Chapter 16
PV and Thermal Solar Systems Application in Buildings. A State of Art in the Context of Circular Economy

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Abstract Solar energy is one of the most promising sources for low carbon energy production. In particular, PV panels and thermal solar collectors can be easily integrated into new and existing buildings to improve their energy efficiency and sustainability. On the other hand, solar-based technologies require extraction of natural resources and processing, thus materials conservation and recovery are vital to effectively contribute to the decarbonization of the construction sector. The paper is meant to be a brief state of the art that summarizes the relevant issues for achieving the goal of circular economy of buildings with the focus on solar energy application, with the novelty of considering and comparing two technologies, photovoltaic and thermal. Most of the scientific literature was dedicated to PV technologies due to the increasing importance of the electrification process and the usage of materials with reduced availability. Thermal solar collectors were mainly analysed developing LCA without a larger point of view embracing circularity concepts. Apart from the technological matters, the investigation highlights social, behavioral, and economic aspects that can be crucial to trace the route to circular economy.

Keywords Solar energy · Buildings · PV · Thermal solar collector · Circular economy

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16.1 Introduction

16.1.1 Energy Efficiency of Buildings and Cities

In 2021, the European Commission proposed new legislation to promote the decarbonization of buildings and reduce methane emissions by 80% in 2030. Moreover, in 2022, new requirements to improve the sustainability of products and constructions were introduced with the aim to reduce primary energy consumption [1]. In the background of the energy transition, buildings are responsible for about 40% of the total end-use energy consumption. Generally, the residential sector consumes more energy than the commercial sector. Energy demands for space heating and hot water production predominate in the residential sector [2], while energy for HVAC systems and lighting are higher in commercial buildings [3]. In the future, due to the global warming, a significant increment in cooling demand of the residential sector is predicted [4]. The Nearly Zero Energy Buildings (NZEB) concept and diffusion could be a proper response to reduce energy consumption according to the Energy Performance of Buildings Directive (EPBD) [5].

The development of envelope materials is an important action to reach the NZEB target and apply eco-friendly and economical solutions in parallel with the installation of renewable energy technologies. The use of renewable energy systems can significantly contribute towards net positive energy balance of buildings [6] coupling smart electricity distribution grids and smart metering systems [7].

Buildings should become energy producers contributing to the opportunity to reach a balanced energy infrastructure. In the light of these changes, it is also important to underline the role of Micro-CHP, high performance HVAC systems, smart-grids and predictive Building Automation and Control Systems [8].

Moreover, the development of efficient building energy modelling (BEM) tools is valuable since there is a gap between measured and predicted energy demands. This gap depends on the specific building facility and on the building standards that generally simplify the definition of design parameters related to occupants' behaviour [9]. Occupants' behavior, habits, preferences, contribute to the mentioned mismatch between the designed (predicted) and real building energy performance. Occupant monitoring and the development of novel models, incorporated in building simulation tools, are still challenging research tasks [10].

The progressive integration of renewable energy in buildings and cities is an important step towards more circular material flows. But the materials needed to decarbonize electricity and mobility are supplied by natural resource extraction. Critical technologies to the clean energy transition, such as wind turbines, photovoltaic, batteries and vehicles, still primarily utilize feedstocks from natural resources instead from waste for processing and production. Moreover, robust and complete end of life (EoL) management strategies are not well developed for these materials. In the future, renewable energy manufacturing could be affected by depletion of metal reserves and consequent price volatility. Increasing metal recovery rates is a multilayered problem complicated by the inefficient collection and processing of metals at EoL and the still low-cost supply of certain metal reserves [11].

The aim of this paper is to synthesize current research themes, initiatives, and opportunities for the circular economy of solar technologies applied in buildings as pivotal to energy transition and decarbonization of the building sector.

The main novelty of the study is the consideration of both the systems, PV and thermal, following the leading concept that encourages energy mix and technologies integration.

The research questions that led to the study are the following:

(1) What are the application trends of PV and thermal systems and related implications in circular economy?
(2) What are the advantages and disadvantages of these two technologies in the light of the energy transition and circular economy?
(3) What are the main issues and potentialities in terms of materials used, EoL management, regulations, and social aspect in European countries?

To answer to these questions, documents were searched from the Scopus database and the websites of consortia, associations, and institutions that provide reports and information on renewable energy application at the European level.

16.2 Solar Energy Application in Buildings

Documents were searched from the Scopus database using the following key words: PV AND circular economy, solar thermal AND circular economy, PV AND LCA, solar thermal AND LCA. PV and thermal were also used in the same search. The documentation was enriched by reports and regulations collected on official websites. In total, 57 papers were found on photovoltaic panels, 15 papers on thermal systems (only considering LCA), 17 reviews on the solar systems application in buildings with related technical, environmental, and economic aspects. Only 4 research papers were collected on the comparison of the two technologies.

The documents listed in this paper, for the sake of brevity were limited to those that were informative to the research questions avoiding a pure description of a sole solar system. This section is dedicated to the two first research questions.

16.2.1 Electricity and Heat Production

Solar energy in buildings is used for electricity production from PV technologies and heat production from solar thermal systems. Integrated photovoltaic thermal PV/T systems are also available for production of thermal energy as well as electricity, but they are less market attractive due to relatively high investment cost [12]. The current problem with PV technologies is the high investment compared to their limited efficiency. PV market is mainly silicon based (about 95%) with a conversion efficiency usually ranging from 12 to 17%. The development of new PV technologies is oriented to organic and hybrid (organic–inorganic) Perovskite PVs, organic, or ones with the application of nano-technologies, such as nanopillar solar cells. The mentioned novel PV technologies are still not ready for an expected wide market application, due to present technical shortcomings and unfavorable economic viability [11].

The main types of solar thermal collectors can be classified in: glazed flat-plate solar collectors, the most versatile and widespread type that has good efficiency and guarantees the production of hot water with a variable temperature between 40 and 70 °C, and can be used all year round; unglazed solar collectors that are cheaper but also less efficient; evacuated and heat pipe solar collectors that have higher efficiency but present a more complex operation and technology.

The development of hybrid energy systems could be an effective solution to integrate in buildings renewable energy technologies based on the utilization of solar energy, and recent investigations, such as [13], evaluated different hybrid energy options for residential applications.

PV/T technology is particularly suitable in hybrid energy systems, but further development of PV/T plants is necessary to improve efficiency and reduce unit costs. Different PV/T configurations have been recently investigated and mainly focused on the technical aspects by simulation [14] or experimental approach [15].

16.2.2 Solar Systems and Circular Economy

The installation of silicon based solar modules continues worldwide. Waste management linked to this technology is a pressing problem considering that PV have 25–30 years of productive life. The predicted EoL PV modules could be 80 million tonnes globally by 2050 [16] and waste generated from solar panels is considered as one of the future challenging waste streams [17]. The materials that can be recovered from EoL photovoltaic waste include glass cullet, silicon wafers and granulates, silver, indium, tin, molybdenum, nickel, zinc, copper, aluminum, steel, tellurium, cadmium, selenium, gallium, ruthenium, and plastics. PV panels can also be a source of smelter flux by metals recovering. Plastics are in backsheets and encapsulants. The backsheet is usually made of polyvinyl fluoride that can be difficult to recycle due to toxic hydrogen fluoride halogen compounds [11]. Solar thermal (ST) installation recorded a market decline since 2010 [18]. Generally, this contraction is due to less attractive incentives, whereas the industrial sector and technology are well-experienced. This fact produced also the perception of more difficulties in this investment choice than PV one [19]. Overall, in the European countries, the ST market suffered the current economic crisis and can be found quite dependent on political support programmes. A comparison between the trends of diffusion of the two solar technologies is presented in Fig. 16.1a, b.

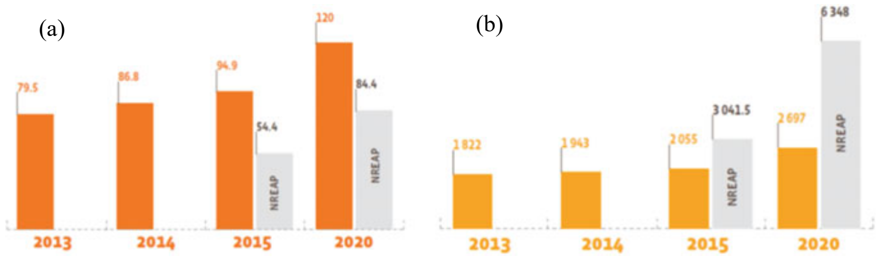

Fig. 16.1 **a** Comparison of the current trend of photovoltaic capacity installed (in GWp) and **b** of thermal solar systems (in ktoe) against the NREAP (National Renewable Energy Action Plans) roadmap. *Source* [20]

The variety of materials involved in ST systems is minor, but a large amount of metals and glass is implicated. As a consequence, recovery and recycling appear to be reasonable alternatives to final disposal to landfill or incineration [21].

The decline of ST application can also be the reason why a lot of the literature concerning circular economy development in the solar sector was focused on PV systems, neglecting the problems related to the ST already installed and the applicability of this technology in the future.

Both PV and ST systems can offer advantages and disadvantages from the environmental and economic point of view and potentialities in the light of the energy transition and circular economy.

Few studies are still available in the literature focused on the comparison of these two solar technologies. As an example, the authors of [22] compared the economic benefit related to the installation of Domestic Solar Water Heater (DSHW) and Building Integrated Photovoltaic (BIPV) systems for households and found that the convenience of these technologies is strongly related to the roof surface availability and incentives.

The authors of [21] posed the following question: "If a given surface of domestic roof is available, which is the best option in term of energy and environmental impacts for solar energy exploitation?". They considered the end of life of PV and ST technologies assuming that metals and glass can be recovered. In particular, LCAs were conducted to compare flat solar thermal collectors with four types of PV modules (mono-Si, multi-Si, CdTe and CIS) by considering a domestic usage. ST registered the highest number of favorable indicators: eight out of ten, in the case of no-recycling of materials after dismalting phase, and six out of ten in the case of recycling of materials after dismantling phase.

Also in [23] LCAs analyses were developed to compare the environmental performances of a PV system with mono crystalline cells and a ST system with evacuated glass tube collectors. The results demonstrated that the solar panels are responsible for the most impact in both the systems. ST system provided more than four times release to air than PV, and the outputs by a PV system to soil and solid waste were about one third that of a ST plant. The study also highlighted the importance of the selection of the system components (solar panels, battery, and heat storage), taking into account the problems related to toxicity.

The advantages of combining ST into PV panels were illustrated in [24]. The author promotes this integration in manufacturing, retrofitting of deployed panels, converting EoL panels. Overall, an extension of the productive life of PV can be obtained and also the performances of the heat production and storage can be improved using phase change materials.

16.3 Barriers, Challenges, and Opportunities

The implementation of circular economy embraces environmental, economic, and behavioral variables that can constitute positive drivers or obstacles.

This section provides information regarding the issues related to the usage of natural sources and materials, the problems still encountered in the EoL, the development of regulations at the European level, and some considerations on social aspects.

16.3.1 Materials and Manufacturing

Energy transitions and decarbonization will increase demand for certain materials and it is important to get product designers to think about recycling to reduce the impacts from mining. Elevate attention should be paid to metals, glass, and plastics.

Crystalline silicon PV panels require silver, quartz, copper, metallurgical silicon, aluminum, and tin. Thin-films PV made of CdTe require tellurium, cadmium, molybdenum, or tin. Thin-films made from copper indium gallium selenide (CIGS) require copper, indium, gallium, selenium, cadmium, tin, or zinc depending on the buffer layer used. Perovskites depend on lead and tin compounds.

The usage of plastics includes both recycling and degradation designs. Plastic degradation answers to the economic and environmental need for disposal at EoL. Different types of backsheets are available, and also batteries can include plastics that can be recovered or produced with recycled material. Bioplastics are alternative solutions. Bioplastics for batteries and PV panels must be stable during the operation phase and should provide end of life degradation under diverse environmental conditions [11].

Glass has an important role in energy transition. Flat glass is used both in PV (80–97% glass by weight) and thermal panels. Other kinds of glass can be found in batteries [25].

Solar technologies require glass with specific optical characteristics, generally low iron glass. Antimony and cerium are present in pre-2000 PV glass. The variety of glass composition and presence of impurities can complicate the recycling phase.

Overall, the percentages of recoverable materials that can be used in the production of modules are significant for glass and aluminum (97 and 100%, respectively), for copper and tellurium (about 80%), lower for rare metals such as indium and gallium (75 or 99%, respectively) that have a great value, despite are only 1% of the weight of the panel [26].

16.3.2 End of Life

The oldest generation of PV panels permits more than 80% recovery rates of components through the separation of plastics using a heating process and the manual recovery of the solar cells, glass, and metals. The process presents two critical issues: the necessity of manual activities, and the availability of many different silicon based solar cells that require specific treatments.

Automated processes for treating crystalline silicon modules need developments. The process employed by First Solar achieves elevate recycling rates for glass and semiconductor material (about 90%) [27].

Several studies are conducted in order to test processes applicable to emergent and new PV technologies (CIS, CIGS), for which it is still difficult to make predictions regarding the implementation of suitable EoL.

Moreover, a process of dematerialization in the production phase of the modules can have benefits in terms of costs and management of EoL. Recent and ample literature highlights as LCA is also a useful method to be applied to the solar technologies supply chain in order to ensure a “closure of the loop” [26].

16.3.3 Regulations and Standards

During the last decade, the EU enforced specific regulations concerning PV waste treatments. In particular, the extended producer responsibility principle (EPR) supports that producers are responsible for treating their EoL products [28].

The European Union’s Waste and Electrical Equipment (WEEE) Directive included photovoltaics in waste regulations and established that producers have to prefinance anticipated reclamation and recycle costs. Moreover, Restriction of Hazardous Substances (RoHS) Directives prompted PV producers selling into the EU to plan take-back and collection on site [29].

Thus, basically, EPR organizations require compliance with EU standards (CENELEC or WEEELABEX) by contract operators, and EU prohibits collection of PV panels with construction and demolition waste, requires separate treatment of silicon and non-silicon PV panels; imposes depollution requirements on metals like cadmium, selenium, and lead. Moreover, thermal, chemical, and mechanical treatments of PV panels need the removal of dangerous substances [30].

The transition from linear to circular economy can provide benefits from diverse points of view: environmental protection, increasing security of the supply of energy and materials, stimulating innovation and competitiveness, and creating new job opportunities. With this aim, several countries in the world such as China, Japan, Canada, and also European nations like Germany, UK, The Netherlands, Sweden, and Finland promoted the CE concept [31].

16.3.4 Social Aspects

A recent and influential study based on the application of agent based model and machine learning techniques [16] highlights the importance of considering social factors in circular economy developments. The authors claim that a significant improvement of PV material circularity can be obtained by social interventions targeted to increase customer attitudes towards used PV modules. Also the authors suggested the question "Could it be possible to have a secondary market for used PV as strong as the market for used cars?".

In addition, as reported in [32], waste production is affected by recycling behavior that varies from the type of economy. This study underlines the difficulties encountered in the populations of the European countries to understand the relationship between waste reduction and resource efficiency.

The education of the population is a key action to increase people awareness and to understand the importance of the contribution of each of us to the waste management.

16.4 Conclusions

The paper presents an overview of potentialities and issues concerning the application of circular economy to solar systems for energy production in buildings. The study starts from two relevant challenges for the European Union: energy transition and sustainable protection of natural resources. In this framework, the buildings sector is recognized as a key target by the scientific community and governments.

The installation of solar systems in buildings can answer to the need for decarbonization and can reduce the dependence from fossil fuels. Solar thermal (ST) systems are a mature technology able to ensure low costs and adequate efficiency, but it is penalized by scarce incentives that decelerated a massive diffusion. This can be the reason why scarce scientific literature and governmental initiatives support the inclusion of ST in structured concept of circular economy, despite of the significant usage of materials such as glass and metals. Attention was devoted instead to PV systems that still have low efficiency and require the application of a higher variety of raw materials. LCA analysis was effective to demonstrate the clear environmental advantages that both these systems can provide, especially if recycling or reuse of components is prevised at EoL. Moreover, new systems can be developed in the future, such as the combined PV/T panels. Technical and environmental issues affect the treatments at EoL and regulations and standards were focused on resolve them.

Despite the availability of European directives, EU members considered the problem with different attention and efforts. Moreover, human and behavioral aspects related to the application of circular economy in the real society are neglected in the majority of initiatives.

The study demonstrates the complexity of the problem, in terms of the diverse nature of driver factors and contexts, that requires more cooperation between the scientific disciplines as well as more organized frameworks connecting public and private sectors of the economy. On the other hand, this state of art is limited to be a general overview, and deeper analyses could be drafted considering issues and initiatives for each European country.

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