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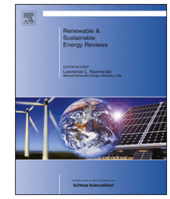

Exergoeconomic analysis of high concentration photovoltaic thermal co-generation system for space cooling

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ABSTRACT

This paper provides an exergetic analysis of a 10 MW high concentration photovoltaic thermal (HCPVT) power plant case study located in Hammam Bou Hadjar, Algeria. The novel HCPVT multi-energy carrier plant converts 25% of the direct normal irradiance (*DNI*) into electrical energy and 62.5% to low grade heat for a combined efficiency of 87.5%. The HCPVT system employs a point focus dish concentrator with a cooled PV receiver module. The novel "hot-water" cooling approach is used for energy reuse purposes and is enabled by our state-of-the-art substrate integrated micro-cooling technology. The high performance cooler of the receiver with a thermal resistance of $<0.12\ \text{cm}^2$ K/W enables the receiver module to handle concentrations of up to 5000 suns. In the present study, a concentration of 2000 suns allows using coolant fluid temperatures of up to 80 °C. This key innovation ensures reliable operation of the triple junction PV (3JPV) cells used and also allows heat recovery for utilization in other thermal applications such as space cooling, heating, and desalination. Within this context, an exergoeconomics analysis of photovoltaic thermal co-generation for space cooling is presented in this manuscript.

The valuation method presented here for the HCPVT multi-energy carrier plant comprises both the technical and economic perspectives. The proposed model determines how the cost structure is evolving in four different scenarios by quantifying the potential thermal energy demand in Hammam Bou Hadjar. The model pins down the influence of technical details such as the exergetic efficiency to the economic value of the otherwise wasted heat. The thermal energy reuse boosts the power station's overall yield, reduces total average costs and optimizes power supply as fixed capital is deployed more efficiently. It is observed that even though potential cooling demand can be substantial (19,490 MWh per household), prices for cooling should be 3 times lower than those of electricity in Algeria (18 USD/MWh) to be competitive. This implies a need to reach economies of scale in the production of individual key components of the HCPVT system. The net present value (*NPV*) is calculated taking growth rates and the system's modular efficiencies into account, discounted over 25 years. Scenario 1 shows that even though Algeria currently has no market for thermal energy, a break-even quantity (49,728 MWh) can be deduced by taking into account the relation between fixed costs and the marginal profit. Scenario 2 focuses on the national growth rate needed to break even, i.e. +10.92%. Scenario 3 illustrates thermal price variations given an increase in the Coefficient of Performance (COP) of a thermally driven adsorption chiller after year 10. In this case, the price for cooling will decrease from 18 USD/MWh to 14 USD/MWh. Finally, scenario 4 depicts Hammam Bou Hadjar's potential cooling demand per household and the growth rate needed to break even if a market for heat would exist.

Contents

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1. Introduction

The economics of solar energy have been changing in the recent years in terms of cost, champion technology and locations. Photovoltaic (PV) deployments in subsidized markets grew beyond expectation in the last five years. During 2011, Italy and Germany provided about 57% of new PV operating capacity for the European Union [1]. However, reduced incentives and dramatic module cost reduction cause a shift of primary markets to more sunny locations. In addition, reduced module cost makes balance of system (BOS) cost more important which places a higher value on efficiency. This is advantageous for concentrated photovoltaic (CPV) systems with a module efficiency exceeding 30%. More concretely, advantages of CPV are a lower capital investment [2] and a steeper learning curve because of the reduced usage of semiconductor material. CPV systems show a higher energy yield per module and a lower levelized cost of energy (LCOE) because their active tracking system improves the match between output and load profile.

Several studies evaluated the economic feasibility of PV plants [3–5] through the LCOE metric. The latter is calculated using a mix of independent variables. Some of those variables have a direct impact in the LCOE, affecting the final results. To understand how each individual variable impacts the final LCOE a sensitivity analysis is usually performed. Those studies also identify the advantage PV has over CSP when it comes to capturing diffuse and direct solar irradiation [6]. While the technology with the largest deployment in hot climates has been concentrated solar power (CSP) [3] with trough collectors, thermal storage, and steam engines, this technology is coming more and more under pressure [7]. Despite the recent large progress in efficiency, photovoltaic as well as solar thermal installations can only make use of a minor fraction of the incident radiation, typically less than 30%. This motivates the design of solar systems that combine the production of electrical energy with usable heat, i.e. for cooling applications to achieve total (exergy compensated) yields beyond 30%.

Concentrating solar radiation onto the surface of a solar cell has been used since the 70s [8–10] and photovoltaic thermal (PVT) technologies with active cooling and heat use have been developed in parallel because of large thermal loads on PV cells [11–15]. Concentrated Photovolatic Thermal (CPVT) systems started spreading when analytical work showed how PV becomes more efficient and cheaper with concentrated irradiance [16]. This required the development of optics and tracking systems [17,18] and combinations between solar systems, heat pumps, and heat use [19]. The key metric combined electrical and thermal efficiency started rising reaching values of 69% [20] which eventually opened the path to concentrating photovoltaic thermal plants [21,22]. The need for investment into high performance cooling solutions and low resistance electrical packaging became apparent with the inverse relationship between the temperature in the solar cell and the electrical and the effect of series resistance [23]. Several overviews describing all details for concentrating PV systems are available in recent literature [24–28] and summaries on more recent efforts on standardization of actively cooled CPV and CPVT systems are available as well [29].

Exergy is the best quantity to outline the capability of the system to generate a thermal and an electrical output in an efficient manner. Exergy reveals the available useful energy necessary for energy planning and the commercialization of a power plant. In fact, commercial and residential consumers demand energy services offered by different power providers. Co-generation and tri-generation plants are characterized by complex interactions between the generation, storage, conversion and the transportation system. These power plants are able to produce electricity, heating and/or cooling from a particular energy source. Co-generation and tri-generation plants enable energy savings while being environmentally friendly [30]. To improve energy savings in cogeneration systems a bigger yield should be achieved from the process and consequently reducing the consumption of the natural resource [31]. A number of studies addressed the proportion of solar radiation converted into electricity and heat [32–34]. The exergy analysis of the PV module and thermal energy carriers such as air and water are proposed in Refs. [35–39], while a more detailed economic analysis was conducted in Refs. [40–46].

The main reason for the changes in the field of solar energy and increased attractiveness of co-generation technologies is attributed to the growing demand for cooling and desalination. The International Energy Agency (IEA) predicts nearly a tripling of worldwide cooling demand, with even higher growth in emerging economies in the Sunbelt [47] in the timeframe from 2010 to 2050. In these economies, demand for cooling can only be satisfied almost completely with compression chillers. Increased consumption will strain electrical grids and power stations, which in turn opens new opportunities for energy transport. In recent years, more efficient thermally driven sorption cooling methods have been developed, i.e. absorption and adsorption cooling. Absorption cooling relies on sorption of a working fluid in another fluid while adsorption cooling works with desorption and adsorption of a working fluid from a porous solid. While the optimal driving temperature for absorption cooling needs lies above 90 °C, adsorption cooling can operate efficiently with driving temperatures below 90 °C [48]. On the other hand, the demand for desalination in water scarce regions is growing even faster than the demand for cooling. High population growth in these arid regions, changes in rainfall patterns, waterway pollutions and depletion of “fossil water” in aquifers are driving the human population to seek alternative renewable water resources, i.e. desalination. Traditionally, desalination can be carried out with mechanically driven membrane separation processes like reverse osmosis (RO) and thermally driven methods such as multi-stage flashing (MSF), multi-effect boiling (MEB) and membrane distillation (MD). Comparing the thermally driven desalting methods, conventional MSF and MEB rely on high driving temperatures, typically higher than 100 °C, while MD requires driving temperatures of 70–90 °C, which is comparable to newer generations of low temperature distillation systems (LT-MED). In general, the medium grade heat requirement of adsorption cooling and membrane distillation enables new approaches for solar multi-generation making them the perfect candidates as potential thermal users of the HCPVT system [49].

The challenge of such a co-generation system is to fairly assess the relative economic value of the electrical and thermal output in view that a multi-objective-optimization process can be applied. An important challenge is the transport system to the user, since electrical and thermal transport have very different investment cost, maintenance cost and distance dependent losses. One of the advantages of the HCPVT solar farm resides in the transportation