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Analysis of a polygeneration plant based on solar energy, dual mode solid oxide cells and desalination

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ABSTRACT

Fossil fuels are stored energy during millions of years and we are using it in a rate that new fuels cannot be formed. Renewable energies are not available all the time and there is a need to find ways to store them. One way of storing renewable energies is in fuel form, similar to the fossil fuels and then use this stored fuel whenever needed. The plant design proposed in this paper consists of Dish-Stirling collectors supported by a reversible solid oxide cell acting as a power generator and storage unit, and therefore offering dispatchable power on demand. Further, the system reuses the waste heat for seawater desalination. The present work is an analytical study in which the performance evaluation of a self-sustainable polygeneration system with integrated hydrogen production, power generation, and freshwater production is conducted. An evaluation for selected days, representative for summer, fall, winter and spring in an area with low solar irradiation is studies to investigate the potential of this system to supply 500 kW continuously and simultaneously producing a considerable amount of freshwater. The study shows that the plant can produced hydrogen even in low irradiation winter days together with at least 6500 L of freshwater daily.

Introduction

While energy demand in this fast developing world is increasing, its future is being compromised by the CO_2 emissions produced through the burning of fossil fuels and associated global warming. Owing to global warming and its consequences, renewable energy production technologies will be called to play a significant role in the future. Further, it is essential to find a new, effective solutions that allow for the integration of sustainable energy production techniques into the current existing systems and thereby decreasing the emissions. Clean energy technologies are available, but there are still barriers hindering their full integration into the society, the majority of which are economic and social. Energy policies moderate such transitions, and ensure that a specified threshold is met. However, it is desirable that such transitions occur in harmony with the present socioeconomic situations and that they utilize current technological achievements in clean energy production. Furthermore, it is key that these solutions are cost-effective and can be used for polygenerations purposes such as electricity, fuel and freshwater production. In such designs, direct electricity, heat (or cool) and freshwater can be generated from a renewable source such as solar and wind energies, when the source is available.

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Electrolysis technology such as solid oxide electrolyte cell (SOEC) can be used to store the excess energy in fuel form when the renewable source exceeds the demand. The stored fuel can then be used to generate power heat/cool and fresh-water by solid oxide fuel cell (SOFC) when the demand exceeds the renewable. This implies that there is a need for a reversible solid oxide cell (RSOC) that can produce synthetic fuel from excess electricity, or produce electricity from stored fuel when reversed. Viviani et al. [1] showed the feasibility of the concept and successful reversible operation of a dual cell through electrochemical tests carried out by impedance spectroscopy. A recent study demonstrates that such system may not only be feasible but also beneficial as the lifetime of the device increases significantly by decreasing cell degradation [2]. They came to the conclusion that by operating the cell in a simple electrolysis mode its microstructure tends to deteriorate in the proximity of the interface between the oxygen electrode and electrolyte layer. But surprisingly if the cell is operated in reversible mode no microstructural damage is observed. In other words, dual mode operation eliminates cell degradation. Ni et al. [3] reviewed technological development of hydrogen production from a SOEC system in terms of materials, cell configuration and electrode depolarizations. Chen et al. [4] studied a reactor combining a SOEC section with a Fischer Tropsch section for methane production and [5] carried out an experimental study to demonstrate the heat spreading capabilities and power limitations of high-temperature applications in SOEC/SOFC stacks.

Solar energy is going to play an important role in the future power plants for multi-generation products. Owing to the common nature of fluctuation in energy (also for other renewable sources), most of renewable based plants need a storage unit. With that, renewable energy plants can provide dispatchable power, enabling stand-alone systems for facilitating the grid operation. Parabolic trough solar water heating is a well-proven solar energy technology that is being used on a commercial scale. High-temperature parabolic trough solar collector (PTSC) systems are currently operating in solar electric generating systems. For example, [6] conducted thermal simulation of a PTSC to estimate the transient performance of a solar industrial water heating system. Coccia et al. [7] developed a mathematical model for PTSC and compared the results with experimental data, finding a small percent error. Li et al. [8] designed and experimentally validated an adsorption ice-maker driven by PTSC, and integrated it with a sensible thermal storage tank successfully. Bortolato et al. [9] experimented on innovative flat aluminum absorbers for process heat and direct steam generation in small PTSC systems. Akikur et al. [10] studied a RSOC with photovoltaic (PV) to design a possible future power plant using solar energy that can produce electricity at any time of the day, for example, at night.

Direct contact membrane distillation (DCMD) is a thermal separation process where only the water vapor (or other volatile) passes through a micro-porous hydrophobic membrane while impurities, such as salt, cannot cross the membrane. The vapor pressure gradient created by the temperature difference between both sides of the membrane drives the process. Burgoyne and Vahdati [11] reviewed the desalination of seawater by the DCMD system, and its performance from laboratory scale to pilot projects. Shirazi et al. [12] showed experimentally that 99.99% of salt can be separated from hot water at 80 °C in optimum conditions and with optimum membrane material selection. Desalination powered by solar energy is an attractive solution that can address the worldwide water-shortage problem without contributing significantly to greenhouse gas emissions. It is worth noting that often there is shortage of fresh water where solar radiation is high. As deliberated in Ref. [13], a promising system for renewable energy desalination is the utilization of low-temperature DCMD systems. The study by Ref. [14] showed that experimental data agreed very well with the calculated results in terms of vapor mass flux, as well as membrane and total heat transfer coefficients. In addition, such a technique has a great advantage because it works at lower temperatures, even down to 40 °C (313 K), which allows it to use lower temperatures sources and avoid the great latent heat of water [15].

In this work, a poly-generation system is presented that uses a Dish-Stirling units to convert solar radiation into electricity and drive a RSOC for storing renewable energy source in fuel form. Further, the waste heat is recovered for seawater distillation through a DCMD technique. Such a system will result in a self-sufficient and flexible poly-generation plant driven by solar power only that can be regulated for different output combinations of hydrogen, electricity and freshwater. A complete balance of plant is designed and its performance is analyzed thermodynamically. The plant is then evaluated for selected days in different seasons (summer, fall, winter and spring) accounting for different solar irradiation in low solar energy climate. The present study is completely new and no similar study can be found in the open literature. The objective is thermodynamic analysis and cost estimation is out of the scope of present study.

Plant overview

The block diagram in Fig. 1 illustrates that the plant delivers power to the grid by converting the solar energy collected by the Dish-Stirling devices. Further, the design supports a RSOC system in order to overcome the fluctuating nature of the solar radiation by producing hydrogen when solar energy is low or not available. The idea is that the Dish-Stirling delivers part of its load to the RSOC for storage by producing fuel (hydrogen) during the peak hours of radiation (SOEC mode). Then during low or zero radiation, the RSOC uses the produced and stored fuel to produce power and cover the power demand (SOFC mode). At the same time, the design supports a seawater desalination plant that uses the excess heat to produce freshwater continuously. Furthermore, a parabolic trough solar collector (PTSC) uses the solar energy to generate steam for the system.

It is worth to point out that such plants are rather complex and challenging. One of the challenges is the plant price and payback time. The prices for RSOC and DCMD are unknown since they are not commercialized yet. Even though there is a good price approximation for each of them but still they cannot be certain. Political decisions and governmental subsidies will also have a great impact on future price development of such devices [16]. Another challenges is the proper functionality of the RSOC under real condition. Even though

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