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Overview of solar technologies for electricity, heating and cooling production

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ABSTRACT

The efficient use of local renewable energy sources is a key factor to reach the EU's targets on climate change and renewable energy. In this review, the available technologies to convert solar energy into electrical and thermal energy are investigated. Photovoltaic panels, thermal collectors, heat pumps, solar cooling and energy storage systems are analyzed with a particular attention to their market availability for small-scale applications. Different ways to provide heating, cooling and sanitary hot water from solar source are analyzed and compared from an efficiency, economic and environmental perspective.

1. Introduction

In the Horizon 2020, the European Commission defined the strategy for a 'smart, sustainable and inclusive growth' and identified renewable energies as the basis of this development, setting three important goals to be achieved by 2020: 20% cut in greenhouse gas emissions compared to 1990 levels, enhance the energy savings by 20% and 20% increase of renewable energy consumption. The European Directive 2009/28/EC, provides the framework for 'the promotion of the use of energy from renewable sources' and establishes the objectives to be achieved by each EU Member State, while the measures for the enhancement of the energy efficiency are provided in the 2012/27/EU Directive. An other important step towards the 2020 targets is represented by the European Directive 2010/31/EU [1] on the energy performance of buildings, which points out the importance of reducing energy consumption and promotes the use of renewable energy sources in the building sector. Buildings account for 40% of total energy consumption in the European Union and this percentage is likely to increase, due to population growth, enhancement of the comfort levels and services provided, as Perez-Lombard et al. [2] underline in their survey of building energy consumption.

In 2015, new objectives for 2030 have been approved: 40% cut in greenhouse gas emissions compared to 1990 levels, 27% share of renewable energy consumption and 27% energy savings. The central role of renewable energy is then evident.

This review focuses on solar energy and aims at analyzing the application of solar renewable energy systems for the production of electricity, heating and cooling, to guarantee the best service to the end-user while ensuring optimal energy conversion and usage, based on the best available technologies. Various studies are available in literature which describe the different options to produce electrical and thermal energy from solar energy. Solar technologies are mainly analyzed in terms of efficiency and installation costs. Sarbu et al. [3] provide a detailed technical description of the different solar systems (solar PV, solar thermo-electrical, solar thermo-mechanical and solar thermal cooling). Similarly, Lazzarin [4] describes solar electrical and thermal solutions, comparing the different options based on the overall system efficiency and the investment cost. In 2008, according to the economic analysis carried out by Kim et al. [5], solar thermal cooling was representing an attractive solution. However, due to the severe reductions in the prices of PV systems and the increase in heat pump efficiencies, a more recent analysis carried out by the same authors in [6], shows solar electric as an interesting option from both an economic and efficiency point of view. This conclusion is in agreement with the projections of Otanicar et al. in [7]. While previous studies focused on the use of solar technologies for cooling purposes, this work will tackle the analysis of solar systems by comparing their suitability for different applications as well as widening the range of possible alternatives based on recent market trends; with hybrid systems which are gaining more attention.

Moreover, in spite of the wide variety of studies on solar technologies, only few of them analyze the environmental impact of the different options to convert solar energy into electrical and thermal

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energy. The contribute of each renewable energy system to the emissions is usually evaluated on its own by different authors and based on different assumptions, making more difficult the comparison of different technologies. Even though, the life cycle assessment (LCA) methodology to determine the environmental impact of a certain process or product is described in the ISO 14040:2006, there are no strict guidelines, leaving the choice of functional unit (i.e. the reference to which all data are normalized) and boundary conditions up to the user. Thus, one or more process steps (manufacturing, installation, maintenance and decommissioning phase) can be excluded from the analysis. This work aims at summarizing the findings of more than one hundred scientists, not only to provide an updated state-of-the-art of the various systems, which could be a baseline for non-specialist in the solar renewable energy field, but also to compare the various conversion process chains from different perspectives, so to provide readily available information for decision making process.

The study is organized in two parts. In the first section, the different solar technologies and storage systems are individually described, underlying advantages and disadvantages, while in the second part, various combinations of photovoltaic systems and solar thermal collectors with heat pumps and solar cooling technologies are compared in terms of conversion efficiency, environmental impact and installation cost. Additionally, different possibilities to integrate appropriate storage media are evaluated. Storage systems in combination with solar technologies allow to increase the amount of self consumed energy and guarantee a more continuous supply, ensuring better matching between electrical power generation and demand, consequently reducing power fluctuations and risks of over-voltage/under-voltage. The stochastic nature of renewable sources and the forecasted increase in penetration of distributed energy systems highlight the importance of a better integration of renewable energy generation. The energy produced by high penetration of renewables cannot be passively injected into the grid without jeopardizing the grid safety and reliability. In this scenario, the relevance of storage and energy management systems rises, leading to the development of the concept of microgrid [8]. Sechilariu [9] defines a microgrid as a "form of decentralized energy production, able to operate grid-connected and off-grid. …The microgrid controls on-site generation and power demand to meet the objectives of providing local power, ancillary services and injecting power into the grid if required."

This developing trend shall be taken into account in the analysis of the different solar renewable energy technologies and their flexibility, when integrated in a microgrid, shall also be assessed.

2. Solar thermal and electrical systems

Solar energy is the most abundant and inexhaustible source of energy. The interest in developing efficient technologies to convert solar energy into electricity or thermal energy has been increasing, since the energy crisis in the 1970s. The state-of-the-art of both thermal and electrical solar systems shall be considered in this section. The term solar thermal refers to those systems which convert solar energy directly into useful heat, which is transferred to a specific medium. An example of these systems are thermal collectors. The term solar electrical, on the other hand, refers to those strategies which allow the conversion of solar energy into electricity. Photovoltaic panels are the most known example of solar electrical systems. Other alternatives are available, such as thermal collectors coupled with a Stirling engine or a Rankine cycle. However, these systems will not be discussed in this paper and the reader is referred to the work by Zeyghami et al. [10]. Section 2.1 and 2.2 describe the different types of thermal collectors and photovoltaic cells and advantages/disadvantages of the respective systems are highlighted.

2.1. Solar thermal collectors

Solar collectors are particular types of heat exchangers, which absorb the solar radiation and convert it into useful heat transferred to a working fluid. A wide variety of thermal collectors is available on the market. They can be classified in two main groups: non-concentrating and concentrating. The latter consist of a reflecting surface which focuses the solar radiation to a smaller area. The ratio between the aperture area and the absorber area is known as concentration ratio. In non-concentrating collectors, the intercepting area coincides with the absorbing area. Thus, the concentration ratio is equal to 1. Flat plate collectors (FPC) and evacuated tube collectors (ETC) belong to this group, while compound parabolic (CPC), parabolic trough (PTC), linear fresnel reflectors (LFR) and parabolic dish (PDC) are examples of concentrating collectors.

A FPC consists of an absorber plate integrated with passages to transfer the heat from the absorber to the working fluid. In order to minimize the heat losses, an insulation material is placed at the bottom and a transparent cover on the top, ensuring low radiative emissions through a proper choice of the cover material. Usually glass is used because of its high transmittance of up to 90% of the incident solar short-wave radiation and the low transmittance for long-wave radiation emitted by the absorber. Both beam and diffuse radiation can be absorbed and no tracking system is required. This collector type is widely used in domestic applications due to the very low maintenance required and its operating temperature (30–80 °C), relatively low, if compared to other collector types, but suitable for both space heating and Domestic Hot Water (DHW). The best performance is obtained under warm climatic conditions, when the temperature difference between the thermal fluid and the ambient is low. This occurs since high temperature differences increase the thermal losses with a consequent reduction of the collector efficiency. Very high temperature and radiation, instead, expose to the risk of overheating. Flat plate collectors can be further subdivided as glazed or unglazed. Unglazed air collectors are suggested by Collins [11] as an interesting option to produce pre-warmed air used in HVAC systems, significantly reducing the heating load. Glazed collectors instead are suitable for domestic hot water production and can be single or double glazed depending whether one or two covers are used to further reduce the thermal losses. Flat plate collectors can also be classified based on the working fluid, usually air or water. The latter ensures a better heat transfer, but in cold regions a mixture of water with antifreeze has to be employed, even though with the development of polymeric collectors the use of antifreeze is often no longer needed [12]. The effect of using alternative working fluid on the collector performance has been widely investigated. A review is provided by Al-Shamani [13], that analyzes the use of nanofluids for both solar thermal collectors and photovoltaic/thermal (PV/T) systems.

Even if the performance of FPC has been improved through the use of selective coating, better performance in cloudy and cold conditions is ensured by evacuated tube collectors (ETC). These consist of a heat pipe surrounded by a vacuum tube, which reduce the thermal energy losses. The pipe contains a fluid (methanol) which, due to the solar radiation evaporates moving to the condensing region, where the accumulated heat is released and transferred to a second fluid. Due to gravity, the condensed vapor moves back to the evaporating section, restarting the cycle. Similarly to what occurs in FPCs, both direct and diffuse solar radiation can be absorbed and no tracking system is needed. However, due to the lower conduction and convection heat losses, the outlet fluid temperature of ETC can be higher.

Among the concentrating solar collectors, compound parabolic (CPC) are the only one that allow to concentrate both the direct and the major part of the diffuse radiation incident on the aperture. They consist of a parabolic reflector which conveys the radiation from the aperture to the absorber. CPC produces high outlet temperatures of 200–250 °C, making them suitable for enhanced heating applications. However, higher maintenance and manufacturing costs, with respect to FPC and ETC, limit their diffusion in the residential sector.

Parabolic trough collectors (PTC) consist of a reflective parabolic trough which concentrates the direct solar radiation to a tubular