumption during production, taken from the literature reported in the Table 6-7 is 2,1 m^3/$kWh_{nominal}$ while the average LU value is equal to 3,2 m^2a $crop_{eq}$/$kWh_{nominal}$ (Feng et al., 2022b; Guo et al., 2023b). Between production and use, the production phase makes the largest contribution in the water and LU categories (Guo et al., 2023b). In the production phase, the construction of the two electrodes and the energy consumption resulted in the highest contributions for both water use and LU. Each of the three processes had water impact values of 2 to 3 orders of magnitude and land use values of 1 to 5 orders of magnitude higher than other production processes. Overall, for cell production alone, electricity consumption had the highest contribution in 14 of the 18 impact categories during production (Botejara-Antúnez et al., 2024). Studies sometimes provide an inventory, but often a breakdown of the materials or processes associated with each impact outcome is not offered.

As for the other impact categories, the production phase was often the one with the greatest contribution. In (Guo et al., 2023b), eutrophication of freshwater and marine water, ecotoxicity of freshwater and marine water, carcinogenic and non-carcinogenic toxicity to humans, and formation of fine particulate matter were affected to a large extent by production. Similar results were observed in. (Feng et al., 2022b). On the contrary, in (Quan et al., 2022), the use phase, in particular the second use, was found to be the main life cycle phase in various categories, such as the depletion of abiotic (fossil) resources, the potential for eutrophication, the depletion of the ozone layer and the potential for acidification. The authors attribute the second use to a greater contribution to abiotic depletion (fossil fuels), acidification and ozone-creating potential, as the battery has a lower capacity and charges and discharges more frequently, therefore requiring more energy from the grid and ultimately releasing more pollutants.

6.4.5 End of life

Recycling offers numerous environmental and social benefits. As the five main components of LFP batteries, namely lithium, phosphate, aluminium, graphite and copper, are on the 2023 EU Critical Raw Materials List, reuse reduces the need for virgin materials (REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020, 2023). (Ioakimidis et al., 2019) and (Quan et al., 2022) concluded that the environmental impact of remanufacturing the battery for a second life, even with reduced efficiency, is lower than in the production of a new battery. The integration of production scrap into new products is also a useful approach to achieving recycling targets (Fichtner et al., 2025).

6.4.5.1 Battery Regulations

Globally, regulations to promote the collection, recycling and reuse of batteries are multiplying. EoL pathways (reuse, recycling and landfilling) and current European legislation relating to electronic products in general are described in Section 3.4.8**Error! Reference source not found.**. The EU is taking further steps with the New Battery Regulation, EU Regulation 2023/1542, which entered into force in 2024 and will be implemented in stages. This regulation applies the following concepts to batteries of various uses but for all chemical compositions: i) the ease of repair with common tools, ii) the definition of methodologies to calculate recycling efficiency, iii) the unification of reporting documentation for recyclers, vi) the recycling and recovery efficiency targets (a recycling efficiency of 65% and 70% for lithium batteries in 2025 and 2030, respectively, and a recovery rate of 50% and 80%, respectively, by 2027 and 2031), (v) implement transport rules, and (iv) set limits for various hazardous components and require information on hazardous components to be made public (Directorate-General for Environment, 2025; Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC, 2023; Supplementing Regulation (EU) 2023/1542 of the European Parliament and of the Council by establishing the methodology for calculation and verification of rates for recycling efficiency and recovery of materials from waste batteries, and the format for the documentation, 2025).

In Italy, foreign manufacturers selling on the Italian market must designate an authorized representative within the country to manage regulatory compliance (PV Cycle, 2025). A battery collection point can be found on the website of the National Coordination Centre for Batteries and Accumulators. The types of batteries accepted are indicated on the website and do not include the most powerful batteries that would be used for EVs or for storing large amounts of energy (National Coordination Centre & National Coordination Centre Battery and Accumulators, s.d.). In addition, Italy has issued Legislative Decree no. 49/2014 to transpose EU Directive 2012/19/EU into the Italian legal system (IEA, 2025). Further ministerial decrees (No. 65 of 2010, No. 121 of 2016 and No. 68 of 2017) support the implementation and enforcement of the roles of producers and distributors in the end-of-life phase of household WEEE In Austria, there are around 2000 registered collection points available for WEEE. Federal Law BGBl. II No. 159/2008 was enacted in 2008 and BGBl. II No. 311/2021 is an amendment enacted in 2021. These laws set out requirements for the collection and treatment of waste batteries, labelling, limits of hazardous components, producer responsibilities and calendar year references for reporting the quantities placed on the Austrian market and the quantities of batteries collected (Battery Ordinance, 2008; Battery Regulation Amendment 2021, 2021).

The United States Environmental Protection Agency mandates non-residential lithium-ion battery manufacturers to test hazardous waste and dispose of it accordingly. Batteries in household waste are excluded from the classification of hazardous waste, but it is recommended not to mix them with municipal waste and to handle them with care (U.S. EPA, 2025c).

6.4.5.2 Difficulties of Recycling and Ongoing Projects

The implementation and regulation of money laundering presents several difficulties. (T. Zhao et al., 2024) summarises these obstacles as a lack of legislative pressure and public awareness, the limited availability of collection points, and the ongoing process of development and standardisation of recycling methods. The authors emphasize the requirement for government commitment to pass laws, establish educational programs at the local level, and facilitate collection. Companies also have a responsibility to optimize recycling possibilities. Technical barriers include i) the treatment limitations of each recycling method, such as hydrometallurgy which is specific to chemistry and the fact that recycling plants separating battery types are expensive, ii) some layers are difficult to separate, such as organic binder, iii) the general risk of contamination during component regeneration (scrap fragments entering the reused electrolyte), (vi) the complexity of the structure of batteries, which may require automated disassembly and hinder industrial-scale production, and (v) the fact that some technologies are still being tested in the laboratory, such as direct recycling. Looking to the future, actions aimed at facilitating recycling consist of the implementation of battery passports that can help identify the chemical composition, origin of materials and the internal structure of batteries, the design of batteries that take into account recycling processes and the widespread dissemination of collection and recycling points (Fichtner et al., 2025).

Research continues to identify EoL pathways for LFP batteries, often through multinational research collaborations. The EU-funded Battery 2030+ coordination and support initiative facilitates research projects (such as ReUse and Revitalise) related to battery functionality, production and recycling, while promoting knowledge exchange, the circular economy and European production independence (Battery 2030+, 2025). Altri progetti includono Important Project of Common European Interest (IPCEI) on Batteries and IPCEI European Battery Innovation (IPCEI, 2025). The EU-India Trade and Technology Council has selected 8 start-ups from the EU (with representatives from Italy, Poland and Germany) and India to promote trade, showcase recycling facilities and projects, and collaborate on battery recycling techniques (Directorate-General for Research and Innovation, 2024). Across the European continent, there are companies that offer small-scale battery recycling services or are developing the facilities, such as Midac (Italy), Paristokierratys (Finland), Altilium (UK), among other groups that focus on setting up collection points (Ecotic Bat, Romania) (Eucobat, n.d.).

6.4.5.3 Reuse, Recycling, and Landfilling

Similarly, as with PV panels, there are three ways of managing the EoL phase of batteries: reuse, recycling and landfilling.

- Reusing the battery in its current condition would likely result in it being used for a purpose that requires less power consumption. Reuse may require reconditioning and is referred to as direct recycling. More information can be found at the recycling point below.
- Recycling: Battery components are usually separated by physical, thermal, chemical processes, or a combination of the three. The following are the potential separation pathways, but they are not limited to these options, and the order may vary (Müller et al., 2024). Before any treatment, the battery should be discharged to reduce the risk of fire (Torabian et al., 2022; U.S. EPA, 2025d).
    - Physical process: Dismantling, cutting, shredding, crushing, grinding, screening, the use of magnets, eddy currents, high-pressure washing, and floating separation. The powder obtained from shredding batteries is called the black mass and can be subjected to further treatments to separate smaller components (e.g. metals) (Barbosa De Mattos et al., 2025). These steps can be performed manually or mechanically, depending on the available resources, and allow metals (iron, copper, aluminum) and plastics to be recovered (Silva Silveira Camargo et al., 2024; Zhong et al., 2019).
    - Thermal processes (pyrometallurgy): The starting material can consist of battery cells, modules, or as a black mass (Rinne et al., 2025) and the general steps are melting, calcination, and pyrolysis. The separators, electrolytes and binder are separated, the organic components (the binder and graphite) are decomposed and the lithium is volatilized. The metals are reduced to slag, which contains an alloy of iron and phosphorus, copper and aluminum. The gas is treated and the volatilized lithium can be collected from the flue gas (Rostami et al., 2024; Zhong et al., 2019). Waste can include gases such as fluorinated compounds, alkanes and oxygenated organic compounds, as well as carbon dioxide (Jiang et al., 2025; A. Li et al., 2025; Liu et al., 2019). Disadvantages include high heat requirements, difficulty in differentiating the materials present in the slag, and loss of lithium within the slag, but the advantages are that the process requires little equipment and reduced processing time (Zanoletti et al., 2024).
    - Chemical processes (hydrometallurgy): The black mass is immersed in a bath of inorganic or organic acid with oxidizing agents to precipitate lithium salts (Li_3PO_4 or Li_2CO_3, depending on the acid added), the iron phosphate alloy (Choi et al., 2025; H. Li et al., 2017; Müller et al.,

2024), aluminium and copper (Carvalho et al., 2021). Lithium and iron phosphate compounds can be used in new cathodes (Choi et al., 2025 Research is underway to optimize the hydrometallurgical process (Golmohammadzadeh et al., 2023). Waste includes wastewater containing reagents and salts, air pollutants such as dust, HF, VOCs, HCl mist, and solid waste consisting of metal scraps (aluminum, copper), plastics, and graphite (Quan et al., 2022). Environmental disadvantages include large amounts of chemical inputs and difficulty in wastewater treatment (Van Beek et al., 2025).
    - Foam flotation: a technique that combines physical and chemical processes to separate materials. The hydrophobic nature of graphite and plastic is exploited to separate these materials from the rest of the black mass (Müller et al., 2024). Flotation has been successful for several lithium-ion batteries, but the scientific literature presents conflicting results on its specific success for LFP batteries (Rieger et al., 2025; C. Wang et al., 2024).
- Direct recycling: After disassembly, using the methods described above, reusable components from one battery are further processed and placed in a new battery (Feng et al., 2022a). An example is cathode regeneration and its subsequent use in a different battery. This process is currently being tested, but has not yet reached the industrial level (Van Beek et al., 2025).
- Landfilling: The battery is disposed of together with other municipal solid waste or other electronic waste. Disposal of batteries is not recommended.

7 POWER-TO-HYDROGEN-TO-POWER (P2H2P)

7.1 POTENTIAL FOR INTEGRATION INTO ENERGY COMMUNITIES

Hydrogen is an energy carrier capable of storing and releasing significant amounts of energy per unit mass, without producing CO_2 emissions during its use. The hydrogen produced can also be further processed as required, for example into ammonia, methane, methanol or other chemicals used in industry.

Hydrogen can be integrated into a REC through the Power-to-Power (PtP) process, also known as Power-to-Hydrogen-to-Power (P2H2P), in order to more efficiently manage the flow of renewable energy to users. A technical explanation is provided in Section 7.2. The first step is Power-to-Hydrogen, in which renewable energy, such as solar or wind, is converted into hydrogen via an electrolyzer and subsequently stored. The next step is Hydrogen-to-Power, in which hydrogen is converted back into electricity via a fuel cell.

The excess energy produced can then be converted into hydrogen, stored for long periods of time (Oxford Institute for Energy Studies, 2025) and subsequently used to cover energy needs when sources such as solar or wind are not available or are unreliable (Lokar & Virtič, 2020). In this context, the EU-funded project "Hydrogen Storage and Fuel Cells for Optimised Renewable Energy Communities" (H2SCORE) is investigating the integration of hydrogen technologies in RECs (Polytechnic University of Turin, 2025).

Additionally, (G. Raimondi & Spazzafumo, 2023), by dividing a REC into two communities with a 60%-40% ratio and using the excess energy produced by the first (REC1) to produce, through an electrolyser, hydrogen to be stored and subsequently used in the second REC (REC2) for the production of electricity through fuel cells, it is possible to increase self-consumption from 68,6% to 83,7%. Furthermore, the flow of renewable energy sold to the grid is reduced from 69,5% to 9,1%. A diagram of the REC system with photovoltaic/wind and P2H2P described in (Giulio Raimondi, 2023) is reported in Figure 7-1 .

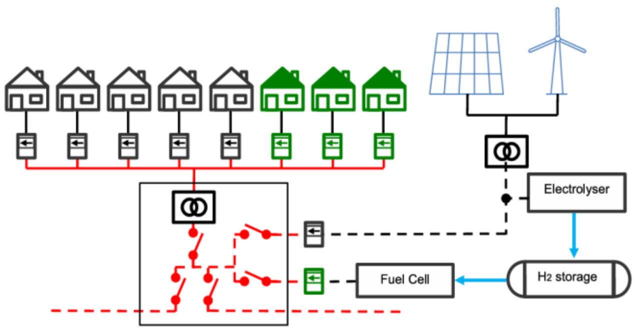


Figure 7-1. Renewable energy community configuration with hydrogen (G. Raimondi & Spazzafumo, 2023)

(Lokar & Virtič, 2020) tested the self-consumption of a residential pilot system consisting of a 6,7 kWp PV system integrated with P2H2P, obtaining a self-consumption of 62%. The authors also highlight how the integration of an electrochemical storage system can bring additional benefits. A diagram of the system with photovoltaic/wind, P2H2P and battery is shown in Figure 7-2. Configuration of a system Integrated with hydrogen, wind turbines unit, photovoltaic panels, and auxiliary battery storage. WT = wind turbines and PV = photovoltaic (Arsalis et al., 2022).

The integration of a hydrogen P2H2P system between two RECs is therefore a particularly effective solution to increase self-consumption and reduce the energy fed into the grid, although to date it is not yet economically viable due to the high costs associated with hydrogen storage and fuel cells (G. Raimondi & Spazzafumo, 2023).

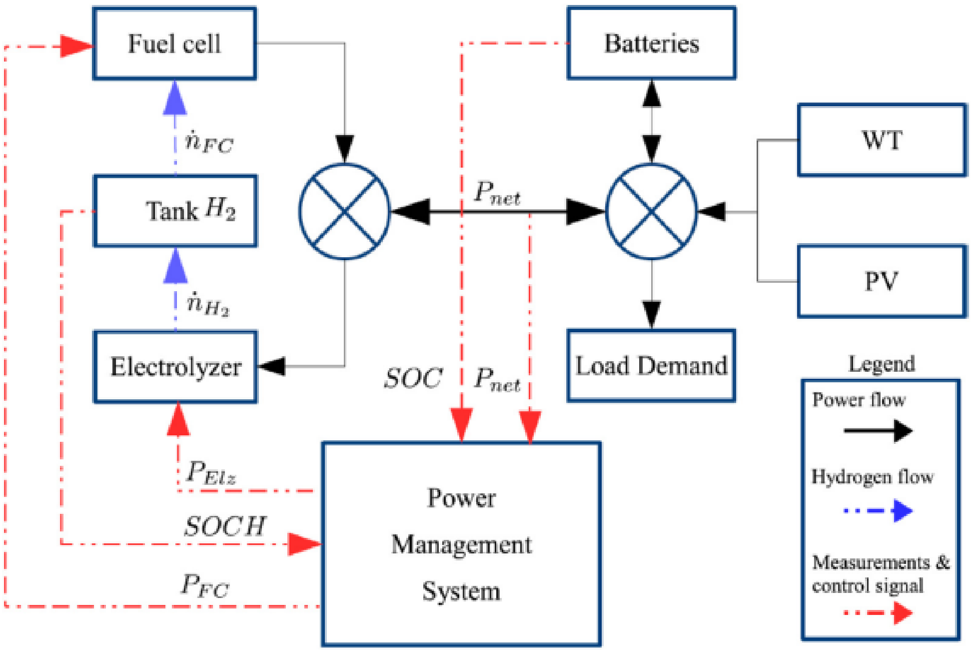


Figure 7-2. Configuration of a system Integrated with hydrogen, wind turbines unit, photovoltaic panels, and auxiliary battery storage. WT = wind turbines and PV = photovoltaic (Arsalis et al., 2022)

7.2 Technical information

A P2H2P system consists of three main components: the electrolysis system, the storage facility, and the fuel cell system.

7.2.1 Electrolysers

An electrolysis system consists of a combination of several components, such as power supply, water treatment system, electrolyzer stack, process consumers, process cooling, gas cooling, gas purification, and gas compression, necessary to operate the electrochemical conversion units under the expected operating conditions (temperature, pressure, water quality, etc.). The electrolyzer stack is composed of multiple electrolyte cells, the different chemistries of which are discussed in the following sections. In addition to these components, there are storage tanks, pipes, ducts and control systems. The whole system is called the balance of plant (BoP). Figure 7-2 shows the electrolysis system for alkaline water electrolysis (AWE) technology (Tsotridis & Pilenga, 2018). Inside the stack, in each cell, electrical energy is used to separate a medium, in most cases water, producing oxygen and hydrogen.

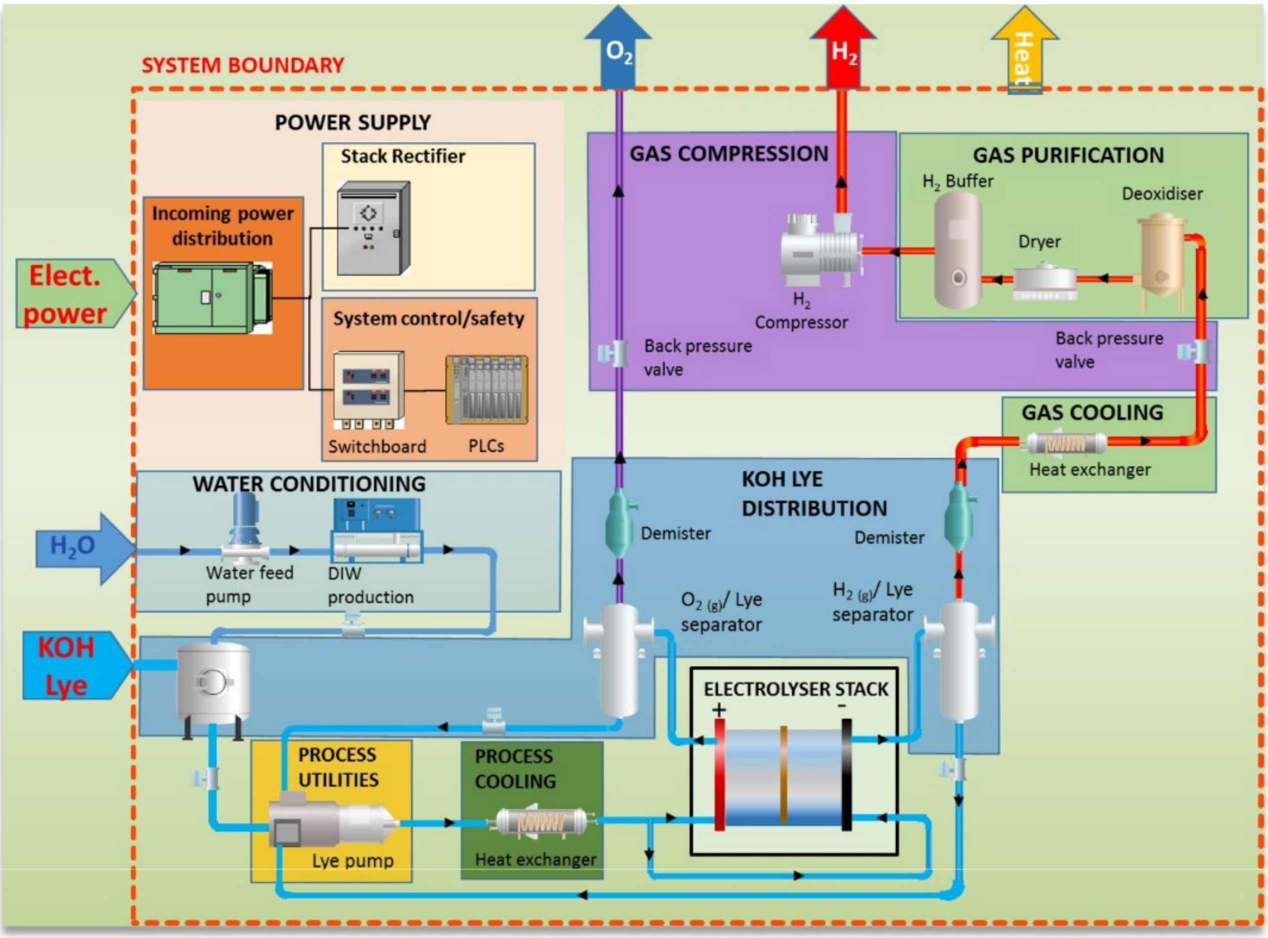


Figure 7-2. Electrolysis system based on AWE cell technology (Tsotridis & Pilenga, 2018)

There are four main electrolyser technologies for the production of green hydrogen, the characteristics of which are listed below (Akyüz et al., 2024). Figure 7-4. Diagram of four electrolysis technologies: (a) AWE, (b) PEM, (c) SOEC and (d) AEM (K. Zhang et al., 2022) shows diagrams of the four technologies.

- AWE is the most traditional and operates at low temperatures (60 - 80°C) with high concentrations of KOH as an electrolyte. In addition, this technology allows the use of non-noble and cheap materials.
- Proton exchange membrane (PEM) electrolyzers use a solid polymer electrolyte membrane to conduct protons and facilitate the separation of hydrogen and oxygen. PEM water electrolysis is considered one of the most promising and popular technologies, due to its compact cell size, high efficiency, and remarkable current density capabilities.
- Anion exchange membrane (AEM) electrolyzers employ an alkaline membrane as the electrolyte. AEM electrolyzers offer the advantage of using cost-effective catalysts, resulting in a significant reduction in system costs. However, AEM electrolyzers face disadvantages such as a lower current density than PEM and a shorter operating life. Despite these limitations, the potential to improve the current densities and durability of AEM technology is evident as it continues to progress. Currently, AEM electrolyzers are available in systems up to 5 kW with a system efficiency of up to almost 70% and temperatures ranging from 40 to 80 °C.
- Solid oxide electrolyzer cells (SOEC), also called solid oxide elctrolysers (SOE), are a type of water electrolyzer that operates at higher temperatures than other technologies. A solid ceramic material is the electrolyte. When a current is applied, the water fed into the cathode converts to hydrogen gas and oxide ions. The oxide ions then travel to the anode, where they react to form

oxygen gas and release electrons for the external circuit. Then a SOEC cell uses electricity to produce fuel through the process of electrolysis.

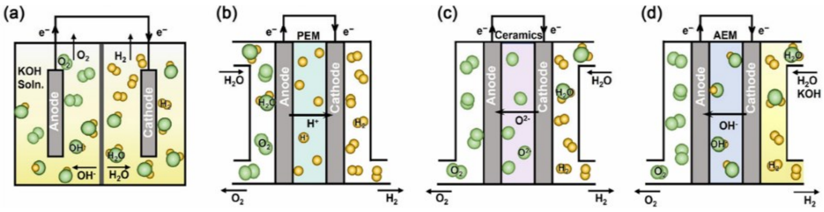


Figure 7-4. Diagram of four electrolysis technologies: (a) AWE, (b) PEM, (c) SOEC and (d) AEM (K. Zhang et al., 2022)

7.2.2 Storage

Hydrogen storage is a crucial aspect, given its wide range of applications. Due to its low density at room temperature, its volumetric energy density is also limited. For this reason, several storage methods have been developed that can store it in conditions that increase its energy density per unit volume.

Hydrogen can be stored in three main ways (Mulky et al., 2024; Singla et al., 2021):

1. Compressed or gaseous storage (at pressure 350 - 700 bar). Compressed H_2 tanks operate under extreme stress and should be inspected regularly to ensure their safety. Despite being required by law, high-pressure tank checks are rarely necessary.
2. Cryogenic or liquid storage (at 20,28 K or -252,87 °C). A technique used for storing H_2 gas at very low temperatures, usually below its boiling point of -252,87 °C, is known as cryogenic hydrogen storage. Hydrogen can be stored for a longer period by being cooled to such low temperatures, which turns it into a liquid with a significantly higher density. The enclosures are made of materials such as stainless steel or aluminum and are normally highly insulated.
3. Electrochemical storage or solid storage in the form of a chemical compound in porous materials. Chemical hydrogen storage, also known as hydrogen atom storage, is the practice of storing hydrogen in a form that allows for large storage densities because hydrogen atoms have a powerful interaction with the primary material. This method suffers from poor kinetic efficacy of H_2 ad/desorption, which greatly limits the applicability of this technique. However, the physical storage of H_2 is superior because H_2 is adsorbed in the molecular state and has a weaker bond with the parent component.

7.2.3 Fuel Cells

The main components of a fuel cell system are the humidifier, cell stack, cooling system, power conditioning unit, and condenser, as shown in Figure 7-5. Diagram of a fuel cell system (Nik Zaiman et al., 2022). There are multiple cells inside the stack, connected in order to obtain the desired voltage and power. Inside each cell is the membrane electrode assembly, i.e. the electrode-membrane assembly in which the electrochemical reaction takes place. There are several cell technologies; six main ones are illustrated below, the diagrams of which are shown in Figure 7-3 - Figure 7-11. Direct methanol fuel cell (Viet Long et al., 2012). The hydrogen fed into the system can come from electrolysis or from thermal, photochemical, or biological processes (U.S. Department of Energy, s.d.-a). As reported in Equation 6, the overall reaction inside the fuel cell consists of the combination of hydrogen and oxygen, with the production of water, electricity and heat (EG&G Technical Services, Inc., 2004).

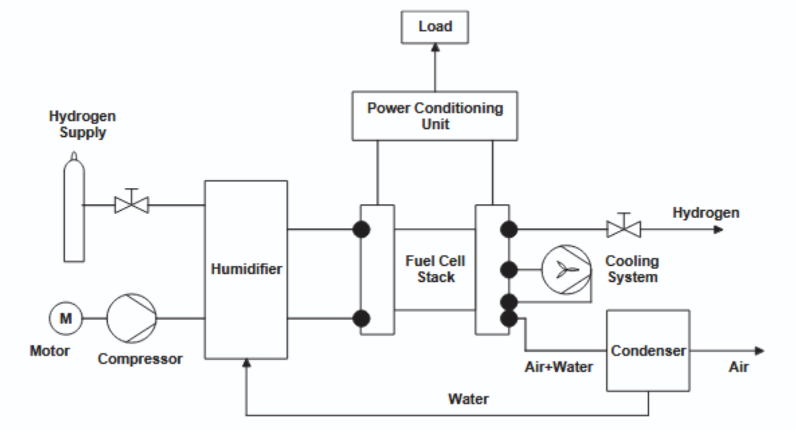


Figure 7-5. Diagram of a fuel cell system (Nik Zaiman et al., 2022)

$$2H_2(g) + O_2(g) = 2H_2O\ (g) + electricity + heat \qquad (6)$$

The cell chemistries are as follows (Singla et al., 2021):

- Alkaline Fuel Cell (AFC): The cell has a potassium hydroxide electrolyte and operate at temperatures between 60 and 120 °C. They are technologically mature, but their use is mainly limited to specialized applications such as military and space, requiring extremely pure feed gases. Generally, KOH is the electrolyte used in this type of cell. Usually, 85% concentration of KOH is used for high-temperature operations, while 35 to 50% concentration is used for low-temperature operations. A typical alkaline fuel cell might operate between the temperature ranges of 50 and 200 °C.
- Polymer and Electrolyte Membrane Fuel Cell, also called a Proton Exchange Membrane Fuel Cell (PEMFC): The cell has a polymer membrane with high proton conductivity as an electrolyte and operate at temperatures between 70 and 100 °C. They are widely used in traction and small-scale generation/cogeneration (1 - 250 kW). It consists of a solid membrane electrolyte made up of a polymer called perfluorosulfonic acid (commercially known as Nafion). This membrane electrolyte acts as a proton exchange medium between the anode and cathode of the PEMFC. This is the most widely used fuel cell due to its fast start-up time and shutdown time and simplicity. Its operating temperature ranges from 50 to 100 °C and the efficiency is between 40 and 60%.
- Phosphoric Acid Fuel Cell (PAFC): As the name suggests, phosphoric acid with a concentration of 100% is used as an electrolyte in this type of cell. Its operating temperature is between 150 and 220°C. The electrocatalyst used is reportedly generally platinum, both on the anode and cathode side. The charge carrier in this fuel cell is H+ ions. Because PAFC involves external reforming of the fuel, it takes hours to start working. The performance of this cell is lower than that of the alkaline fuel cell. It is the first conventional fuel cell to be commercialized.
- Molten Carbonate Fuel Cell (MCFC): The cell uses a molten solution of alkaline carbonates as an electrolyte at the operating temperature of the cell (650°C), especially suitable for electricity generation and cogeneration from a few hundred kW to a few tens of MW. Carbonate ions are the charge carriers in the cell, and nickel acts as a catalyst. The end plates of this fuel cell are made of stainless steel to prevent corrosion, and the fuels used are CH4, H2, and CO2. The efficiency of MCFC ranges from 55 to 65%.
- Solid Oxide Fuel Cell (SOFC): The electrolyte used in this cell is a solid, non-porous metal oxide. Its operating temperature is between 700 and 1000°C. This cell has the highest operating temperature among all fuel cells. O= ions are the charge carriers, and the

catalysts used in this cell consist of perovskite. The primary components of the cell are ceramic. The efficiency of this cell is similar to that of MCFC, and the power density of this cell is between 1,5 and 2,6 (kW/m^3).

- Direct Methanol Fuel Cell (DMFC): The cell operates at temperatures between 80 and 100°C and use a polymer membrane as an electrolyte, developed primarily for portable applications. This fuel cell is also known as a direct methanol proton exchange fuel cell. It is a special type of low-temperature fuel cell that works on the principle of PEMFC. Various components of DMFC are two bipolar end plates that act as an anode and cathode, catalysts, and an electrolyte membrane. In this type of fuel cell, H+ ions are the charge carrier and the platinum-based material acts as a catalyst. The main fuel in typical DMFC is methanol, and the average cell efficiency is up to 30 – 40%.

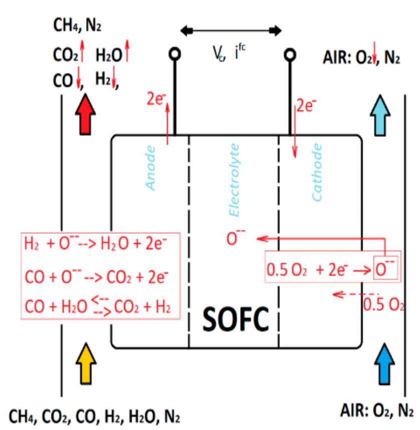


Figure 7-3. Solid oxide fuel cell core fed with a reformed or syngas stream (Corigliano et al., 2022)

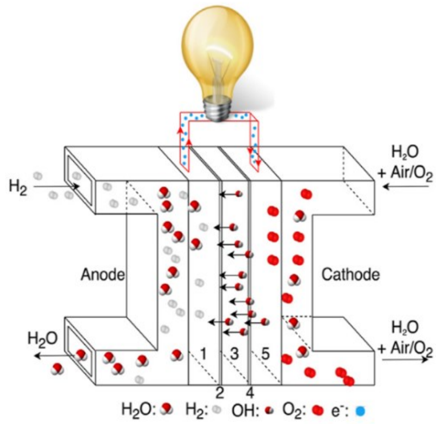


Figure 7-7. Alkaline fuel cell (Ferriday & Middleton, 2021)

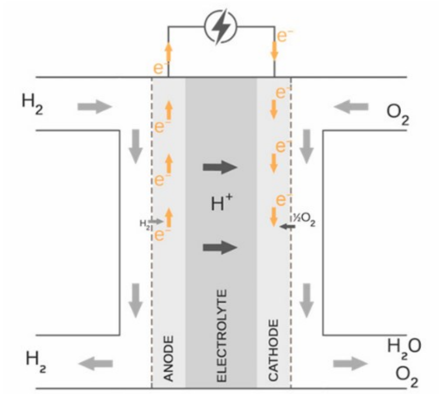


Figure 7-8. Polymer and electrolyte membrane fuel cell (Shuhayeu et al., 2024)

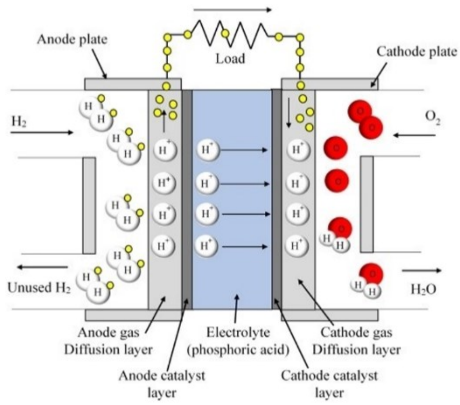


Figure 7-9. Phosphoric acid fuel cell (Gupta et al., 2024)

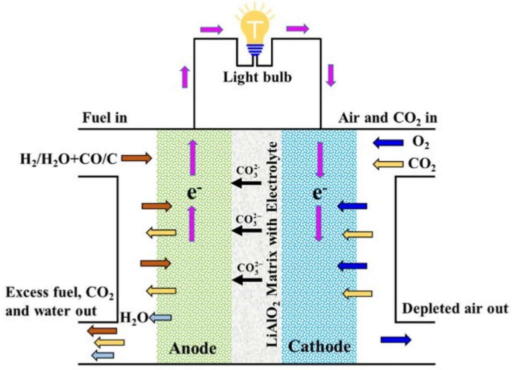


Figure 7-10. Molten carbonate fuel cell (Gao et al., 2023)

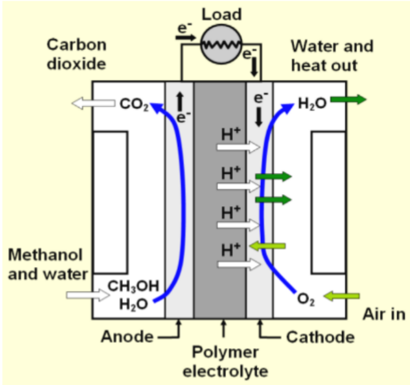


Figure 7-11. Direct methanol fuel cell (Viet Long et al., 2012)

7.2.4 Technical Parameters

This section presents the technical parameters taken from the literature and from the technical data sheets. A list of standardised terminology and equations relating to low-temperature electrolysis in aqueous solution is available in (Tsotridis & Pilenga, 2018). Figure 7-1 presents the operating parameters of four electrolyser technologies and Figure 7-2. Configuration of a system Integrated with hydrogen, wind turbines unit, photovoltaic panels, and auxiliary battery storage. WT = wind turbines and PV = photovoltaic (Arsalis et al., 2022) presents the parameters of four models currently available on the market. Figure 7-2 lists operating parameters of four fuel cell technologies and Figure 7-4. Diagram of four electrolysis technologies: (a) AWE, (b) PEM, (c) SOEC and (d) AEM (K. Zhang et al., 2022) provides the technical parameters of four fuel cell models currently available on the market.

Table 7-1. Technical data from the literature for different electrolyser technologies (Nasser et al., 2022)

Technology	PEM	AWE	AEM	SOEC
Operational temperature	70 - 90 °C	65 - 100 °C	50 - 70 °C	650 - 1000 °C
Operational pressure	15 - 30 bar	2 - 10 bar	up to 35 bar	<30 bar
Efficiency	67 - 84%	62 - 82%	-	90%
Duration	< 40.000 hours	< 90.000 hours	> 10.000 hours	< 40.000 hours
Cell voltage	1,80 – 2,40 V	1,80 – 2,40 V	~ 1,85 V	0,95 – 1,30 V
Energy consumption	4,5 – 7,5 kWh/Nm³	4,5 - 7 kWh/Nm³	~ 4,8 kWh/Nm³	2,5 - 3,5 kWh/Nm³
Start-up duration	<15 minutes	15 minutes	-	>60 minutes

Table 7-1. Data sheets for different models of electrolysers available on the market

Model	**Silyzer 200 PEM Siemens Energy**	**Pressurized alkaline electrolysis McLyzer 200 AWE**	**AEM NEXUS 1000 (Enapter)**	**SOE HSL-25 (H2Electro)**
Power class	1,25 MW	1 MW	968 kW	25 kW
Duration	> 80.000 hours	>20 years	-	-
Nominal fow rate of H_2	20 kg/h 225 Nm^3/h	200 Nm^3/h	210 Nm^3/h 453 kg/24 h (O_2 flow= 105 Nm^3/h)	15,4 kg/24 h 7,1 Nm^3/h
Operating temperature	-	-	-	800-850°C
Purity H_2	99,5% - 99,9%	>99,998% after cleaning of the gas	99,95%	-
Delivery pressure H_2	Up to 35 bar	27 a 30 bar	Up to 35 bar	-
Consumption	-	4, 7 kWh/Nm^3 (DC) 5,1 kWh/Nm^3 (AC)	4,6 kWh/Nm^3H_2	-
Efficiency	-	-	51,3 kWh/kgH_2	86%
Operational field	-	20 - 100 %	1 - 100%	-
Reaction time	<10 sec start-up time (from cold standby)	<30s from hot stand-by to the 100% of the electrical load	0 - 100% in 135s (start a caldo)0 - 100% in 25 min (start a cold)	-
Ramp-up	-	>5%/s	-	-
Ramp-down	-	20%/s	-	-
Electrolyte	-	Solution aqueous KOH to the 30%	-	-
Citation	(Siemens Energy, 2020)	(McPhy, 2023)	(Enapter Handbook, 2026)	(H2Electro, n.d.)

Table 7-2. Technical data from the literature for different models of fuel cells (GenCell, n.d.)

Fuel Cell Technology	**PEMFC**	**PAFC**	**MCFC**	**SOFC**
Temperature operational	<120°C	150 - 200°C	600 - 700°C	500 - 1000°C
Typical stack size	<1 - 100 kW	5 - 400 kW, 100 kW module	300 kW - 3 MW, 300 kW module	1 kW - 2 MW
Efficiency	60% direct hydrogen; 40% reformed fuel	40%	50%	60%
Start-up time	< 1 minute	-	10 minutes	60 minutes

Table 7-3.Data sheets for different models of fuel cells available on the market

Fuel Cell Model	**HyModule S8 (PEMFC) Proton Motor Fuel Cell GmbH**	**Hyaxiom Pure Cell Model 400 Hydrogen (PAFC)**	**1500 Carbonate Fuel Cell System (MCFC) FuelCell Energy**	**SolydEra G8X (SOFC) SolydEra**
Operating Temperature	-	-	-	650 - 800°C
Stack size	8,4 kW	440 kW	1.250 kW	10 kW
Efficiency	<57%	90%	50%	63%
Hydrogen supply pressure	1,5 – 7,5 bar	-	15 – 20 psig	-
Hydrogen consumption	0,6 kg/h	26.4 kg/h	9,250 SCFH (0 – 50% hydrogen fuel mixture)	-
Voltage	-	480 VAC	480 VAC	>120V
Duration	-	-	-	60.000 h
Citation	(Proton Motor, 2023)	(HyAxiom, 2023)	(FuelCell Energy, 2026)	(SolydEra, n.d.)

7.2.5 Safety and Regulations

There are several challenges related to safety on the use, storage and transport of hydrogen due to the following characteristics (Calabrese et al., 2024):

- High reactivity due to its particular chemical-physical properties;
- Low ignition energy: an order of magnitude lower than that of hydrocarbons;
- Tendency to evaporate: this can cause safety problems and economic losses;
- Wide flammability limits: 4-75% in air, very wide compared to methane (different ATEX category);
- Transition from deflagration to detonation: the transition can occur easily and is often observed in the case of a high-scale-system;
- High combustion rate: the laminar combustion rate is significantly higher than that of many other fuels;
- Hydrogen is colorless, odorless, and tasteless: additives cannot be added easily;
- High reactivity with materials (embrittlement): huge investments are required for the investigation of materials;
- Low density and diffusivity of the gas: particular behavior in case of release, and can stratify in the upper part of confined spaces.

According to (Calabrese et al., 2024), there have been 208 major hydrogen-related accidents in the last 50 years. One can see the initial event that led to the loss of hydrogen in accidents and the incident category in Figure 7-12. Initial event that led to a leak of hydrogen (Calabrese et al., 2024) and Figure 7-13. Category of the incident (Calabrese et al., 2024), respectively.

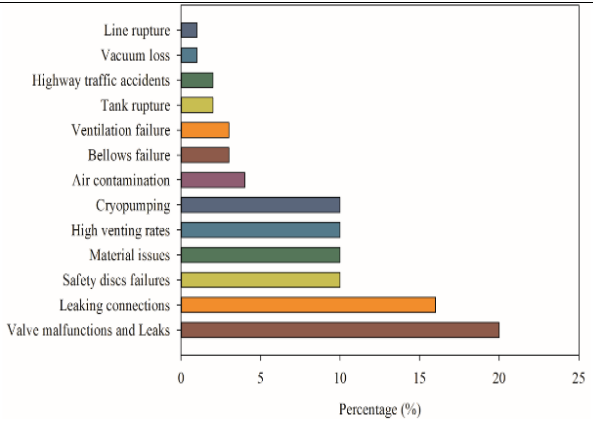


Figure 7-12. Initial event that led to a leak of hydrogen (Calabrese et al., 2024)

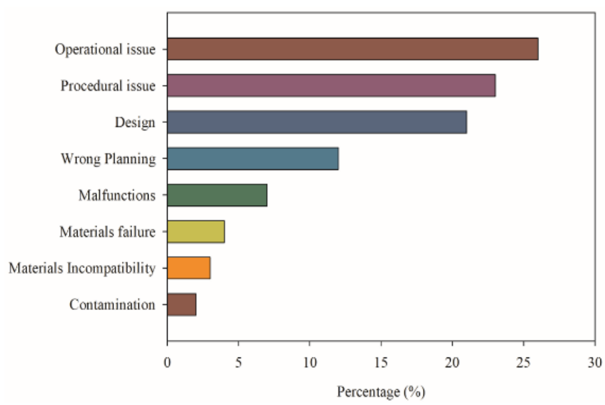


Figure 7-13. Category of the incident (Calabrese et al., 2024)

For the production and use of the P2H2P process, there are various European standards to be complied with, listed in the Table 7-4 (Calabrese et al., 2024).

Table 7-4. European standards for the P2H2P process

Hydrogen Value Chain Stages	**European Standards**
Production (electrolysis)	CEN-CENELEC
Storage and transport (pipeline, storage, cryogenic tank)	ISO 19884-1, EIGA Doc: 171/23, 15/21, 121/14, 6/19; SAE J2579/1; NrFPA 55:2025; NFPA 2:2023.
End-use (fuel cell mobility, refueling)	ISO 19880-1:2020, ISO 14687:2025; SAE J2579/1; CEN-CENELEC
Process control (sensors and detectors)	IEC 60079-29-1:2016; SAE J3089:2018; CEN-CENELEC; EN ISO 26142:2010; NFPA 2.

7.3 Economic Data

The main CAPEX and OPEX of a P2H2P plant are incurred for the installation, maintenance and operation of electrolysers and fuel cells.

The CAPEX of the electrolyser system consists of the following costs (European Hydrogen Observatory, 2024):

- Stack: The electrolysis cells and their components.
- BoP: The rectifier, transformer directly connected to the rectifier, gas/liquid separation, water/lye supply, gas purification, water cooling, water purification, control system and gas container, and compressor.
- Engineering, Procurement and Construction: The installation of equipment; civil engineering; design, procurement and project management; shipping of products; and housing on site.

An important figure to consider is the levelized cost of hydrogen production through electrolysers using energy from renewable sources. This value stands at around €6,61/kgH_2 for the EU (European Hydrogen Observatory, 2024). Table 7-5 provides CAPEX and OPEX values from the literature for four electrolyzer chemistry configurations. The Table 7-6 reports the same economic data for 4 chemical configurations of fuel cells.

Table 7-5. Economic data from literature for different models of the electrolysers

Technology	**PEM**	**AWE**	**AEM**	**SOE**
CAPEX	1.970 €/kW	1.666 €/kW	1.000 $/kW	1.192 €/kW
OPEX [€/year]	64 €/kW/yr	43 €/kW/yr	0,5% CAPEX	3% CAPEX
Citation	(European Hydrogen Observatory, 2024)		(James et al., 2024)	(Bühler & Möst, 2025)

Table 7-6. Economic data from literature for different models of fuel cells

Technology	**PEMFC**	**SOFC**	**PAFC**	**MCFC**
CAPEX	2500€/kW	10,000 €/kW	4000-5000 €/kW	4000-6000€/kW
OPEX [€/year]	0.1€/kWh	0.1€/kWh	1.4% CAPEX	1.4% CAPEX
Citation	(Clean Hydrogen Partnership, 2022)		(Cigolotti et al., 2021)	

7.4 Environmental Impacts

LCAs can be applied to P2H2P system components.

Table 7-7 reports environmental and human health impact for AWE, PEM, SOEC and AEM electrolyser cells and for PEMFC, SOFC and MCFC fuel cells. As discussed in Section 1.2.2, the reader is suggested to dig deeper into the citation for specific details.

Table 7-7. Environmental impacts of various model of electrolyser and fuel cells

Technology	Chemistry	Climate Chang Potential/Functional Unit	Scarcity of Resources Abiotic/Functional Unit	Human health/ Functional Unit	Health of the Ecosystem/ Functional Unit	Functional unit	Citation
Electrolyser	AWE	778 t CO_{2eq}	MRS: 121 t Cu_{eq}	HTP_c: 1.917 t 1,4 DCB_{eq}	-	1 element: system AWE from 5 MW	(Hoppe & Minke, 2025)
	PEMEC	1.800 kg CO_{2eq}	MRS: 460 kg Cu_{eq}	HTP_c: 230 kg 1,4 DCB_{eq} HTP_{nc}: 29.000 kg 1,4 DCB_{eq}	TA: 130 kg SO_{2eq}	1 m² of the area of the stack -	(G. Zhao et al., 2020)
	SOEC	109,3 kg CO_{2eq}	MRS: 6,5 kg Cu_{eq}	HTP_c: 21 kg 1,4 DCB_{eq} HTP_{nc}: 1.800 kg 1,4 DCB_{eq}	TA: 23 kg SO_{2eq}		
	AEM	99,2 kg CO_{2eq}	ASR: 3.359 ELU	HH: 2,5 x10^{-4} DALY	EQ: 44,8 PDFm^2yr	Stack from 1 kW	(Wei et al., 2024)
Fuel cell	PEMFC	112 kg CO_{2eq}	ADP: 1,9 x10^{-3} kg Sb_{eq}	HTP: 228 kg DCB_{eq}	AP: 2,1 kg SO_{2eq}	1 kWe of PEMFC and 20.000 h of funzionamentoElettrolisi of the H_2 used	(Stropnik et al., 2019)
	SOFC	0,6 kg CO_{2eq}	FRS: 5,46 x10^{-3} kg oil_{eq}	HTP_c: 5,3 x10^{-2} kg 1,4 DCB_{eq} HTPnc: 3,3 x10-2 kg-andDCB	TA: 5 x10^{-4} kg SO_{2eq}	1 kWh of electricity produced	(Naeini et al., 2022)
	MCFC	0,3 kg CO_{2eq}	ADP: 1,9 x10^{-3} kg Sb_{eq}	-	AP: 3,05 x10^{-4} kg SO_{2eq}	1 kWh of electricity product from MCFC from 2.5 MW	(Kim et al., 2021)

ELU = Unit of load environmental, DALY = Years of life adjusted for disability, DCB = Dichlorobenzene, HTPc = Potential of toxicity for the humans, carcinogenic, HTPnc = Potential of toxicity for the humans, non-carcinogenic, TA = Acidification terrestrial, EQ = Quality environmental, ABS = Resources abiotic of basis, ABD = Potential of exhaustion abiotic, elements, MRS = Scarcity of resources mining, AP = Acidification potential, FRS = Scarcity of fossil resources

7.4.1 End of Life Management and Circularity

The focus on end-of-life is currently on PEM electrolysers and fuel cells, due to the difficulty in finding a sufficient quantity of the critical raw materials. PEM technologies contain numerous critical materials such as titanium, nickel, natural graphite, manganese and platinum group metals (PGMs). Given the quantities and assessed risk, PGMs are currently the only ones classified as "high risk" by the European Commission. On a technical level, recycling is already feasible for about 90% of the materials in a stack thanks to European hydrometallurgical chains capable of returning high-quality PGMs; Digital watermarks and product passports are being tested to identify the composition before treatment. Very few PEM stacks have already reached EoL. Economically attractive EoL flows will emerge only in the second half of the 2030s, when installed capacity will have generated sufficient waste. Repair and reuse strategies are studied in much less detail. Current projects of the European Clean Hydrogen Initiative and the EU focus on the eco-design of fuel cell and hydrogen products to facilitate future repairability and exchangeability of subcomponents (Axt et al., 2025).

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