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A review of solar energy based heat and power generation systems

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ABSTRACT

The utilization of solar energy based technologies has attracted increased interest in recent times in order to satisfy the various energy demands of our society. This paper presents a thorough review of the open literature on solar energy based heat and power plants. In order to limit the scope of the review, only fully renewable plants with at least the production of electricity and heat/hot water for end use are considered. These include solar photovoltaic and solar thermal based plants with both concentrating and non-concentrating collectors in both solar-only and solar-hybrid configurations.

The paper also presents a selection of case studies for the evaluation of solar energy based combined heat and power generation possibility in Denmark. The considered technologies for the case studies are (1) solar photovoltaic modules, (2) solar flat plate collectors, (3) a ground source heat pump, (4) a biomass burner, and (5) an organic Rankine cycle. The various cases are compared on the basis of economic profitability and environmental performance. The results from the case studies indicate that it is economically and environmentally beneficial to invest in both small and large capacity solar-biomass hybrid plants for combined heat and power production in the Nordic climatic conditions. The results also suggest that the configuration with an organic Rankine cycle with solar thermal collectors and a biomass burner is particularly attractive for large capacity plants.

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1. Introduction

The five ultimate primary energy sources on the earth are (1) the sun, (2) geothermal energy, (3) the motion and the gravitational potential of the earth, the sun, and the moon, (4) human-induced nuclear reactions, and (5) the chemical reactions from mineral sources [1]. Of these, the three renewable sources of energy are the sun, the geothermal energy from the earth, and the energy from the planetary motion. Among these, the incident power from the sun is the dominant renewable energy source. Even after excluding hydro power, biomass, and wind energy as indirect forms of solar energy, the amount of the incident solar radiation is still enormous. For this reason, the utilization of solar energy based technologies has attracted increased interest in recent times in order to satisfy the various energy demands of our society. These include, for example, electricity and heat [2,3], refrigeration and cooling [4–6], industrial process heat [7], rural electrification [8], methanol production [9], hydrogen production [10], polygeneration container use during disaster and emergency situations [11], micro combined heat and power (mCHP) generation [12], desalination [13], various energy needs for agricultural greenhouses [14], and the improvement of the indoor environment conditions [15].

For the residential consumers, electricity is the most important energy demand in most parts of the world. With regards to the generation of electricity, Fig. 1 presents a vision for satisfying the global electricity demand in 2050 with various energy sources [16]. In this vision, the solar energy based systems are predicted to occupy the highest share by the year 2050. Similarly, the International Energy Agency estimates that by the year 2050, the solar energy systems will be supplying about 17 % of the global electricity demand in the 2 degree rise scenario, and about 27 % in the 2 degree rise, high renewable energy mix scenario [17]. The 2 degree scenario means that the average global temperature rise should be kept below 2 °C as compared with the pre-industrial levels. In the high renewable energy mix scenario, the above share makes solar the dominant source for electricity. In several regions, other end products such as hot water, space heat, cooling, and potable water could be equally, or sometimes more important for the consumers than electricity. For example, the heat demand in residential buildings account for about 60–80% of the total energy demand in cold climates, while as high as about 30–40% in warmer climates [18]. In this regard, solar thermal systems are pertinent for (1) the countries which rely heavily on imported gas or oil to cover their heating demands, (2) the countries where increasing heat demand is covered using electrical boilers thereby straining the electricity grid, and (3) the countries with high cooling demand during sunny periods [18].

The Nordic countries have some of the highest per capita heating demands in the world. At the same time, these countries have also set ambitious climate and energy targets for the coming decades. These include Denmark setting a target of becoming a 100 % renewable energy based society and Norway and Sweden seeking to reduce their greenhouse gas emissions by 100 % by 2050 as compared with their respective 1990 emission levels [19]. For this reason, it is interesting for these countries to consider solar energy based systems in their energy portfolio. A huge interest in the solar energy systems for satisfying the heating needs is already evident from the enormous increment in the installed collector area for solar district heating projects, both small and large scale, that have come up in Scandinavia in the last decade [20]. Most of these district heating plants are however operated together with a natural gas boiler in order to satisfy the demand during the winter period when there is little sunshine. It is therefore interesting to evaluate the possibility of increasing the renewable share in providing both heat and electricity. In this regard, the combined heat and power (CHP) systems can prove to be highly useful in utilizing the locally available solar resource while effectively meeting the various consumer demands. In fact, the world's largest renewable energy based district heating plant with a significant share of solar energy in the energy input is the SUNSTORE4 plant in Denmark [21].

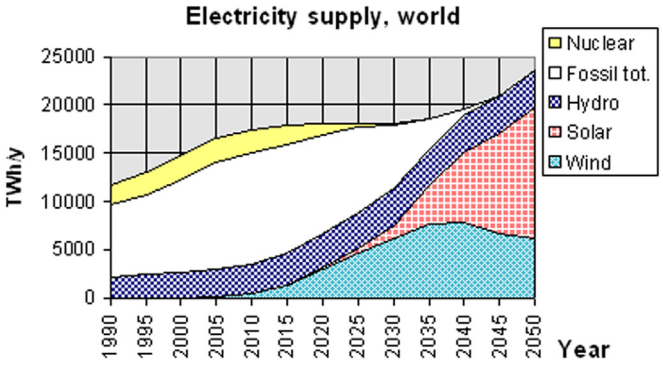

Fig. 1. Global electricity supply – Vision 2050 [16].

When it comes to the utilization of any energy source, particularly a renewable source, it is advantageous to operate with cogeneration or multigeneration [22,23]. Classically, the term *cogeneration* has been used to represent the simultaneous generation of electricity and heat using a single fuel or energy source at a single site [24]. However, recently it has also been used to denote the generation of heat and cooling [25,26], electricity and water [27,28], electricity and cooling [29,30], and electricity and hydrogen [31]. Therefore in order to avoid any confusion, the term *combined heat and power* (CHP) is used in this paper to represent the generation of electricity and heat from the same plant, but without restricting the energy input to a single energy source.

The primary objective of this paper is to present a thorough review of the open literature on solar energy based heat and power plants. To the authors' knowledge, such a review has never been done. Given the immense potential of the solar energy based CHP plants from both thermodynamic and economic perspectives, the paper also identifies relevant areas for further research. The review mainly focuses on the renewable plant configurations with *at least* electricity and heat/hot water as the end-user demands. An overview of the studies with plants generating additional products is also presented. Since the solar photovoltaic-thermal (PVT) systems have already been extensively reviewed [32–35], only the most recent reviews and research publications are discussed here. In the literature review, the various studies are grouped based on the energy input configuration, i.e. as solar-only or solar-hybrid energy input. An alternate overview, with the reviewed literature grouped based on the key technologies used in the various studies, is also presented in the Appendix. This includes the different power and CHP technologies, fuel cell related technologies, energy storage technologies, water purification technologies, and refrigeration, cooling, and heat pump related technologies.

The paper also presents some case studies in order to evaluate

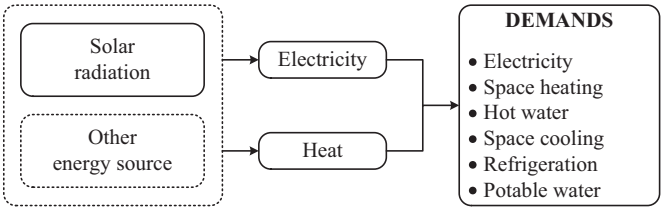

Fig. 2. Possible configurations for the utilization of solar energy based CHP plants in order to satisfy various residential end-user demands.