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Review article

End-of-life of renewable energy technologies in urban environments. A state-of-the-art on installation trends, materials, and best practices in the EU

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A R T I C L E I N F O

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A B S T R A C T

The European Commission is promoting the production of thermal energy and electricity from renewable sources, coupled with storage systems, to decarbonize the built environment. However, these technologies use prevalently virgin raw materials, and end-of-life (EoL) circular frameworks are still difficult to be implemented due to technical, regulatory, and market barriers. This paper aims to present a state-of-the-art on the trends in installation, materials, EoL strategies, and companies active in renewable energy systems recycling. Solar, wind, and geothermal sources are examples of technologies easily incorporated into cities. The purpose is to provide information to stakeholders that should design technical solutions according to circularity criteria. The information, from both scientific and grey literature, showed that solar technologies represent the most widespread

Abbreviations: Ag, Silver; Al, Aluminum; a-Si, Amorphous Silicon; BNEF, BloombergNEF; BREEAM, Building Research Establishment Environmental Assessment Methodology; C, Carbon; CAGR, Compound Annual Growth Rate; CCS, Calcium Chloride Solution; Cd, Cadmium; CDW, Construction and demolition waste; CdS, Cadmium Sulfide; CdTe, Cadmium Telluride; CE, Circular Economy; CENELEC, European Committee for Electrotechnical Standardization; CIGS, Copper Indium Gallium Selenide; CIS, Copper Indium Selenide; CLSM, Controlled Low Strength Material; CNTs, Carbon Nanotubes; Co, Cobalt; CSP, Concentrating Solar Power plants; c-Si, Crystalline Silicon; Cu, Copper; DHW, Domestic Hot Water; DSSC, Dye-Sensitized Solar Cell; EAHX, Earth-Air Heat Exchanger; EC, European Commission; EGS, Ethylene Glycol Solution; EIT, European Institute of Innovation and Technology; EoL, End-of-Life; EPDM, Ethylene Propylene Diene Monomer; EPR, Extended Producer Responsibility; EPS, Expanded polystyrene; ERP, European Recycling Platform; ESS, Energy Storage Systems; EU, European Union; EUCOBAT, European Association of National Battery Collection Systems; EV, Electric Vehicle; EVA, Ethylene-Vinyl Acetate; F, Fluorine; Ga, Gallium; GaAs, Gallium Arsenide; GFRP, Glass Fiber Reinforced Plastics; GHE, Ground Heat Exchanger; GHG, Greenhouse Gas; GSHP, Ground Source Heat Pumps; GW, Gigawatt; GWEC, Global Wind Energy Council; GWe, Gigawatt electrical; GWh, Gigawatt hour; GWth, Gigawatt Thermal; GWP, Global Warming Potential; H, Hydrogen; HC, Hot Carrier; HDPE, High-Density Polyethylene; HFCs, Hydrofluorocarbons; HJT, Heterojunction solar cell; HTF, Heat Transfer Fluid; HVAC, Heating, Ventilation, and Air Conditioning; IAQ, Indoor Air Quality; IGA, International Geothermal Association; In, Indium; IRENA, International Renewable Energy Agency; ITES, Institute for Technical Energy Systems; LCA, Life Cycle Assessment; LEED, Leadership in Energy and Environmental Design; LFP, Lithium-iron-phosphate; Li, Lithium; LIB, Lithium-based battery; Mo, Molybdenum; MPG, Monopropylene Glycol; MW, Megawatt; MWe, Megawatt electrical; MWth, Megawatt Thermal; N, Nitrogen; Ni, Nickel; NiCd, Nickel-cadmium; NICE, Non-Invasive Crystalline Encapsulation; NiMH, Nickel-Metal Hydride; NREL, National Renewable Energy Laboratory; nZEB, net Zero Energy Building; O, Oxygen; OPV, Organic Photovoltaic; PB, Polybutylene; Pb, Lead; PCM, Phase Change Material; PE, Polyethylene; PERC, Passivated emitter rear contact solar cell; PET, Polyethylene Terephthalate; PGS, Propylene Glycol Solution; PK, PET/Kyner; PP, Polypropylene; PPE, PET/EVA; PSCs, Perovskite Solar Cells; PUR, Polyurethane; PV, Photovoltaic; PV/T, Photovoltaic/Thermal; PVF, Polyvinyl Fluoride; PVC, Polyvinyl Chloride; QDs, Quantum Dots; R410A, Refrigerant 410A; SCS, Sodium Chloride Solution; SDG, Sustainable development goal; Se, Selenium; Si, Silicon; SLB, Second life battery; Sn, Tin; ST, Solar-thermal; Te, Tellurium; TES, Thermal Energy Storage; TFPV, Thin-film Photovoltaic; TOPCon, Tunnel oxide passivated contact solar cell; TPT, PET/Tedlar; UK, United Kingdom; US, United States; UTES, Underground Thermal Energy Storage; WB, Waste Batteries; WEEE, Waste Electrical and Electronic Equipment; WEEELABEX, WEEE Label of Excellence; XPS, Extruded polystyrene; Zn, Zinc; ZnO, Zinc Oxide.

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type of systems, with a considerable number of best practices and companies specialized in recycling. Wind technology follows in installation trends and activity of reuse-oriented companies. Geothermal, on the other hand, offers a reduced number of reference examples. Furthermore, this review provides an overview of the installation and potential EoL scenarios of electrical and thermal energy storage systems, highlighting significant differences in the implementation of circularity strategies. The study closes with considerations and suggestions for practical applications.

Introduction

The adoption of the paradigm of circular economy (CE) has gained prevalence in relevant areas, such as environmental sustainability, productivity and green business success, and resource efficiency [1–4]. The transition from a linear to a circular model involves many obstacles such as the lack of economic, technological, and government support, and lack of public awareness [5]. The economy of the European Union (EU) was mainly linear, just thinking that the production of annual waste amounts to 2.2 billion tons and the rate of recycled materials reintroduced into the economy amounted to only 12 %. The EU has been committed for over a decade to updating existing legislation and addressing waste management to reduce negative impact on the environment, improving security of supply of raw materials and promoting competitiveness, innovation, and employment [2,6].

In 2015, the First Action Plan for the Circular Economy was launched [7]. Between 2015 and 2019, a series of directives were enacted with the aim of promoting CE principles: the directive on the restriction of hazardous substances [8], the directive on packaging and own waste [9], and the directive on the reduction of plastic products [10]. Furthermore, considering the construction sector, 60 % of the current building stock will still be in use in 2050 with poor energy efficiency. The solution to this issue is defined in the new EU Action Plan for the Circular Economy, the "Renovation Wave" initiated by the European Green Deal [11] doubling renovation rates in the next 10 years by making buildings more efficient and focusing on: energy efficiency, circular economy, and affordability. In particular, in 2020, the Second Action Plan for the Circular Economy [12] introduced obligations related to the circular design of products and production processes of different areas. Successively, the European Parliament's 2021 legislative package identified buildings as a key sector, and aims to incentivize their decarbonization reducing methane emissions by 80 % by 2030. In 2022, the REPowerEU [13] was launched as a sustainable, affordable, and secure energy plan.

In fact, the European Commission (EC) states that the life cycle of buildings is responsible for: 50 % of total energy consumption, 50 % of raw material extraction, and 40 % of total greenhouse gas (GHG) emissions [14,15]. Although European regulations promote the installation of renewable energy systems to decarbonize buildings, key technologies such as wind turbines, photovoltaic (PV) panels, and batteries still use virgin rather than recycled raw materials [4].

Then, the energy sector plays an essential role in CE as material processing requires the use of electricity and heat. In this context, renewable energies are of primary importance to promote CE and contribute to sustainable development [1]. The most common forms of renewable energy are solar energy (thermal and photovoltaic) and biomass [16,17] due to their easy integration in an urban environment, functionality, and limited space requirement compared to others, such as geothermal and wind energies. The most important renewable energy infrastructure in Europe is solar and wind energy production. Going into detail, some researchers believe that PV solar energy has greater possibilities to power urban areas, while wind energy outside the city can supplement demand [18].

The present review manuscript aims to afford current literature knowledge and perspectives on some renewable energy technologies (solar, wind, and geothermal) to identify barriers and opportunities for their implementation towards a more circular and sustainable energy transition in Europe. Moreover, thermal and electric storage are considered as complementary technologies for the aforementioned renewable energy systems integration. This study analyzes and presents those CE strategies at the end-of-life (EoL) of renewable energy technologies in cities, emphasizing installation trends, materials, and best practices at the European level. This would serve as a guideline to stakeholders from the renewable energy industry and policymakers on promoting the extended products life cycle by guiding them on technical solutions and designs optimizing waste management approaches at the EoL phase, towards promoting a more sustainable and circular development in Europe.

Promoting sustainable energy efficiency in cities and buildings: The role of renewable energies

Cities require large amounts of materials and energy [19,20]. The strategic design and integration of innovative technologies and management, such as efficient energy districts, energy supply from renewable sources, and CE strategies, should aim at reducing energy consumption and carbon emissions promoting the implementation of urban plans for sustainable environments in cities [21–23].

Many energy and comfort related factors, such as heating, domestic hot water provision, ventilation, lighting, intervene in the energy efficiency of buildings and can relate to circular activities [24]. The promotion of energy efficiency of new buildings and renewable energy uptake have become among key regulatory priorities in Europe [5].

A building with almost zero energy balance is inspired from that being designed and constructed under the criteria of the Passivhaus standard. Other standards, such as BREEAM (Building Research Establishment Environmental Assessment Methodology) or LEED (Leadership in Energy and Environmental Design) certificates are used as a reference for the construction of nearly energy self-sufficient buildings. At European level, the Directive 2010/31/EU [25] defines the specific criteria for a building to be considered as having almost zero energy balance, nearly Zero Energy Building (nZEB), and this goal can be achieved by including energy production in site by means of renewable energy.

Among the strategies to improve the energy efficiency and reduce the environmental footprint of a building would be the integration of renewables energies, such as solar energy (PV or solar-thermal panels), geothermal, and aerothermal, which allows energy savings while reducing carbon dioxide (CO_2) emissions [21].

Renewable energy systems and urban planning in a circular economy framework

Trends in world urban population growth should be accompanied by sustainable energy models, supporting responsible energy consumption, and avoiding the intensive use of fossil resources [20,26]. It is essential to promote an energy efficient nexus among architecture, engineering, and urban planning. Transformative change in urban planning is fundamental to address city energy requirements by using renewable energy while promoting a circular urban metabolism [20]. Thus, renewable energy has a fundamental role within the energy and environmental context, also aligned with the EU objectives on mitigating and adapting the effects of climate change, reducing carbon intensity and GHG emissions, and diminishing energy dependence by design. In this sense and from policy recommendations, urban planning is evolving towards a more sustainable model; and cities are integrating renewable energies into public spaces, incentivizing the adoption of CE strategies [27]. The authors of the manuscript from Barragán-Escandón *et al.* (2017) [20] identified eleven renewable energy technologies that could be implemented towards circular cities: biofuels, biomass, biogas, waste, energy from the sea, wind power, geothermal, hydroelectric, solar PV, solar-thermal (ST), and thermoelectric solar. However, the resource availability, policies, costs, and stakeholder acceptance condition the adoption of these related circular renewable energy models.

The continuous improvements in the installations and usability of renewable energy systems have led to an expansion of their integration in buildings, thus being adapted to urban environments and public spaces of different characteristics. Moreover, the installation possibilities offered by renewable energies have boosted the self-consumption concept, although financial resource availability determines the investment in renewable solutions in some European regions [28]. According to the report from Kiviranta *et al.* (2020) [24], renewable energy systems are predominantly local, and being dependent on their respective regional conditions. The concept of community renewable energy is reported as elemental for the sustainable energy system transition, contributing to the energy autonomy achievement and the development of communities [29].

Energy transition and circular economy towards renewable energy acceleration

Current EU policies and agendas commit European countries to the goal of being climate neutral by 2050, by achieving net-zero emissions, evolving towards a decarbonized economy, and implementing sustainable energy models [5,30,31].

Systematic applications of the principles of CE in new energy production models would be essential to promote and achieve a successful low-carbon energy, and ecological and circular transitions in Europe [1,5,32,33]. From this process, waste originating from renewable energies would multiply in the coming decades [4,34]. To this extent, the energy sector would require rapid implementation of circular principles to adequately manage waste and optimize energy efficiency [4]. Thus, regarding energy is highlighted: the advance of fuels and energy vectors substitution by new ones with lower emissions; and promote and encourage diversification, savings, and energy efficiency, as well as the use of renewable energies [32]. In terms of environmental quality and ce. monitoring of polluting activities and contamination; promoting adequate management and treatment of construction and demolition waste (CDW) and renewable energy facilities; implementing and mapping of CE principles and objectives; and promoting actions towards the efficient implementation of optimal and sustainable resource systems, as reducing consumption of critical raw materials.

Energy transition efforts could demand significant material resources while generating substantial volumes of new types of waste. The renewable energy sector would evolve concerning the adoption of emerging technologies, such as the development and implementation of energy storage, and to ensure maintenance and replacement of new infrastructures. The principles of CE can support the energy sector to mitigate the effects of the transition changes by providing synergistic effects that include: circular models and activities with higher responsibilities from producers and industries, sustainable and circular designs to facilitate the reuse of infrastructure components, reduction of energy demand, optimization of recycling process to maximize material recovery [35,36]; and GHG emissions mitigation and reduction [3,24,32,37]. The study of Jakubelskas and Skvarciany (2023) [37] reported CE understanding by means of renewable energy and sustainable development, concluding that the following European countries: Sweden, Luxembourg, Ireland, Latvia, Estonia, Malta, the Netherlands, and Bulgaria are among the most efficient towards implementation of sustainable development goals (SDGs).

Scientific literature searches and scope of the study

The existing literature was explored to verify the availability of scientific papers presenting a state-of-the-art, and comparison of the end-of-life strategies and processes related to solar, wind, and geothermal energy. Thermal and electrical storage were also considered.

The literature search was conducted on the Scopus database, using the following inclusion criteria: temporal range of publication (2014–2024), subject area (Energy, Environmental Science, Materials Science, Engineering, Chemical Engineering), type of document (only reviews), language (English), source type (only journal), and publication stage (final paper).

Successively, a screening phase was completed considering the subjects and findings of each paper. This phase led to the exclusion of reviews which were considered as not relevant to the topics covered in this study.

Table 1 presents the research queries and the number of scientific papers provided by the Scopus database, in total and after the screening phase.

The results of the literature analysis highlighted a predominant scientific production on the EoL of PV technology (40 reviews), followed by the electrical storage (38); that it would be attributed due to the interest in the applied materials and the importance of these markets. Also, wind energy was well considered in 15 reviews. Thermal solar, geothermal, and thermal storage technologies received very limited attention (Table 1).

Thus, the literature search demonstrated the absence of review studies collecting information and providing comparisons on the different renewable energy systems and energy storage in European countries.

Considering this lack in the literature, this review presents the state-of-the-art from theoretical knowledge to best practices related to the most important renewable energy infrastructures in Europe: energy production from solar, wind, geothermal sources, and energy storage from the perspective of applying CE principles at the EoL stage. To this extent, four main sections will be presented, regarding: (1) Solar energy – including PV panels and thermal solar collectors; (2) Wind energy; (3) Geothermal energy; and, (4) Energy storage – both electrical and thermal.

In particular, and considering the investigated renewable energy technologies, the research questions that inspired the study were:

- What are the current and predicted trends in installation?
- What are the potentialities of materials and components to be applied in the CE of buildings and cities at the EoL stage?
- Are there reference examples and best practices in research, projects, and companies related to CE implementation in urban environments?

Table 1
Scientific review provided by the Scopus database in total and after the screening phase.

Research query	Total	After screening
Photovoltaic* **OR** PV **AND** End of Life	53	40
Solar Thermal **AND** End of Life	1	0
Wind energy **OR** Turbine blade* **AND** End of Life	18	15
Geothermal Energy **OR** GSHP* **OR** EAHX **AND** End of Life	2	1
Electrical storage **OR** Batteries **AND** End of Life	62	38
Thermal storage **OR** TES **AND** End of Life	1	1
Photovoltaic* **OR** PV **AND** Wind energy **OR** Turbine blade* **AND** End of Life	0	0
Solar Thermal **AND** Geothermal Energy **OR** GSHP* **OR** EAHX **AND** End of Life	0	0
Photovoltaic* **OR** PV **AND** Solar Thermal **AND** End of Life	0	0
Electrical storage **OR** Batteries **AND** Thermal storage **OR** TES **AND** End of Life	0	0

The novelty and utility of the study can be summarized in the following points:

- Examine the EoL of renewable energy technologies at the urban level by a multidisciplinary approach (energy and civil engineering, urban planning, material science), and investigate the relationships between the energy transition, cities decarbonization, material flows, and CE principles;
- Analyze in parallel different renewable energy sources in terms of trend in installation, materials, and current EoL approach, highlighting similarities and differences in barriers and opportunities to CE implementation.
- Outline the crucial aspects of both thermal and electrical storage systems in the light of the circular economy;
- Compare the final stages of the technological components life cycle and illustrate best practices adopted by companies and consortia in different renewable energy technologies.

In this sense, the study aims at informing interested stakeholders such as promoters, policymakers, entrepreneurs, on the potentialities and gaps to design future coordinated strategies, incentives, and decision-making tools on renewable energy for an efficient CE transition in Europe.

Methodology and documentation

The information presented in this manuscript was collected with the aim to answer the aforementioned research questions, and it was extracted from documents belonging to both scientific and grey literature.

Different sources were explored: journal papers from the Scopus database, conference communications, reports and websites of European and International institutions and associations, websites and datasheets of companies. The variety of the documentation allowed a larger view of the topic considering both the scientific developments and the real applications in industries and urban planning.

A specific section was dedicated to each renewable technology following the structure below:

- Presentation of trends in installations, mainly considering accredited reports and data;
- Analysis of the used materials highlighting the typology and characteristics that can be crucial in CE implementation, such as availability, cost, environmental impact, recyclability;
- EoL related problems and potentialities in terms of regulations and processes;
- Best practices promoted in projects, companies, and municipalities.

Synthesizing and comparing opportunities and challenges, the study would enrich existing knowledge on the efficiency of EU countries in the implementation of CE strategies in the renewable energy systems integrated at building and city levels.

Solar energy

PV technologies still present high investments compared to the low efficiency (usually ranging from 12 % to 17 % for the first generation of silicon (Si)-based panels). New PV panels, such as organic and hybrid Perovskite, organic, or including nanotechnologies and nanopillar solar cells, are not ready for a wide market application, due to low economic viability [38].

PV technology can be potentially integrated in buildings and urban equipment; the tendency is to adapt coating products or accessories and integrate them into urban architecture [20].

Solar-thermal (ST) systems can be small-scale and large-scale implemented. The distinction lies in their installation, either in smaller family homes for hot water provision, or in larger residential areas for heating and supplying domestic hot water. Solar thermal collectors can be categorized in two types: concentrating and non-concentrating. Non-concentrating collectors have a surface area equivalent to the absorber area, whereas concentrating collectors incorporate optical concentrators making them ideal for use in solar power plants [39]. Furthermore, hybrid PV/T (photovoltaics/thermal) systems exist, which merge direct PV conversion to electricity with thermal conversion and thermal waste heat recovery [40].

PV panels: Trends in installation

The PV market is growing steadily. In the decade 2006–2016, an average annual growth of 50 % was recorded, while between 2016 and 2017, the growth rate was 32 % [41]. The world's highest cumulative solar PV capacity of 942 GW was recorded in 2021 [42]. Installed PV capacity is led by Asia and Oceania with 216 GW and a 68 % share, followed by Europe with 55.3 GW (17 %), the Americas with 36.5 GW (12 %), and finally, Africa and the Middle East with 8.2 GW (3 %) [43].

Considering the European zones, the largest installed PV capacity is Western Europe (58 %) followed by Southern Europe (31 %), Eastern Europe (9 %), and Northern Europe (3 %) [44,45]. Germany has the highest PV capacity (59.37 GW) equal to about 30 % of MW installed in the EU. PV capacity in Italy is the first in Southern Europe and the second one in the continent (22.59 GW) with a share of about 14 % of the MW installed in the EU [46]. France, thanks to solar subsidies, has seen an unprecedented increase in PV installations, with a 12 % share of MW installed in the EU and an installed capacity of 14.81 GW. Slightly more PV capacity is registered in the Netherlands (14.91 GW). The other European countries with significant installed PV capacities are Spain (13.71 GW), Turkey (10.92 GW), Poland (7.42 GW) and Belgium (6.01 GW) [44,45]. Fig. 1 summarizes the installed PV capacity in European countries.

Types of PV collectors and materials

The basic element that makes up a PV panel is a PV cell which is made by doping semiconductor materials such as Si and cadmium (Cd). A PV panel consists of several modules assembled in a common structure (from 36 to 72 cells) [47]. The cells are encapsulated in two transparent polymers (EVA, ethylene–vinyl acetate) films, in which on the top a low-iron glass is applied to protect the cells from UV rays and weathering, on the bottom a layer is placed that usually consists of polyethylene terephthalate (PET) and polyvinyl chloride (PVF) or glass to ensure better mechanical stability. The module is sealed with a special adhesive while the frame is made of aluminum [48]. A typical PV panel consists, in summary, of tempered glass, encapsulate, soldering materials and polymer sheets, while the most common metals used are aluminum (Al), copper (Cu), lead (Pb), Si, and silver (Ag) [49]. PV modules can last up to 30 years, but they are often scrapped earlier due to technical problems.

PV technologies are divided into three generations: first (Single and Multi c-Si), second (a-Si, amorphous silicon; GaAs, gallium arsenide; CdTe, cadmium telluride; Cds, cadmium sulfide; CIGS, copper indium gallium selenide; CIS, copper indium selenide), and third (Perovskites, DSSC, Organic, Quantum Dots) [47]. According to IRENA (International Renewable Energy Agency), the first generation has already reached commercial maturity, and c-Si covers nearly 80 % of the global market [50]. A crystalline Si module classically consists of a high-transmittance, tempered glass cover (75 % of total weight), an encapsulating transparent polymer adhesive layer, typically EVA consisting of a mixture of ethylene and ethyl vinyl acetate (10 % of total weight), an Al alloy frame (8 % by weight), crystalline Si wafers with a thickness of 180–200 µm (5–6 % of total weight), copper and lead-coated wires (1 % of total weight), and by silver wires (0.1 % of total weight) and other metals such as tin and quartz that represent a negligible percentage of the total weight of the module [50,51,52]. Although silver is present in small amounts (10 to 600 mg/kg) it is the most valuable metal present in the

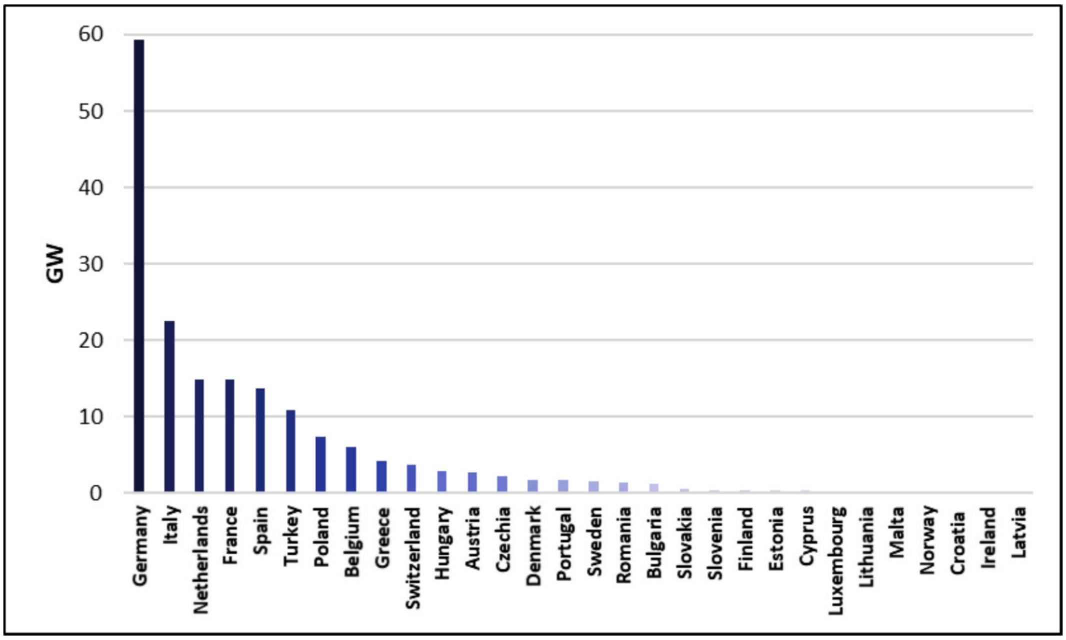

Fig. 1. Photovoltaic capacity installed in European countries [44,45].

PV panel with a cost of $1,050/kg [49,50]. PV cells are sandwiched between two encapsulated polymer layers (EVA): the top layer is a glass to which a sheet is applied on the backside that includes polymers such polyvinyl fluoride (Tedlar), polyvinylidene fluoride or ethylene chlorotrifluoroethylene; the back layer can be of three types: PK (PET/Kyner), TPT (PET/Tedler), and PPE (PET/EVA) and includes Carbon (54.9 %-63.8 %), Hydrogen (4.3 %-6.6 %), Oxygen (24.5 %-30.5 %), Nitrogen (0.2 %) and Fluor (0–9 %) [50]. PERC solar cells are an evolution of the traditional c-Si and are the dominant PV technology in the market over the last decade due to their lower cost and higher efficiency obtained by the addition of a back passivation layer. Generally, this layer is made of SiOx and SiNx [53]. Another innovative structure is represented by the TOPCon solar cells that use an ultra-thin tunnel oxide layer for passivation [54].

The second generation is known as thin-film PV (TFPVs) and include: a-Si, CdTe, CIGS or CIS, GaAs technologies. The aim of TFPVs is to develop PV panels that are flexible, low cost and use little material [51]. Second-generation solar cells account for 6 % of the global market [50]. According to IRENA, CIGS or CIS technology is spreading slowly (25 % of the total market share of TFPVs); in contrast to CdTe PV whose market diffusion is happening faster (65 % of the total market share of TFPVs), while the other technologies (a-Si) are used more for research purposes and not for marketable purposes (10 % of the total market share of TFPVs) [47,51]. CdTe technology has, in addition to the glass surface (about 96 %) and EVA layer (2 %), some elements namely, Cadmium Tellurium – CdTe (0.11 % –0.13 %), Copper – Cu (0.02 %), Tin Dioxide – SnO_2 (0.02 %) and Cadmium Sulfur – CdS (0.01 %) [50]. CIS PV modules have significant amounts of Cu, selenium (Se) and indium (In), in detail and net of the EVA layer and glass cover, consist of the following elements: Cadmium sulfide – CdS (0.0003 %), Zinc oxide – ZnO (0.035 %), Molybdenum – Mo (0.025 %) and $CuInS_2$ (0.04 %) [52]. CIGS thin films are composed of Cu, In, Ga, Se, Cd, tin (Sn), or zinc (Zn), and this technology is a modified CIS by replacing 15 % indium (In) with the same amount of Ga with the aim of improving its efficiency [52]. Amorphous Si technology has the advantages of low cost and low toxicity but disadvantages such as low durability and lower efficiency than other TFPVs, which is why future projections predict that the market for a-Si modules will fade away [47].

In recent years, HJT structure solar cells recorded a large diffusion due to their high efficiency, low-temperature production technology, and enhanced degradation properties. These cells combine the advantages of crystalline and amorphous silicon. Typically, the heterojunction is formed by using a flat n-type crystalline silicon wafer with a thin layer of p-type amorphous hydrogenated silicon deposited on its surface [55].

The third generation includes different types of solar cells, such as perovskite solar cells (PSCs) which are composed of Pb and Sn [52], dye-sensitized solar cells (DSSCs), organic solar cells (OPVs), and nano-structured solar cells, in turn the latter include carbon nanotubes (CNTs), hot carriers (HCs), and quantum dots (QDs). Third-generation technologies are very expensive and are not yet commercialized [47].

EoL and best practices

The rapid installation of PV modules leads to a consistent estimated waste production of 60–78 million tons by 2050. Significant efforts are necessary to recover materials from EoL of PV and implement robust frameworks of CE with consequent benefits for the environment. The recovery of metals from the first-generation of PV and critical elements (Te, In, Se, and Ga) from the second-generation PV are sufficiently reached [50].

The encapsulation of solar cells is the main technical obstacle in the EoL of crystalline PV modules. In fact, it avoids high-value recycling or remanufacturing, limiting the lifetime of materials [51].

Thereby, new solutions are required at the design stage of panels. The current and most common encapsulation method uses EVA that presents disadvantages in terms of recyclability.

Currently, thermoplastic polyolefin material and the structure of NICE technology are considered as possible alternatives [48].

At the EoL stage, the most commonly employed strategy to free the cells from encapsulation is incineration. This method is easy to be applied but energy-intensive and hazardous gasses emitter [49].

Once the layers are separated, metals such as Pb, Cu, Ga, Cd, Al, and Si can be recovered. In addition to finding new design solutions, researchers and companies are developing recycling processes. Such as an example, in 2007, the consortium PV CYCLE [56] has commercialized in Europe a process of recycling mono or multicrystalline Si modules based on two stages: the separation of the Al frame and the junction boxes, and the extraction of the other materials by a mechanical process similar to that one used for electronic waste. The process is still downcycling (the value of the collected material is low) and the maximum percentage of recovered materials is about 80 %, which is not sufficient for new requirements [51].

Recycling processes of thin films are under development or near implementation in Italy, Japan, and South Korea. But despite the efforts, these processes do not have competitive costs and are still complex and at laboratory scale. A positive aspect is that the recovery rates can reach 95 % and the materials recovered have appreciable value [57].

The environmental advantages and profitable outcomes derived from PV waste recycling encouraged initiatives in providing regulations and developing industrial processes.

In particular, the EU provided a legislative framework based on two directives: the Waste Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU [58], and the Restriction of Hazardous Substances (RoHS) Directive 2011/65/EU [59].

In short, since 2014, the EU regulated the extended producer responsibility (EPR) principle of PV modules and prompted PV manufacturers to act early in planning for a take-back system in their territories.

Moreover, EPR organizations require compliance with standards (CENELEC or WEEELABEX) by contract operators. EU prohibits mixed collection of PV panels with construction waste and imposes depollution requirements on some metals, such as Cd, Se, Pb, and special care during the extraction of exhaust air and the removal of dangerous substances that can be produced during thermal, chemical and mechanical treatments [46].

The recycled materials can contribute to produce new PV panels within EU, and ensuring a sustainable source of raw materials which will contribute to cover the urgent demand for minerals and metals of low-carbon technologies.

ENF Recycling [60] provides the largest database of recycling companies in the world, listing companies specialized in the recycling of PV. Fig. 2 shows the global distribution of companies already contained in the ENF database [61] and additional companies located by the authors using their websites.

Globally, 21 out of 63 (33 %) companies operate in Europe. A consistent activity of PV recycling is also recorded in America and Asia. The list of virtuous European companies in solar waste recycling can be consulted in Table 2. Italy, Germany, and Switzerland record at least 3 companies.

The EU promoted several projects in synergy with the various solar waste recycling companies scattered across its territory. Such as an example, the Ramp-PV project was coordinated by the French company ROSI (2020–2022) [62] with the aim of including PV into a CE by revaluing wasted raw materials along the value chain, proposing innovation on processes more environmentally friendly and economical. In particular, it aims to create different reuse routes to employ Si in some strategic fields (such as PV, electronics, and battery storage), developing several PV waste recycling sites, and carrying out continuous research and innovation activities to maximize the added value of recycled materials.

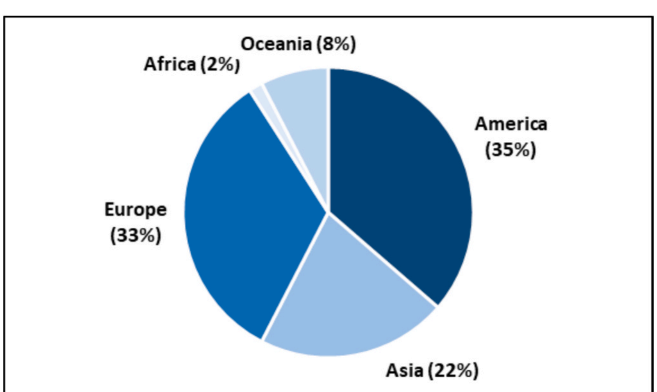

Fig. 2. Geographic distribution of companies dealing with PV recycling.

Table 2
Solar waste recycling company in European countries.

Countries	Companies
Italy	Compton Industriale Srl, 9-Tech, Tialpi
France	RoSi Solar, Veolia
Spain	Soluciona Energía – SolRecycle
Ireland	Recycle Solar, Purevolt
Germany	Antec, SolarWorld, Loser Chemie
Denmark	Ostred
Norway	Sintef
Netherlands	Rinovasol
Poland	Jamko
Slovakia	AMEC
Swiss	Immark, KWB Planreal, SENS eRecycling
U.K.	H&H Pro, Recycle Solar Technologies

Another remarkable project, started in 2017, is the ReSiELP that has received funding from the European Institute of Innovation and Technology (EIT), including eight companies and several European research institutes [63]. The goal of ReSiELP was to bring together technologies from different fields with the aim of recovering critical and valuable raw materials also present in PV waste through innovative technologies based on the concept of CE aiming for a zero-waste approach [64]. The project was based on three pillars: the recovery of EoL modules, the reuse of Si after the purification stage, and the reuse of glass for the development of building materials.

Recovered materials are fed back into various production systems, except for Cu, Al and Ag which are directly sold, recovered glass is incorporated into mortars and concretes and then tested with the aim of producing environmentally sustainable solutions, while Si is processed to generate high-quality solar Si so that it can be reintroduced into the PV chain to close the loop. The PHOTORAMA project is a three-year EU-funded project (2021–2024) with the goal of mapping out a circular and sustainable chain to have a carbon–neutral PV industry, and develop, recycle and recover useful materials from PV panels at EoL stage [65].

Thermal solar collectors: Trend in installation

The global market for solar-thermal (ST) energy has experienced an average annual growth rate of 73 % over a span of 23 years (2000–2022). This growth is due to an increase in ST capacity from 62 GWth in 2020 to 542 GWth in 2022. Considering data from 2021, the regions of the world with the highest installed capacity are Asia and Oceania with a value of 406.12 GWth (79 %), followed by Europe 59.89 GWth (12 %), North and South America with 38.26 GWth (7 %), and finally Africa and the Middle East with a capacity of 9.65 GWth (2 %). In Europe, in descending order, the installed capacity of ST collectors comes from Western Europe (54 %), Southern Europe (31 %), Eastern Europe (9 %), and Northern Europe (6 %) [66]. Fig. 3 shows a complete overview of the cumulative installed capacity of ST collectors in European countries.

Data from the year 2022 shows that Germany is the leading European country in ST collectors installed on rooftops of residential buildings with an installed capacity of 15,470 MWth, followed by Greece (3,808 MWth), Italy (3,708 MWth), Spain (3,053 MWth), and Austria (2,568 MWth) [67]. Considering data from the years 2021 and 2022, the most significant growth of small-scale ST systems in Europe was reported in Italy (83 % growth in 2021 and 43 % growth in 2022), which was driven by increased construction activities combined with a new tax reduction scheme for energy-efficient buildings. Considering data from 2022, high growth rates in ST markets in Europe were also in France (29 %), Greece (17 %), Germany (11 %), and Poland (11 %) [66].

PV/T technology is mostly installed in tertiary buildings such as hotels, restaurants, leisure centers, and retirement homes. 950,155 m^2 of PV/T (corresponding to 473,789 kWth) was in operation in Europe in 2022. France is the leading European country in installed PV/T capacity, with a 40 % share. In 2023, the total number of District Heating

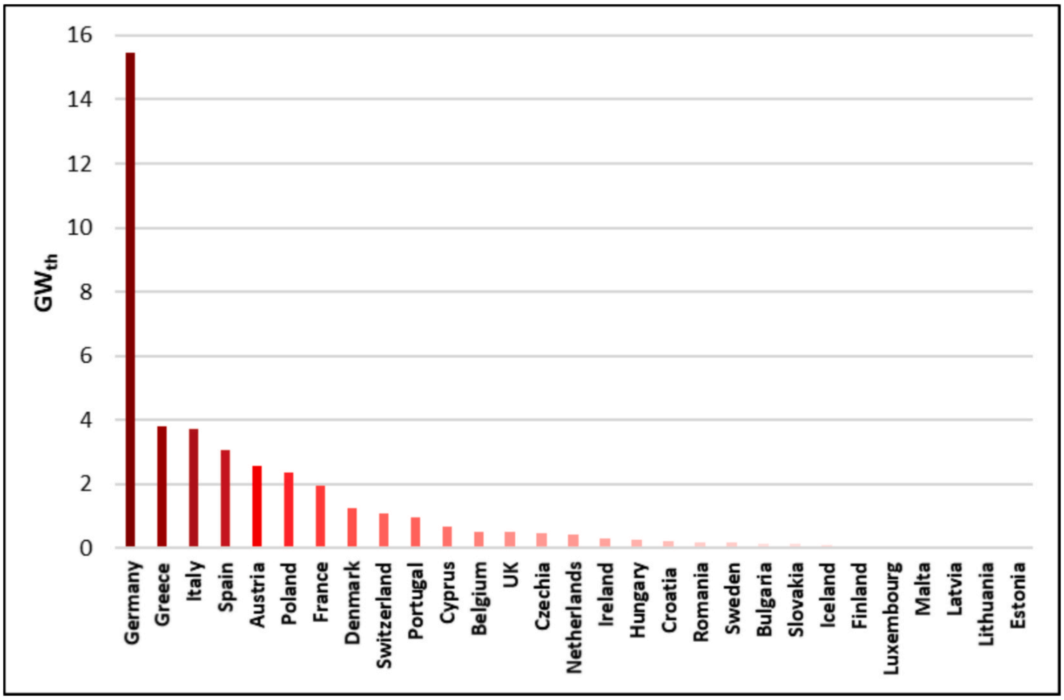

Fig. 3. Installed operating capacity of solar thermal collectors in European countries [67,45].

networks (e.g. large-scale ST systems) existing in the EU reached 271 (with a capacity of 1,373 MWth), representing 83 % of the total Solar District Heating networks in the world. The leading European country in ST systems for district heating is Denmark with 124 district heating networks in operation, followed by Germany (51), Austria (40), and Sweden (23) [66,67].

Types of solar thermal collectors and materials

In Europe, the most commonly used solar-thermal collectors are flat-plate collectors (88 % of all solar thermal systems installed in the year 2021) that represent the primary application in the built environment [66,67].

Flat-plate collectors consist of an absorber plate, riser tubes containing the heat transfer fluid, a glazed cover, an enclosure with thermal insulation, and shorter vertically installed pipes (known also as riders), which attach the collector to the mounting structure [68–70]. The whole ST system additionally includes recuperating tubes and a storage tank.

Generally, the absorber plate is in the form of a Cu or Al sheet. Other high-conductivity metals can also be used as the absorber plate, such as brass, iron, and steel [71]. Moreover, new materials are sought to be applied for absorbers such as biopolymers, silver nanoparticles, films made of polymers with gold, etc. [39]. A dark coating (the most efficient is black chrome) is applied to the sun-facing side of the absorber assembly to increase the absorption of solar energy. A relatively new coating on the market is the titanium-nitride-oxide layer, which is applied via a steam-in-vacuum process [72].

Heat-absorbing riser tubes are attached to the absorber plate and contain heat transfer fluid [73]. Water is the most used heat transfer fluid, other possible heat transfer media are: glycol, molten salts, hydrocarbon and other synthetic oils, and liquid sodium [39,68]. The efficiency of ST collectors can also be improved with the use of nanofluids [69]. Nanoparticle suspension is used as both a heat transfer medium and an absorber in some new technological developments in the field of ST collectors [39]. If a heat transfer fluid is used, a heat exchanger is typically employed to transfer heat from the solar collector fluid to a hot water storage tank. The glazing transparent cover typically consists of single or multiple sheets of glass [73]. The glass is sealed around the edges with EPDM (ethylene propylene diene monomer) rubber. It can be protected by an Al capping, which is fastened by steel screws [74]. In higher-performance ST collector designs, the transparent glazing cover is tempered soda-lime glass having reduced iron oxide content. The glass may also have a stippling pattern and one or two anti-reflective coatings to further enhance transparency. Aluminum-doped zinc oxide or tin-doped indium oxide can be added to the glass to improve its glazing transmittance performance [69].

The enclosure can be made of a variety of materials, including Al, stainless steel, glass, or tempered soda-lime glass, which has reduced iron oxide content [72,75]. The sides and back of the enclosure are insulated. Different insulation materials are used such as glass wool, mineral wool, rock wool, and plastic cover made from polyurethane foam or polystyrene to reduce heat loss to the ambient [70,73].

Riders are the metal components (typically stainless steel or Al) used for fixing the collector to the structure, and ensuring that the collector is stable and can withstand wind and other environmental factors.

Recuperating tubes, which transfer the heated fluid from the collector to the storage tank, are typically made of high-conductivity metals such as Cu or stainless steel [76]. These pipes are often insulated with materials like rock wool or glass wool.

The storage tank is most commonly constructed from stainless steel and insulated with high thermal insulating material, such as XPS, EPS, or glass wool [39,77].

The two main types of solar PV cell technologies considered for use in hybrid PV/T collectors are either based on crystalline Si wafers or thin-film semiconductor materials [78]. PV/T collectors are composed of the same basic elements as PV collectors (panels) and incorporate additional elements similar as in the case of flat-plate collectors; e.g., insulation, thermal absorber, tubes for the circulation of heat transfer fluid, and transparent cover (glazing sheet) [79]. The material composition of these building blocks is the same as in the case of the flat-plate collectors.

The lifespan of solar collectors ranges from 20 to more than 30 years [77], depending on the quality of the materials used, the maintenance practices followed, and the environmental conditions where the collector is installed.

EoL and best practices

The CE of ST collectors is a topic on which the scientific literature is still developing [38,80,81]. The EoL of ST collectors is not considered in some life cycle assessment (LCA) studies, but it has to be examined in order to obtain a complete assessment of the environmental impact of these solar systems [82]. However, some LCA analyses [80,83,84] have shown that recycling or reusing ST collector materials in the EoL phase could provide high environmental benefits. Disposal and circularity of ST collectors is critical because ST systems, are composed of similar amounts of metals and glass as PV systems [80]. ST collectors consist mainly of Al and Cu, which account for 60 % of their total mass [82,83]. Recyclable Al from a ST collector accounts for about 4.75 kg of the total mass and comes from the frame and support structure, while recyclable Cu is 70.07 kg of the total mass and comes from the solar storage tank, boiler coils and heat transfer fluid piping [83]. Cu pipes can be reused at the EoL of the ST system. What is required are quality checks, cleaning, and eventual repair [82]. Polyurethane (PUR) foam is a material used in solar applications, however, its disposal at the EoL stage is complex as it has been considered to be incinerated but this would cause the emission of toxic gases [84]. The analyses conducted in Milousi and Souliotis (2023) [82] study, suggested solutions to make the disposal of ST collectors EoL more sustainable and in line with CE principles. In particular, the authors proposed improvements in the design of collectors so that the system components can be disassembled and then recycled or reused. Such solutions would allow materials to be recovered, reducing waste to be disposed of and having greater availability of spare parts so as to extend the life of the system. Moreover, to increase recyclability and reduce environmental impact, one could consider designing the components of the system with materials other than those usually used today. For example, the storage tank can be recycled if made of stainless steel, the heat exchanger and piping could be created from steel instead of Cu, while the thermal insulation could be recycled polyurethane or rock wool, and recycled Al could be used for the collector's frame.

The search for information in this area highlighted that there are few companies capable of sustainable disposal of ST collectors and other components. Such as an example, SolarisKit is a British company that manufactures ST collectors that can be easily repaired, reused and recycled, minimizing waste and meeting CE criteria [85]. DualSun [86] is a French company that has designed and brought to market a PV/T hybrid solar collector and relies on PV CYCLE [56] for the disposal of these panels. The heat exchanger, manufactured by the company, is made of polypropylene (PP), a 100 % recyclable material. At the end of its life cycle, it undergoes a recycling process that involves crushing the material, washing, rinsing, removal of excess water, sieving, and reclamation. The finished product is a granular and reusable PP. The heat transfer fluid is usually a mixture of water (60 %) and antifreeze (40 %). The common antifreeze is monopropylene glycol (MPG) [87]. At EoL, the water-MPG mixture is taken over by the French company Veolia, which applies regeneration processes such as filtration and dehydration to recover the fraction of MPG to be put back on the market [88].

Wind energy

Wind energy is one of the most widely distributed renewable energy sources. A wind turbine is basically made up of a foundation, a lattice or tubular tower, a generator (or nacelle), and blades that include numerous materials. Generally, wind turbines installation is on a large scale, and the implementation in urban environments is very rare due to the reduction in wind speed by structural obstacles. Moreover, visual and acoustic impacts are barriers to optimal architectural integration. Wind turbines can be located on rooftops, integrated into buildings, placed between buildings, integrated into a building's skyline or in double-skin facades [20].

Wind turbines market and materials

The Global Wind Energy Council (GWEC) shows the trends in installation around the world highlighting a rapid evolution over the past two decades. In particular, the highest compound annual growth range (CAGR) rate equal to 26 % occurred in the years 2001–2010, followed by the period 2010–2015 with a growth rate of 17 %, and the CAGR was equal to 11 % in the time range 2016–2022. Currently, there is a developed wind power of 906 GW of which 842 GW onshore and 64 GW coming from offshore farms. In 2022, the country in the world that has the largest wind installations is China, then United States (US), and European countries [89].

Europe has record-breaking onshore wind installations, increasing its market share in the last decade by 4 % to a total of 19.1 GW. The highest increase in capacity growth was noticed in 2022, while the lowest increase was recorded in 2018. A total of 255 GW of wind power capacity is now installed in Europe, 88 % of this (225 GW) is onshore and 12 % (30 GW) is offshore [90].

Considering the different European zones, 41 % of the total capacity is located in Western Europe, while in both Northern and Southern Europe the installed capacity is equal to 26 %, and Eastern Europe counts 6 % of installed capacity.

Germany has the largest installed wind capacity (66 GW), follows a little less than half of the gigawatts installed in Spain (29.8 GW) and then the UK (28.4 GW), France (21.1 GW), Sweden (14.6 GW), Turkey (11.9 GW) and Italy (11.8 GW) [89,90].

Considering the two farms typologies, the largest installation capacities for onshore wind plants are located in Germany (58.2 GW), Spain (29.7 GW) and France (20.6 GW), while the UK has the largest installation capacity for offshore plants in Europe (13.9 GW) followed by Germany (8 GW) and the Netherlands (2.8 GW) [89,90]. A complete overview of wind power installations in Europe is shown in Fig. 4. The Netherlands, Poland, Denmark, Portugal, Finland, Belgium, and Norway have wind turbines capable of generating more than 5 GW; while wind farms in Greece, Ireland, Austria, and Romania provide power about or slightly higher than 3 GW.

The oldest wind turbines in Europe are installed in Portugal and Spain whose average ages correspond to 13.4 and 13.3 years, respectively. Follow countries with average age of the plants higher than 8 years are Italy (11.4 years), Germany (11.3 years), UK (8.7 years), and France (8.0 years). Other countries such as Poland, the Netherlands, Sweden, and Turkey have lower average ages of installed wind turbines (6–7 years) [90].

The materials commonly used in wind turbine construction are steel and iron, Al and alloys, Cu and alloys, polymer materials, glass/carbon composites, electronics/electrics, lubricants and fluids. Each material has its own role and set of advantages that contribute to the overall efficiency and durability of the turbine. The following is an identification of the key materials and their characteristics:

Fiberglass or carbon fiber reinforced composites are favored for turbine blades due to their exceptional strength-to-weight ratio. In addition, composites offer flexibility, crucial for withstand varying wind conditions without fracturing. Carbon fiber reinforced composites are particularly desirable for their superior stiffness and fatigue resistance.

Steel is widely used in towers and gearbox/generator components due to its high strength and durability. For towers, steel provides the necessary support to withstand the mechanical loads imposed by the turbine components and environmental factors such as wind and gravity. In gearbox and generator components, steel and alloys are preferred because of their ability to handle high mechanical stresses and ensure reliable operation throughout the lifespan of the turbine.

Aluminum and steel are included in the nacelle, gearbox and generator that require a sturdy yet lightweight construction. In particular, steel offers robustness and can withstand heavy loads,

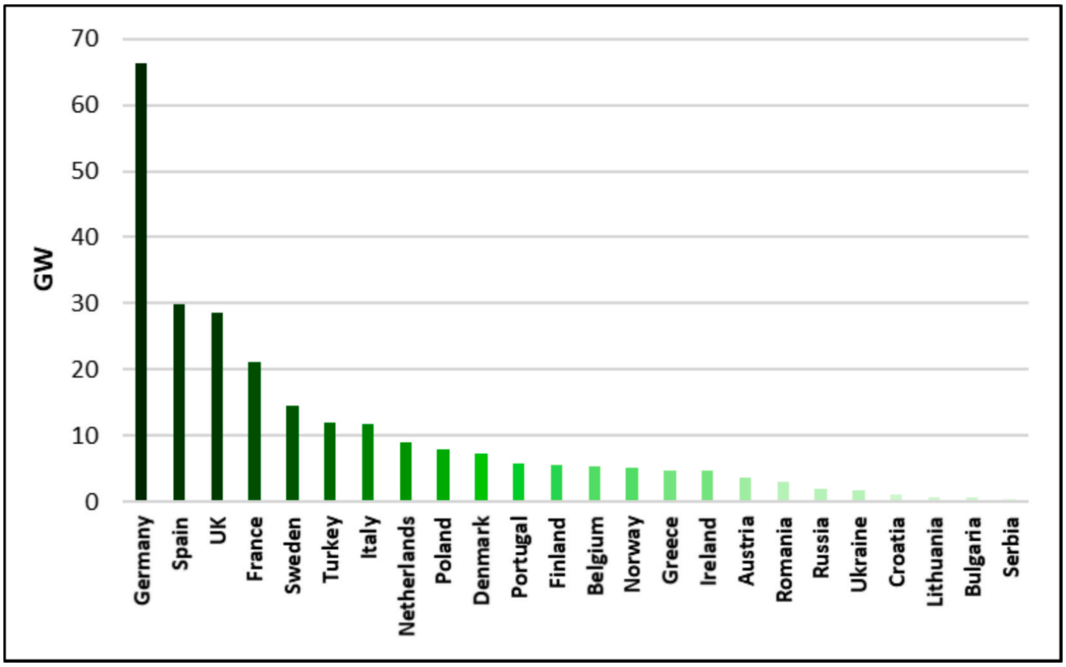

Fig. 4. Cumulative capacity of wind power (onshore and offshore) installed in European countries [89].

while Al provides a lightweight alternative that helps reduce the overall weight.

The towers constitute an important aspect of the wind turbine infrastructure, serving both structural and economic functions. Structurally, they transmit loads from the nacelle to the foundation, while economically, taller towers correlate with increased energy production.

Various materials and design concepts are used in tower construction, including steel (tubular or segmented), lattice, concrete, and hybrid configurations.

Tubular steel towers, characterized by their conical shape and diameter tapering, are widely prevalent. Typically assembled on-site in 3 or 4 sections bolted together, each section spanning 20 to 30 m, these towers are fabricated from cut, rolled, and welded steel sheets. While lattice towers were once common, particularly for smaller turbines, they lost their importance due to significant visual impact and higher construction and maintenance expenses. Despite these drawbacks, lattice towers have several advantages, such as reduced material usage (approx. 50 % compared to standard steel towers of equivalent stiffness) and they produce less shadow. Concrete towers may be a viable option in regions with unusually high steel prices. Constructed from numerous precast components assembled on-site, their main challenge lies in their weight, which can surpass that of the nacelle unless designed with a greater number of smaller pieces. Hybrid towers, used by several manufacturers to mitigate exposure to steel price fluctuations, offer an alternative solution. However, their intricate assembly process results in higher installation costs. Wind turbine blades are considered attractive components that can be reused in the construction sector due to their valuable mechanical and durability properties [91]. In addition, ongoing research focuses on the development of advanced materials to enhance the efficiency and durability of wind turbines. Innovations include the use of new alloys, hybrid materials, and smart materials that can respond to changing conditions. By strategically combining these materials, wind turbine manufacturers can optimize the performance, durability, and cost-effectiveness of their products, ultimately contributing to the growth of renewable energy infrastructure.

According to the National Renewable Energy Laboratory [92], the composition of wind turbines varies depending on their make and model. Generally, wind turbines consist mainly of steel, representing 66–79 % of the total turbine mass. Other important components include fiberglass, resin, or plastic (11–16 %); iron or cast iron (5–17 %); Cu (1 %); and Al (0–2 %). As an example, Vestas [93] wind turbines V162-6.2 MW™ are composed of around 88 % metals; (e.g. steel, iron, Cu and Al), 10 % polymers and composite materials, and the remainder a mixture of electronics/electrical items, lubricants and fluids, etc. As a general trend, steel and iron materials are the most widely used materials in both onshore (83 % to 88 % by weight) and offshore wind turbines (about 82 %). Aluminum and alloys account for 1–2 %. The amount of Cu and alloys used in onshore wind turbines is approximately 0.60 %. In offshore wind turbines, the amount of Cu decreases with capacity (from 1.5 % to 0.9 %). Onshore wind turbines contain a percentage of polymeric materials (epoxy resins, glass and carbon fibers, and thermoplastic polymers) that varies between 2.6 % and 4.7 %. Offshore wind turbines have a percentage of polymeric materials of 1.45 % for 7 MW turbines and a value of 0.9 % for the 15 MW turbine. On average, the amount of glass/carbon composite materials varies between 6 % and 9 % in onshore wind turbines and between 7.3 % (9 MW) and 9.5 % (15 MW) in offshore wind turbines [94].

At the end of its planned operational life, a wind farm developer must decide among several options for the aged facility, including extending its lifespan, pursuing partial or full repowering, or moving towards decommissioning, which involves considerations such as reuse, recycling, incineration, or landfill disposal. Determining the most suitable course of action involves assessing technical, economic, and regulatory factors. In addition, efforts are underway to repurpose entire turbine blades as structural elements in various contexts. The next section presents the best practices now, considering selected examples.

EoL and best practices

Generally, wind farms are installed far from urban environments. Despite this allocation, wind energy can be included in the concept of CE of buildings as there is a crescent number of examples in which dismantled wind turbines are reused in cities. In other cases, waste materials can be used to build small size turbines for urban applications.

For example, the Institute for Technical Energy Systems (ITES) in Germany has demonstrated how, through a do-it-yourself approach, a Savonius wind turbine can be built using almost entirely waste materials. The materials sourced from the university landfill and reused are: two 26-inch bicycle rims, wooden parts from footpads and metal sheets; while the few materials purchased for assembly are: charge controller, dynamo, screws, nuts, bolts and gaskets. The electrical power of the turbine is low (1.5 W), but the example shows how even inexperienced people can build one [95].

Moreover, several companies recycle wind turbines throughout Europe. The Swedish company Vattenfall has launched a pilot project involving the recycling of the blades of the offshore Irene Vorrink wind farm (Netherlands). Vattenfall entered into an agreement with the Danish company Gjenkraftin, which uses blades to make skis, snowboards or products containing fiberglass or carbon [96]. The Danish company Ørsted undertakes to reuse, recycle or recover all the blades of onshore and offshore wind turbines after their dismantling [97]. Companies that produce wind turbines are looking for solutions and adopting new technologies to avoid dumping the turbines. One of them presents a solution applicable to the currently operating epoxy-based blades [93]. In Spain, the EnergyLOOP company created by Iberdrola through its program PERSEO, and FCC Ámbito, subsidiary of FCC Servicios Medio Ambiente, built an innovative wind turbine blade recycling programme in 2023 with the aim of recovering composite materials to be reused in different sectors (energy, aerospace, automotive, textile, chemical and construction industries) [98]. PreZero Spain and Endesa have announced the foundation of a company called Grineo created to manage the blades that will be recycled in plants throughout the Iberian Peninsula [99]. In 2021, Siemens Gamesa wondered about its role in CE and presented fully recyclable wind turbines successively installed in an offshore plant in Kaskasi (Germany) combining different resins that guarantee a solid structure. The company assumes that, at the EoL, the materials can be used to create new products such as suitcases or flat screen cases [100]. Modvion is a Swedish company that produces towers of laminated wood wind turbines in order to reduce costs, facilitate transport and be easily recyclable. Wood is stronger than steel for the same weight, which means that the materials used are more durable and the tower's service life could increase [101]. To extend the life of wind turbine blades and make them more recyclable, Arkema have created a particular thermoplastic resin which has the same characteristics as traditional resins and which is recyclable at the same time [102]. In addition to the actual recycling, some companies such as Enel Green Power (Italy) launched a dedicated section called Open Innovability, where everyone can propose sustainable projects [103]. The company promotes new ideas such as the production of glass wool and insulating materials from recycled wind turbines [104]. Recently, it joined several European projects, including DeremCo, with the aim of creating a circular chain for composite materials for wind turbine blades [105]. Over the years, Enel has also supported several partnerships dedicated to the circularity of wind turbine blades outside Italy, such as the collaboration with Modvion with the aim of creating towers for solid wood wind turbines [106]. The company, in addition to the classic applications in the field of civil and urban engineering of recovered materials, highlights how glass or carbon fibers could be used in the nautical field and in the world of sport [107]. Another interesting collaboration has been sanctioned with the Scottish startup ACT Blade with the aim of developing an innovative wind turbine in a fabric similar to the sails of boats with the dual objective of generating more energy and, at the same time, facilitating the recycling of the materials that compose it. The fabric of the ACT Blade's rotor blades is easily separable from conventional turbines, which ensures material recycling from the turbine design stage [108]. To make the turbine less impactful on the environment and more recyclable at the EoL, the Austrian company Wood K plus decided to replace the traditional glass fiber reinforced plastics (GFRP) with hemp fibers [109]. A number of Danish companies such as LM Wind Power, MAKEEN Energy, and FLSmidth are joining a three-year project (2021–2024) called DecomBlades with the goal of bringing together wind power companies, recycling companies, and universities to lay the groundwork for commercializing the recycling of wind turbines [110]. A solution proposed in the project is the creation of Blade Material Passport, on which the materials contained in the turbine are specified in order to simplify the dismantling and recycling. In the Netherlands, a virtuous example of the repurposing of waste materials is proposed by an international architectural firm called Superuse Studios. The architecture firm develops various projects using reclaimed materials and implements them by working with different partners, companies and municipalities. Attractive installations, such as playgrounds gathering areas and benches, have been designed by the studio and later built in diverse locations: the Blade-Made Willemsplein, the Blade Made Oost Pier Terneuzen, Blade-Made speeltuin Terneuzen and the Blade Made speeltuin Wikado [111]. Table 3 provides a list of virtuous companies.

Geothermal energy

Geothermal energy is a sustainable and reliable source, being used worldwide for multiple purposes. Moreover, it is a cost-effective, long lasting and weather-independent source of renewable energy [112]. A classification can be done considering the geothermal reservoir temperature: high (above 150 °C), medium (90 °C to 150 °C), and low temperature (below 90 °C). The available fluid type (vapor, water), and application (electricity generation, direct heat use), the used technology is different for electricity generation (dry steam, flash steam, and binary cycle), as well as for direct heat use (heat exchanger, geothermal heat pump, and direct heat use) [113]. Moreover, it is possible to take advantage of the huge thermal mass (and heat storage capacity) and very stable temperature, even at shallow depth (1.5 to 2.0 m), making use of Earth-to-Air Heat exchangers (EAHX) [114,115] and Ground Source Heat Pumps (GSHP) [116,117].

Trend in installation: Thermal direct use and electric power capacity

Globally, the use of geothermal energy-based heating, ventilation, and air conditioning (HVAC) systems to heat or cool buildings is growing. At the end of 2019, the total installed thermal capacity worldwide was 107.7 GWth, of which, 72 % were geothermal heat pumps, while the remaining corresponded to geothermal fluids for direct heating and cooling [118,119]. According to IRENA and IGA (International Geothermal Association), the regions with the largest geothermal installation used to heat and cool buildings are Asia and Oceania (45.8 GWth), followed by Eurasia (37.7 GWth), and North America (22.5 GWth). European data on thermal capacity include geothermal heat pumps and other direct-uses: bathing and swimming, greenhouse heating, aquaculture pond heating, and industrial [118]. Fig. 5 shows the distribution of installed geothermal thermal capacity in Europe, showcasing a larger predominance in European Northern (37 %) and Western countries (34 %).

Fig. 6 shows the top ten European countries with the largest installed thermal capacity from geothermal energy, being led by Sweden (6.7 GWth), Germany (4.8 GWth), and Turkey (3.5 GWth). France, Iceland, Finland, and Switzerland have capacity greater than 2.0 GWth

Table 3
Companies that recycle wind waste in Europe.

Country	Companies
Italy	Enel Green Power
France	Arkema, GP Renewables France
Spain	EnergyLOOP (Iberdrola), Grineo, Siemens-Gamesa, Tecnalia
Germany	GP Renewables Germany, Siemens-Gamesa, ABO Wind
Denmark	Miljøskærm, Continuum, Ørsted, Vestas, LM Wind Power, FLSmidth
Norway	Gjenkraft
Netherlands	Superuse Studios
Ireland	Re-Wind Network
Sweden	Modvion
Austria	Wood K plus – Kompetenzzentrum Holz
Poland	GP Renewables Poland
U.K.	Continuum, ACT Blade, Re-Wind Network

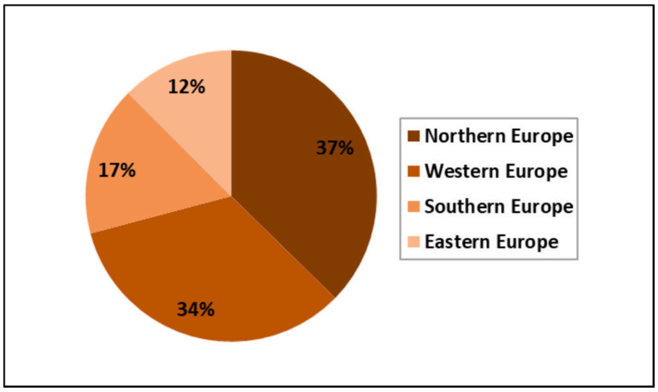

Fig. 5. Distribution of installed geothermal thermal capacity in the European geographic areas (2019) [118].

[118,119]. The nations with the highest number of installations of geothermal heat pumps are Sweden (560,333 units), Germany (431,134 units), and France (172,000 units) [117].

In Sweden, closed-loop shallow systems are mainly installed, while in Germany, deeper wells are used for heat pumps and low-temperature systems [119]. The earliest district heating installation in France is dated from 1969, while the first large-scale geothermal plant used for space heating was originated in Iceland in 1930. In Switzerland, the first geothermal plant for heating and cooling space was created in 1994 [118]. The global electric power capacity increased from 6.8 GWe in 1995 to 12.6 GWe (+85 %) in 2015 [120], and amounted to 15.96 GWe at the end of 2021 (+135 % in relation to 1995 and + 27 % having as reference 2015). The regions with the largest capacity are Asia and Oceania (5.9 GWe), North America (3.7 GWe), and Eurasia (3.5 GWe) [119]. Over the past two decades, electric geothermal capacity in Europe has grown at a higher average annual rate (+5.2 %) than in the rest of the world (+3.2 %). Distribution of installed geothermal capacity for electric power generation is predominant in Southern Europe (74 %), as can be seen in Fig. 7.

The European countries with the largest installed geothermal capacity for electric power generation are shown in Fig. 8, with three countries clearly standing out: Turkey (1,549 MWe), Italy (916 MWe), and Iceland (755 MWe). Electric power generation capacities (Fig. 8) are significantly smaller than thermal capacities (Fig. 6). This leads to the conclusion that geothermal energy in European countries is mainly explored for thermal direct-use.

Italy was the pioneering country in powering an electric generator with geothermal steam in 1913, followed later by Iceland, where its first geothermal power plant began operational in 1969 [119]. The most widely used technologies for generating electricity from geothermal sources include three types of power plants: dry steam, flash steam, and binary cycle [113,119].

Technology and materials

The main three components of a plant with an EAHX are [116]: (1) suction unit, forcing the outdoor air to flow inside the shallow buried pipes (around 2 m depth) that will ventilate the house; (2) filters, to filter the insufflated air; and (3) pipes, through where the air circulates and the heat exchange between soil and air occurs. These systems are usually classified as low-enthalpy geothermal systems.

According to Agrawal *et al.* (2019) [121], the EAHX systems could be

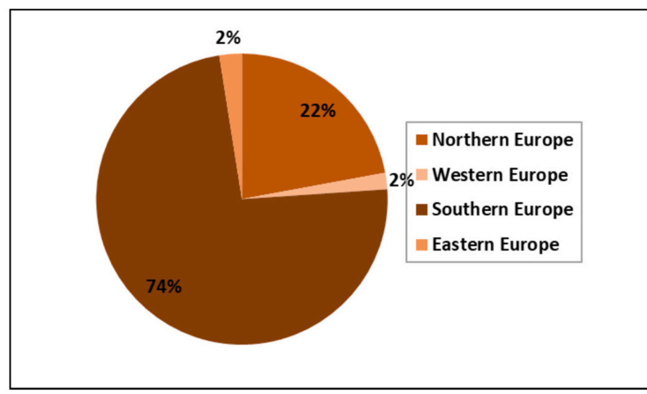

Fig. 7. Distribution of installed geothermal capacity for electric power generation, representing European geographic areas (2020) [119,113].

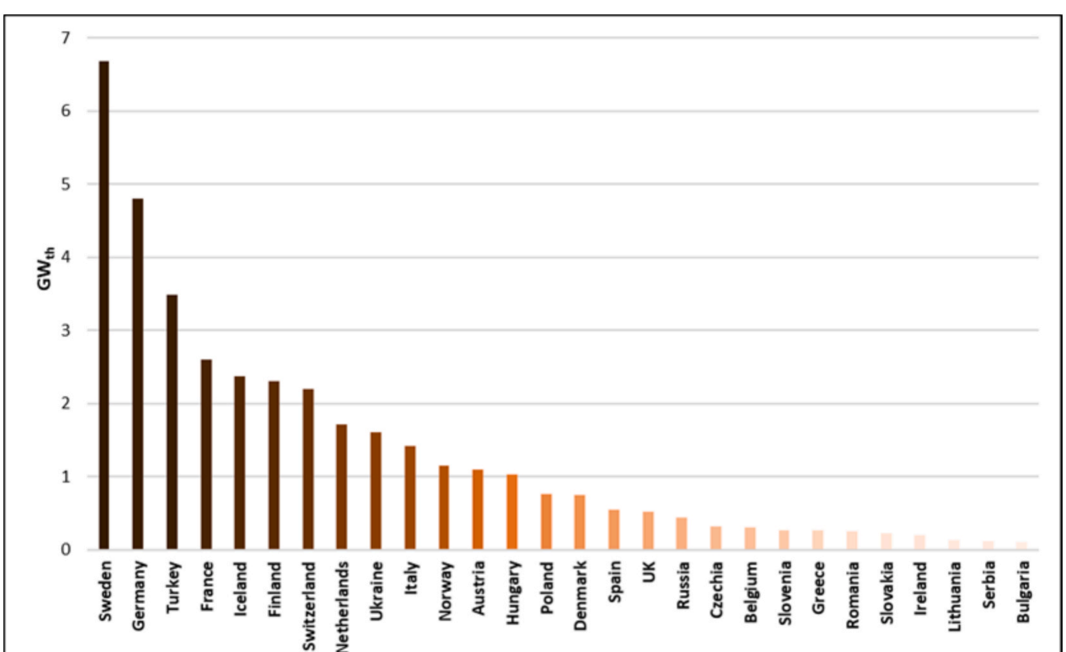

Fig. 6. Installed thermal capacity from geothermal energy in European countries (2019) [118].

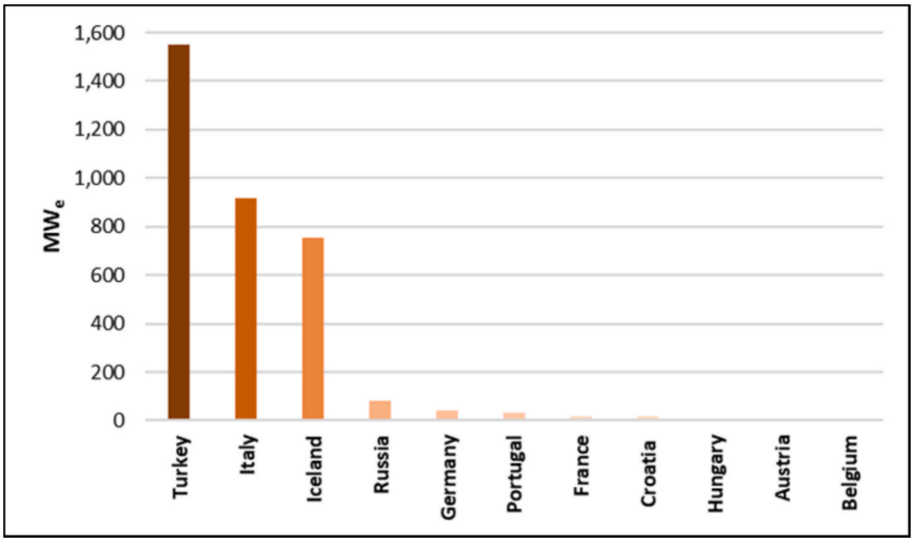

Fig. 8. European countries with higher installed geothermal capacity for electric power generation (2020) [119,113].

categorized based on air circulation (open or closed loop, being the first one more suitable to ensure air renewal and good indoor air quality (IAQ) [114]), pipe orientation (horizontal or vertical, being the first one much more frequent [121]), operation mode (continuous or intermittent, being the second one more efficient [115]), and pipe material (plastic, metallic, cemented, and composites [116]). Regarding the horizontal pipe orientation, there are a lot of possible configurations such as straight, U-shape, S-shape or serpentine, ring shape, coil shape, grid or parallel, slinky, radial, and snail or spiral [121].

The EAHX systems have several advantages, such as those reported by Greco *et al.* (2022) [116]: (1) the working fluid is air (free and without any environmental impacts); (2) lower power consumption, compared to GSHP installations; (3) higher efficiency when coupled to traditional systems; (4) less maintenance and operating costs; (5) eco-friendly installation, since they take advantage of renewable energy without the burdens of using compressors and refrigerants; and (6) promotes IAQ, given the intrinsic air renewable.

Regarding the GSHP installations in buildings, the main three components are, according to Menegazzo *et al.* (2022) [117]: (1) Ground Heat Exchanger (GHE) loop; (2) the heat pump device; and, (3) the heat distribution system within the building. The heat pump system takes advantage of thermodynamic properties of several fluids, known as refrigerants, to perform the thermodynamic reverse cycle, which is driven by electricity. Their main four components are: an evaporator, a compressor, a condenser, and an expansion device. Moreover, the same authors considered heat pump technology (aerothermal and geothermal) to be very suitable for energy refurbishment of the building sector, given the usual compatibility of a new heat pump installation with the existing heat distribution system. Moreover, given its high efficiency and environmental compatibility, the GSHP technology has gained increasing attention. These advantages make the heat pump technology to be recognized as one of the most cost-effective solutions for energy refurbishment of buildings.

From this point onwards, a short review about the trend in materials used in geothermal installations, such as pipes, working fluids, and grout materials, is presented in the following sections.

Pipe materials

The pipe materials used in geothermal applications depend on the type of system; e.g., GSHP or EAHX. The EAHX installations have larger diameter sections, which are often displayed in a horizontal open loop configuration [114,121]. Polyvinyl chloride (PVC) is a very cost-effective material for this kind of earth-to-air heat exchangers [115]. In fact, the study conducted in 2022 by Greco *et al.* [116] stated that: *PVC is better than steel since PVC is cheap, light in weight, easy to assemble, and modification of shape is possible*. Nevertheless, it was found that pipe materials do not significantly affect the EAHX performance given their typically reduced thickness [122]. Therefore, the selection of pipe materials should focus on other parameters, such as: cost, durability, plumbing, and flexibility [117].

Regarding GHE installations, the authors Javadi *et al.* (2019) [123] categorized polyethylene (PE) as the most commonly used pipe material, having a market share of 60 % based on data from the period 2010 to 2018. Next, ground heat exchanger pipes made of steel (14 %), Cu (8 %), PVC (8 %), and polypropylene (PP, 4 %) are mentioned. Other materials like polybutylene (PB), polyurethane (PU), and plastic exhibited the smallest market share (2 %).

More recently (2022), the research presented in the study by Menegazzo *et al.* (2022) [117] mentioned innovative materials consisting of thermally enhanced HDPE, making use of graphite, graphene, aluminum wires, and nanomaterials. In fact, thermal conductivity is a very relevant parameter (usually, the higher value the better for geothermal applications). However, the material choice for a selected pipe is also influenced by other technical requirements such as cost, durability, plumbing, and flexibility. According to the same authors, given its cost-effectiveness and corrosion resistance, the most widely used material in the European market nowadays is HDPE.

Working fluids

Working fluids could be categorized as gaseous (e.g., air in EAHX [114–116]), refrigerant liquids in GSHP devices [117], and secondary liquids in GHE installations [123].

The adequate choice of the fluid flowing in GHEs should consider factors such as good heat transfer properties, environmental safety, low viscosity, high durability, and low cost. Water is often used, but its use is limited, mainly in cold climates, given its freezing point. Therefore, in colder regions such as Northern and Central European countries, the use of antifreeze mixtures is often necessary [117]. Most of these antifreeze mixtures are glycol solutions, followed by alcohols and salts, being the latter two types less used due to their corrosive properties and toxicity [124]. In addition to these conventional heat transfer fluids, the study in [117] also mentioned the use of more recent technologies, such as nanofluids and micro phase change materials slurries (MPCMS).

Regarding GHEs working fluids during the 2010–2018 period, the authors of [123] stated that pure water was the most used working fluid, having a share of 58 %, followed by the ethylene glycol solution (EGS) with a 14 % share. Other liquids, such as antifreeze-water, nanofluids and propylene glycol solution (PGS), have more reduced percentages (6 %). The working fluids having smaller percentages use were assigned to aqueous solution of ethanol and calcium chloride solution (CCS), both with 3 %, followed by sodium chloride solution (SCS) and saline solution, both with 2 %.

Now, looking at the refrigerant fluids used in heat pumps, the study in [117] stated that they have a strong influence in environmental LCA performance; e.g., related to the global warming potential (GWP). During the last 20 years, the refrigerant market has clearly dominated by the hydrofluorocarbons (HFCs). However, there are several restrictions on their use in the EU, due to their high GWP. According to [125], the most used refrigerant in air-conditioning and heat pumps devices is, nowadays, the R410A, due to its near-zero temperature glide and excellent performance. However, its GWP equal to 2088 is huge [117] when compared to the current maximum allowable GWP value of 150 for new heat pump devices in the domestic sector for long-term usage [126]. Therefore, the R410A refrigerant needs to be replaced with another one having low environmental impact, low toxicity and flammability, good chemical stability, and adequate thermodynamic properties. Notice that, when replacing a high-GWP refrigerant with a low-GWP fluid results in a performance decrease, the overall environmental impact of the system may not be effectively reduced. Therefore, there are a lot of proposed R410A substitutes, as stated and compiled by [117] in a table, containing 14 alternative refrigerants.

Grout materials

The main goal of the grout material is to enhance heat transfer between the soil and the GHE, which could significantly increase the geothermal system performance. Menegazzo *et al.* [117] categorized the grout materials used in ground coupled heat pumps as conventional solutions, such as bentonite, cement and innovative solutions, including: (1) thermally enhanced grout, making use of sand, graphite (flake or expanded), and aluminum shavings; (2) controlled low strength materials (CLSMs), which are mixtures of fine aggregates (such as natural sand and coal ash), cement, fly ash, and water; and (3) phase change materials (PCMs) in different forms; e.g., nanoPCMs, shape-stabilized PCMs, and microencapsulated PCMs.

EoL and best practices

In the context of CE, it is usual to mention and adopt the so-called *R-principles*, which are based on the original three ones: Reduce, Reuse, and Recycle. Li *et al.* [127] suggested a set of *R-strategies* to be implemented in geothermal power plants, as listed (by order of preference) and described in Table 4.

Next, a best practice example is presented, showcasing the repurposing of discarded metallic pipes from industrial applications for use in geothermal systems related to residential heating. Specifically, these pipes are used in a vertical GHE of a ground source heat pump installation. The discarded products, possessing certain valuable attributes, are sold on the market and repurposed for another life cycle.

In closed-loop ground source heat pump systems, the borehole is equipped with heat exchanger piping made from materials such as plastic. Typically, HDPE pipes are used due to their low cost and ease of installation. Moreover, these pipes have a long lifespan in the ground, approximately 75 years, and exhibit the highest thermal conductivity among thermoplastic materials. However, the thermal conductivity of HDPE (0.46 W/m·K) is still significantly lower than that of metals. For example, stainless steel exhibits a thermal conductivity in the range of 13–24 W/m·K [128].

EoL metallic pipes from the industrial sector still retain economic value and are applicable for various applications [129]. Repurposing such items aligns with a circular economy approach [130]. A Slovenian company (AC&P inženirski biro, d.o.o.) [131] specialized in geotechnical and hydro-technical studies purchases EoL steel pipes from the oil industry and repurposes them for use as heat exchanger piping materials in boreholes. The repurposing process involves sandblasting to remove paint, followed by the application of new paint and a zinc coating for protection. During the borehole drilling process, these steel pipes serve as the drilling rig. Subsequently, the pipes remain in the borehole as heat exchanger piping materials. It is important to note that the expected service life of heat exchanger piping made from stainless steel is somewhat shorter than when using plastic (HDPE) material, and around 50 years. This estimate considers the corrosion of the external part of the pipe that comes into contact with groundwater [128].

Energy storage

Storage is a key element in renewable energy applications supported by the European Commission (EC) research and innovation funds.

In buildings, electrical storage is obtained by batteries able to solve grid integration issues linked to PV and to increase the self-consumption ratio of PV plants. Despite the reduction of prices, batteries are still not economically viable in all countries and markets. In general, the adoption of batteries is increasing both in the residential and in the commercial sectors because consumers are willing to maximize self-consumption.

Batteries can be used in mini-grids as back-up power, and in standalone systems to extend the duration of energy use. Moreover,

Table 4
R-strategies to be implemented in geothermal power plants, according to Li et al. [127].

(1) Reduce (Most preferred option) Hybrid systems coupling geothermal plants with other renewable energy systems, such as solar panels, wind turbines, and biomass plants may improve energy efficiency and reduce the needed raw materials.
(2) Reuse The main idea of this and the following next three CE principles is to extend the lifespan of components, equipment, and products. In this case, by reusing a discarded product that is still good, the consumption of raw materials is reduced, and the downstream waste is decreased.
(3) Repair Some geothermal power plants components; e.g., heat exchangers, pumps, and condensers could be repaired and, thus, there is an extension of their service life duration, with all the related environmental advantages.
(4) Refurbish Some old products or equipment could be brought up to date through restoration, leading this way to an increased service life.
(5) Remanufacture Similarly, to the previous three CE principles, the main idea is, once again, to extend the life of components, equipment, and products. This way, parts of a discarded product may be used in a new product, which will perform the same function.
(6) Repurpose Transforming disused oil or gas wells and coal mines into geothermal plants is a common practice, typically implemented in non-urban environments.
(7) Recycling Facilitates the integration of waste materials into supply chains. Beyond conventional recyclables like steel and plastic, geothermal brine presents an opportunity for recycling, as it contains various elements such as lithium, lead, and boron. If a different heat transfer fluid is used (not brine), it can also be recycled and employed in heating systems.
(8) Recovery (Least preferred option)Relies on the incineration of waste materials for energy generation (heat and/or electricity). However, these materials often contain elevated levels of carbon, sulphur, nitrogen, heavy metals, and other potentially hazardous and toxic elements.

batteries are installed in large-scale PV plants to stabilize grid injection and to provide ancillary services.

Globally, the largest part of batteries sold are used in EVs, and the volume of stationary storage remains small. However, the rapid development of electric mobility is driving battery prices down, giving a significant push to the development of storage as a tool to facilitate PV installations. In addition, new requirements for grid integration in tenders facilitates the use of stationary batteries in utility-scale plants to optimize grids capacity [132].

Moreover, as an effect of the energy crisis in Europe and electricity costs variability, citizens are increasingly looking at home solar power generation as a key tool to gain control of their energy bills, determining a massive growth in residential battery energy storage [133].

Thermal energy storage (TES) is the storage of heat or cold to overcome the mismatch in time, temperature, power, or location in different applications, involving three steps: charge, storage, and discharge [134]. There are three technologies for TES: (1) sensible TES involves the increase or decrease of temperature of a storage material; (2) latent TES uses the phase change from solid to liquid of a storage material; and (3) the last technology is the one in a lower development stage and includes chemical storage and sorption storage (known as thermochemical TES).

In the built environment, TES can be implemented in many ways, from the inclusion of PCMs in building envelopes to the inclusion of a TES system in the HVAC system; which could be done with any of the cited TES technologies [135]. Moreover, today there is a lot of research on the use of TES in pavements or other strategies to decrease the heat island problem [136]. For each of this application and technology, different materials can be used, and the use of by-products and wastes has been studied in depth.

Electricity storage: Trend in installations and materials

The global market for battery installations is booming and is expected to grow more than 5-fold by 2030 with residential and commercial battery installations accounting for about a quarter of this total. The Americas and Asia are the world leaders in energy storage installations while Europe, the Middle East and Africa are expected to lag behind. Although China's current accumulator installations are low, the BNEF's Energy Storage Market Outlook published in the second half of 2022, predicts that China will represent, along with US, one of the two largest global markets for accumulator installations by 2030. This is due to new energy market reforms implemented by the Chinese government, which have boosted the growth of this sector [137,138]. As the market for energy storage systems is expected to continue to grow, there are developing solutions for reusing batteries at the end of their useful life. Second life batteries (SLBs) can be used again as stationary batteries; i.e., energy storage systems with the purpose of leveling the power produced by a solar PV or wind system [139].

According to BloombergNEF, by the end of 2023, the cumulative capacity of residential batteries worldwide is expected to be 15 GW/34 GWh. However, the high cost of batteries and lack of subsidies in some countries can limit the cumulative capacity of residential batteries in all other markets to less than 1.2 GW/2 GWh [140]. The major markets in the residential sector are Germany, Italy, Japan, Australia, and US, which account for 88 % of the total residential battery market installed. In Latin America, the rapid expansion of solar and wind energy markets could lead to increased battery installations in Chile, Brazil, and Mexico [137]. Currently, China has low residential battery installations because of modest energy tariffs compared to US and Germany. Although the residential battery market in Australia is growing rapidly, solar battery connection rates are relatively limited compared to European markets. Germany is the world leader in installations of energy storage systems for residential use. In 2013, the government provided subsidies to incentivize their installation, which contributed to the highest solar panel battery installation rates in the world (75 % in 2022). Italy is the second largest market. The installation rate of batteries coupled with solar panels passed from 11 % in 2018 to 77 % in 2022. The governments of Greece, Romania, Spain, Croatia, Finland, and Lithuania have also invested in energy storage projects, with funds of more than 1 billion euros. By 2030, installations are expected to increase 10-fold caused by expanding markets in the UK, Turkey, and Greece [137].

In Europe, industrial-scale storage installations are in line with the REPowerEU plan, which sets important targets in the field of renewables [138]. In US, delays have been experienced in utility-scale storage projects in 2022. In Asia, on the other hand, Japan has announced annual incentives for utility-scale batteries, while South Korea has set an ambitious storage target of 25 GW/127 GWh by 2036 [137].

The largest part of the global market is represented by lead acid, lithium-based (LIB) batteries and nickel-based (nickel–cadmium (NiCd) and nickel-metal hydride (NiMH)) batteries (94.8 % of the total in 2016) [141].

Electric vehicles (EVs) and stationary storage are the prevalent markets of LIBs. Both the markets are projected to grow, and currently the EV market is much greater than the stationary one [142,143].

Recycling processes for LIBs exist, but it is difficult to support their collection for recycling with little economic value, or an associated gate fee. Lead-acid batteries have relatively high cost, but a simpler design and chemistry, a low-cost recycling process, and more structured collection programs.

The current method of recycling LIBs uses pyrometallurgy, or comminution followed by hydrometallurgy. These methods lead to low value and recovery products, and furthermore, having a high cost. The materials saving achieved is lower than 20 %. In closed-loop recycling, materials recovered from LIBs can be reused in the manufacture of new LIBs (the cathode recovered from a spent LIB is relithiated and reused). Open-loop recycling includes LIB manufacturing using Si from PV and soot from merchant ships. Alternatively, materials recovered from LIB are used to produce non-LIB products, such as lubricants, sorbents, and catalysts [144]. The recyclability of lead-acid batteries is nearly 90 %, and the main materials recovered are lead and plastic via leaching, carbonization, and thermal decomposition processes [141]. This success, experimented in US, Japan, and Europe, is due to the high cost of lead, the uniformity of the materials and battery design. The materials recycled are mainly used to produce new batteries. In the future, material constraints are predicted to be more crucial for LIBs, in particular the demand for cobalt (Co) is expected to be 50 % greater by 2025, also the demand for nickel (Ni) will be greater [144].

Another potentiality in CE is offered by spent batteries from electric vehicles. A second life of these batteries represents a cost-effective option for energy storage, especially in combination with PV and wind turbines. Generally, these batteries are replaced when they have 70–80 % of the original capacity, and can be located in less stressful applications, such as in buildings for load leveling, transmission support, and grid frequency regulation. The advantages of this application are the extension of the battery lifetime (3–5 years), and 12 %-16 % of economic savings if combined with PV [145].

In Europe, industrial activities and research projects indicate that the second use of LIBs is of great interest in the value chain. However, several barriers can be identified: regulatory barriers (absence of robust framework for battery reuse); technical barriers (scarce data on battery degradation); economic barriers (uncertainty about economic returns and incentives); safety barriers (hazards and fire risks in removing and handling) [146].

EoL and best practices

According to European regulations, waste batteries and accumulators are subject to the principle of "Extended Producer Responsibility" (EPR) [147]. Therefore, all parties involved in the management of WEEE (Waste Electrical and Electronic Equipment) and WB (Waste Batteries), are obliged to join a consortium for the disposal of such waste [148]. Founded in 2002, the European Recycling Platform (ERP) is a consortium active in Europe and around the world. The European countries in which the ERP operates are Austria, Denmark, Finland, France, Germany, Ireland, Italy, Norway, Poland, Portugal, Slovakia, Spain, Sweden, and the United Kingdom. ERP's goal is to adopt solutions that meet both legal obligations and the take-back and treatment needs of EoL solar panels, inverters, and storage batteries [147]. To date, the ERP website shows that the consortium has disposed of more than 40,000 tons of batteries from different sectors [149]. EUCOBAT is the European association of national battery collection systems and ensures that EoL batteries are collected and recycled. The members of EUCOBAT are 27 companies and nonprofit organizations from Austria, Belgium, Cyprus, Denmark, Czech Republic, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Poland, Romania, Slovakia, Spain, and Sweden [150]. In addition to consortia, there are many virtuous companies involved in the recycling of batteries and accumulators. The Sunlight group is a Greek company skilled in the development, production and distribution of batteries for use in various fields including Energy Storage Systems (ESS) installed in renewable energy plants [151]. The Sunlight group is carrying out several research studies with the aim of implementing the existing plant and adapting it to the recycling of lithium–iron-phosphate (LFP) storage systems [152]. The company opened in Komotini (Greece), in 2014, is one of the most advanced lead-acid battery recycling plants in the world [153]. In 2022, the recycling plant produced 45,000 tons of lead, accounting for 50 % of the lead used in the production of new batteries. The company, in the next few years, aims to process more than 25,000 tons of lead-acid batteries to reach an annual recycling rate of 100 %. Another virtuous example is the Swedish company Northvolt whose business is to produce LIBs. Through its Revolt recycling program, the company announced the production of a LIB with metals recovered from the recycling of EoL batteries from electric vehicles, production waste and stationary ESS [154,155]. The company aims to make its recycling plant the largest in Europe, and currently, the recycling process can recover up to 95 % of the metals in a battery with a level of purity equal to that of virgin materials. TES is a company established in 2005 that focuses on providing solutions to reuse EoL technological devices in a responsible and sustainable way [156]. The company has 40 facilities worldwide, and the European ones are located in France, Germany, Italy, the Netherlands, Spain, Sweden, Hungary and England. TES has developed two battery recycling processes: a black mass process and a chemical refining process. In the black-mass process, drilling machines and automatic shredders dismember the batteries into a black mass rich in various precious metals. That plant can process 14 tons of LIBs per day, with a 90 % recovery rate and 99 % purity for some precious materials such as Ni, Co and Li which are later used to produce new batteries. The chemical refining process involves feeding the black mass into several leaching reactors and filter presses to extract graphite, Co, and Li [157].

Thermal energy storage: Trend in installations and materials

TES was already used in ancient times, mostly for food conservation and cooling, but also seasonal storage of ice can be found in ancient references [158]. However, this technology has still not been deployed to its side potential. TES has been identified to have a key role in the energy transition [159], but still only a few applications are clearly widespread, such as water storage for domestic hot water (DHW), ice and chilled water storage, underground TES (UTES), and molten salts storage for concentrating solar power plants (CSP). Other applications, such as the use of sensible TES to increase the thermal inertia in buildings or the use of latent TES in HVAC systems, are understood to be very difficult to quantify. A summary of the installed capacity of TES is shown in Table 5.

TES is implemented through three different technologies; i.e., sensible storage, where the temperature undergoes a temperature change within charging or discharging; latent storage, where the material undergoes a phase change, usually liquid–solid, but also solid–solid; and chemical reactions and sorption, also called thermochemical TES, where the energy is stored due to a chemical or physical transformation of the materials [134].

Table 5
TES installed capacity [158].

TES type	Installed power [MW]	Rated storage capacity [GWh_{th}]	Production [GWh/y]
Hot water tanks (for EU28)	–	125	–
Molten salts for CSP (in 2020)	2,087 (in electric installed capacity)	38	5,574 (electricity production calculated from expected production values)
Ice and chilled water storage	2,111 (peak shift capacity)	19	–
UTES	2,884	–	4,281 (thermal production)

TES – Thermal energy storage; CSP – Concentrating solar power plants; UTES – Underground thermal energy storage.

TES can be included in buildings, such as in many other applications, as active storage or as passive storage [160]. In buildings, active storage systems are those where the storage material is in the HVAC system itself, usually with the TES material in a TES tank; passive storage is considered when the storage material is included within the building envelope.

The materials that can be used in TES are multiple and it is impossible to list all of them in this paper, therefore only a short summary is presented here [161–164]. In summary, sensible TES uses materials with high thermal inertia in passive systems, such as stone, concrete, and earth; in active systems, water is the most used material.

Latent TES for passive systems uses phase change materials (PCMs) that can be included in the material itself, such as in concrete, insulation materials, gypsum, and others; can be added as a new layer, such as in gypsum plasterboard, in sandwich panels, or in the building structure such as in roofs, walls, or windows. Active integration also presents different options. The first one is the building core activation, where PCMs are included in the building structure components such as walls, ceiling, or floors and are activated with air as heat transfer fluid (HTF). Other options are the integration of PCMs in suspended ceilings, the integration of PCMs in the ventilation system, the integration of PCMs in an external solar facade, or even the integration of the PCM in solar collectors.

PCMs can be organic or inorganic. Organic PCMs are paraffin, fatty acids, or esters; the recent trend in the use of bio-based organic PCMs should be highlighted. Inorganic PCMs used in buildings are salt hydrates. Organic PCMs have low thermal conductivity, low density, and low melting point, and are highly volatile, flammable, and have a high-volume change. But on the other hand, they have better physical and chemical stability than inorganic ones, usually showing better thermal behavior. Inorganic PCMs are more attractive in some applications due to their higher energy density, higher thermal conductivity, and lower cost.

In buildings, the so-called thermochemical TES is implemented with sorption systems. Recently, sorption storage has reached plenty of interest, especially because it is seen as high potential for long-term storage also known as seasonal storage. Materials used in sorption storage are zeolites and silica gel in physisorption, and salt hydrates, composites, and ammoniated salts in chemisorption.

EoL and best practices

In the built environment, the use of TES technologies should consider all the same aspects as any system. The one aspect that is different for TES vs. renewable energy systems is when the TES material, usually PCMs, is included in the building envelope. In such cases, the TES material can be included in the material itself [135] or as a new layer [165]. The second option brings higher circularity since deconstruction, and therefore end of life reuse or recycling, is possible.

Here, two examples of the use of by-products in TES for the built environment are summarized, but other cases can be found in the literature [166]. The first example is the revalorization of bischofite as PCM. Bischofite is a by-product of the non-metallic industry that today is commercialized in low added value applications. Bischofite is composed mainly of $MgCl_2 \cdot 6H_2O$, a PCM melting at 114.5 °C with an enthalpy of 135 kJ/kg. Bischofite was found to melt at 100 °C with an enthalpy of 115 kJ/kg [167]. Due to the good results, this by-product was mixed with other salts (also by-product) to decrease its melting temperature to those more optimal to be used in building applications [168].

The second example is the use of wastes and by-products in concrete or mortars used in buildings to increase their thermal inertia or other properties [169,170]. Finally, by-products have also been added to PCMs to improve their behavior in TES systems by changing their thermophysical properties. As such, steel slag, a by-product from the metallurgical industry, was added to stearic acid to improve its thermal conductivity [171] or blast furnace slag is added to PCMs [172,173].

Discussion and remarks

Integrating energy from renewable sources in the built environments such as buildings and cities is a fundamental step for decarbonization and circularity; even if, to date, it has two critical issues:

1. The materials used in the manufacture of PV modules or wind turbines are mostly raw materials, including rare earth metals, extracted in nature rather than using waste or by-products
2. The end-of-life phase of the materials that make up the renewable energy systems are not yet well clear, and a reason for such criticality could be a low flow of materials, coming from such systems

The flow of high value materials from EoL wind and solar plants is currently limited due to the low number of decommissioned facilities. However, an exponential growth of this flow is expected in the near future. It is therefore urgent to find solutions for the reuse of these precious materials, extending their life cycle as much as possible.

The application of energy-saving criteria in buildings and cities and the large-scale integration of renewable energies in urban environments are incentivized towards new energy concepts, zero-energy building scenarios and low-emission cities.

Below there are some observations and remarks regarding the particularities of each of the on-site renewable energy technologies addressed in this paper, viewed from a circular economy perspective emphasized at the EoL stage.

On the one hand, PV capacity is mainly concentrated in Asia and Oceania, followed by Europe, with Western Europe leading European installations. The nominal life of a building is about 100 years, while a PV system records an average life of about 20–30 years. This means that, in the near future, it will be necessary to think of actions that will extend the useful life of energy systems and, at the same time, use less raw materials. Given that PV panels have a useful life up to 30 years, a considerable amount of waste could be generated by 2050. Therefore, the high-value recycling stage in solar modules has not yet been reached, and the cause may be the low flow of discarded solar modules. No continent, except the EU, has enacted rules and regulations on PV module recycling, which is why the largest number of solar waste recycling companies are located in Europe. Recycling of PV modules, regulated by the EU to ensure the safe handling of hazardous materials, is a challenge due to current downcycling practices, such as those of PV CYCLE consortium, which only recover around 80 % of the materials. However, there are several on-going innovative projects that aim to improve recycling processes, recover valuable materials, and increase sustainability within the PV industry.

On the other hand, solar-thermal (ST) technology market has recently experienced a fast growth in Europe, mostly related to large-scale applications, driven by national subsidies and support frameworks. Most of the European ST systems installed are flat plate collectors, with most facilities relying on recyclable materials such as copper and glass. This offers significant opportunities for sustainability in the built environment, particularly through the expansion of large-scale systems such as solar district heating and advances in PV/T systems. However, there is a scope to improve recycling processes and develop circular business models that prioritize longevity, resource efficiency, and waste reduction. Although research on the EoL phase of solar thermal collectors is still limited, it is evident that, even though they share some components with PV systems, they present specific critical issues in the recycling process. In particular, the polyurethane foam (in thermal systems) and the EVA layer (in PV systems) are significant obstacles to recycling. Nevertheless, some strategies common to both technologies can be identified to foster a CE strategy, such as: the development of a secondary market for used modules and the design of modular systems that have removable parts with the aim of facilitating the replacement of individual components.

Wind energy has developed rapidly since 2000, with China being the leading country in installations. In Europe, most of the installations are onshore, mainly concentrated in the Western, Northern, and Southern regions, while UK leads in marine installations. Wind turbines are built from materials such as steel, aluminum, and composites, and efforts are underway to explore new materials and designs to optimize performance and sustainability. At the end of their useful life, wind turbines can be reused, recycled or dismantled, with initiatives leading recycling efforts. Projects, like DecomBlades, aim to standardize recycling practices, while companies like Enel Green Power and Siemens Gamesa focus on developing fully recyclable turbines and innovative reuse applications, promoting CE principles in the wind energy sector.

The use of geothermal-based HVAC systems for heating and cooling of buildings is expanding, with Europe at the head of the world installed capacity, particularly in Northern and Western countries. Europe primarily uses geothermal energy for direct thermal applications, while Southern Europe dominates geothermal capacity for electricity generation. The use of heat pumps, including aerothermal and geothermal technologies, are ideal for the energy retrofit of buildings. Common materials for geothermal systems include polyethylene and polyvinyl chloride for heat exchangers, while recent restrictions on hydrofluorocarbons are prompting shifts toward lower global warming potential refrigerants. Examples of CE practices in geothermal plants, such as the reuse of discarded metal pipes, highlight the potential for greater material circularity, although research on this topic remains limited. Little attention is paid in scientific literature to the EoL phase of geothermal plants, probably due to the low prevalence of such plants, which are concentrated in a few areas of the world.

Energy storage is a key element in most of the renewable energy technologies. On the one hand, electrical storage technologies have seen significant advances and have become crucial in balancing the supply and demand of renewable energy. The global market is dominated by lithium-ion batteries, which are widely used in many applications, from electric vehicles to grid storage, due to their high energy density and efficiency. However, some challenges exist, such as resource scarcity for materials such as lithium, cobalt, and nickel, as well as the environmental impact of battery production and disposal. Efforts are currently underway to address these issues through innovative solutions such as solid-state batteries and recycling programs. For example, companies are developing closed-loop recycling processes to recover valuable materials and reduce waste, while research into alternative chemicals, such as organic and sodium-ion batteries, aims to mitigate resource constraints and improve sustainability. CE practices, including the reuse of battery materials and the development of second-life applications, are increasingly important to improve the life cycle and reduce the environmental footprint of electrical storage technologies. The reuse of spent batteries from electric vehicles as stationary storage systems in renewables promotes circularity. However, this practice is not sufficient to meet growing energy needs. It will therefore be critical to pair it with innovative strategies to optimize high-value recycling of these components and recover their valuable materials. On the other hand, although TES technologies were already used in ancient times, today they are clearly underused in comparison with electrical storage, despite the fact that they play a key role in the energy transition. TES is applied in areas such as domestic hot water, underground storage, and high-temperature solar energy, each of which requires storage materials with different features. While integrating TES into building envelopes presents some challenges, there are opportunities for circularity through reuse of by-products and incorporation of waste materials as TES materials to improve performance and enable recycling.

Summarizing, the main research gaps identified in this review manuscript are the lack of in-depth studies on components reuse, material recycling, and the creation of CE models for each technology. Some practical challenges were also identified, such as difficulties related to the implementation of efficient recycling processes, the lack of adequate infrastructure, and the low adoption of some technologies in certain European regions.

Conclusions

Industry and public administration must apply circular models in the energy transition, thus optimizing sustainability and circularity, and improving the competitiveness of European companies. The application of energy-saving criteria in buildings and cities, and the integration of large-scale renewable energy systems, are currently encouraged toward new scenarios of zero-energy buildings and low-emission cities.

In this technical and economic context, this study confirmed the rapid growth in the installation of renewable energy technologies, especially solar and wind, but highlighted that the production of components involves high quantity of raw and precious materials. Moreover, the reduction of material usage and the implementation of circular end-of-life strategies appear as cross-cutting issues that found valuable approaches and solutions in those examples where researchers, companies, and the market were in synergy and well organized in funded projects.

In particular, and considering the solar systems, it seems to be essential to invest in research of innovative solutions that improve the production process, increase the efficiency and durability properties of photovoltaic modules already well diffused in the market. A remarkable example is offered by the evolution of traditional silicon solar cells in PERC, TOPCon, and finally HJT technology. The market of PV/T technology could be encouraged as it offers the advantage of installing a single system that converts solar radiation into thermal and electrical energy using less materials and components. Additionally, it could be suggested that installers apply scheduled procedures to prevent component dispersion and locate sensitive points to constantly monitor their deterioration.

Best practices, already consolidated in some technologies, could be transferred and adapted to others. This is the case for glass and metals coming from PV and solar thermal systems that could be collected and treated in a common and more effective process, reducing downscaling of value. Furthermore, consortiums that collect spent batteries offer a framework for harvesting the components of photovoltaic, solar thermal, wind and geothermal, avoiding dispersion into the environment and maximizing the recovery of valuable materials. A similar approach can be moved to heat transfer fluids (such as water and glycol) from solar thermal plants and geothermal systems. Although different technologies exist, the solution could be to standardize the disposal process that can occur with the same procedure and company, increasing material flow and economic benefits.

In general, to make the energy systems under consideration towards develop more circular, manufacturers have to conduct detailed analyses of the materials used and assembly techniques in the design phase that were crucial in the successive EoL management, PV panels are an emblematic example of this issue. The aim of a similar effort should facilitate recycling operations and allow the actual flow of materials associated with each production, operation, and dismantling step.

In general, in European countries, the transition to a circular economy in parallel with sustainable energy production still presents barriers originating from fragmented approaches. To date, the lack of ad hoc legislation and guidelines in the area of circularity of renewable energy systems results in several obstacles that need to be addressed by governments and well adopted by practitioners. However, it is necessary to take the opportunity that arises from this challenge to reach significant environmental and socioeconomic improvements, stimulating the creation of new job opportunities in skilled companies.

This study aims to provide valuable knowledge on how to improve sustainability and circularity in renewable technologies implementation; especially regarding materials management, recycling, and system lifespan extension. A focus on recycling processes and innovation in modular materials and designs can provide the basis for a significant shift towards CE strategies in the renewable energy sector. Furthermore, the study identified some research gaps and practical challenges in these areas, which should contribute to advancing current knowledge by pushing researchers and industries to develop more efficient solutions and waste management policies that help mitigate the environmental impacts of renewable technologies. Advancing knowledge in these fields not only facilitates a more efficient transition toward a CE model but also strengthens the long-term sustainability of renewable energy in the context of a resource-limited planet.

CRediT authorship contribution statement

Marilena De Simone: Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Daniele Campagna:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Luisa F. Cabeza:** Writing – review & editing, Writing – original draft, Conceptualization. **Rocío Pineda-Martos:** Writing – review & editing, Writing – original draft, Conceptualization. **Paulo Santos:** Writing – review & editing, Writing – original draft, Conceptualization. **Janez Turk:** Writing – review & editing, Writing – original draft, Conceptualization. **Viorel Ungureanu:** Writing – review & editing, Writing – original draft, Conceptualization. **Gabriel Zsembinszki:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

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

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Data availability

No data was used for the research described in the article.

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