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Concurrent hydrogen and water production from brine water based on solar spectrum splitting: Process design and thermoeconomic analysis

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ABSTRACT

This paper presents a novel process for high efficiency production of hydrogen and desalination of brine water based on the concept of solar spectrum splitting. The advantage of this system is concurrent production of hydrogen and distilled water using a sustainable process at large scale. The harvested energy from the separated solar spectral bands is used to supply the required energy for high temperature steam electrolysis and a double-stage flash distillation system. The integrated solar system is designed to reduce the energy conversion deficiencies, considerably. In order to investigate the performance of this system, a process simulation code is developed. An exergy analysis is conducted and the economic feasibility of the plant is evaluated. The sensitivity of the integrated cycle performance on solar insolation, electrolyzer temperature, and pressure is analyzed, and the results indicate that utilization of concentrator cells, with a multi-band gap mirror can increase the productivity of the cycle, drastically. It is observed that hydrogen and distilled water production rate can be increased by more than 1.6 times, when the harvested solar power increases from 28 MW to 55 MW. It is concluded that the maximum energy and exergy efficiencies of the integrated solar cycle is about 45%.

1. Introduction

The global issues regarding water and energy crisis, as the two strategic commodities for industrial and economic developments, prioritize the research for sustainable methods of brine water desalination and hydrogen production. Solar hydrogen production has been identified as a key solution to the future energy crisis [1]. Although photo-catalytic and thermochemical processes, that utilize solar energy and water, are promising methods for renewable hydrogen production, but their low efficiencies make them economically infeasible [2]. Moreover, the increasing demand for potable water and the associated critical issue since 1990s has turned water to a scarce and vulnerable material. The industrialization of societies and growth in developed areas, even with a wet climate, will be sooner or later makes water as the first concern of human kind [3].

The permanent cycle of production and consumption requires energy and affects the environment by polluting water and air. Therefore, improvements on existing hydrogen production and desalination processes are needed to provide environmentally benign sources of energy and water, which are relatively efficient and economical. Implementation of multi-generation energy systems leads to considerable reduction in thermal losses, wastes, and greenhouse gas emissions. These systems provide multiple generation options with high reliability and less grid failure [4].

Hydrogen production using high temperature electrolysis integrated with photovoltaic cells has been emerged as comparatively more efficient and mature technology in renewable hydrogen industry [5,6]. Solid oxide electrolysis cells (SOEC) that works at high-temperature to split steam into hydrogen and oxygen is appeared to be more advantageous compared with low-temperature electrolyzers, i.e. proton exchange membrane and alkaline electrolyzers [7]. This matter is due to higher ion conduction and the expedited electrochemical reactions at an elevated temperature [8–10]. The integration of SOEC with geothermal or nuclear energy to optimize the efficiency of hydrogen production is also of high interest [11,12].

The demand for brine water desalination has been raised by almost 12 times in the past 30 years. The total capacity of installed desalination plants was 30 million m^3 day^{-1} in 2001 and it will likely reach 58 million m^3 day^{-1} by 2080 [18]. Almost 90% of the

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world's distilled water is provided by either reverse osmosis (RO) or multi-stage flash (MSF) distillation processes. The remaining 10% is produced by other technologies including vapor compression, multiple effect, and electrodialysis. However, these are all energy-intensive processes and those systems that can be integrated with a renewable energy source are preferred.

The application of exergy analysis for evaluating the performance of solar thermal systems from the thermodynamic aspect is of growing interest, because it is a reliable tool to identify the exergy destruction drawbacks and potential second low efficiency improvements [21]. Ahmadi et al. [22] investigated the performance of a multi-generation system that consists of PV/T solar collectors, a reverse osmosis desalination unit, a single effect absorption chiller and a PEM electrolyzer. They performed a sensitivity analysis to evaluate the effects of several design parameters on the system total exergy destruction rate, total cost rate and exergy efficiency. The highest reported exergy efficiency of the cycle based on multi-objective optimization was 60%.

Photovoltaic (PV) cells can provide the required electrical energy to produce hydrogen and fresh water from saline water. However, the high cost and relatively low efficiency of PV panels persuaded many researchers to investigate the effect of concentrated solar radiation on these devices, as reported by Luque et al. [23]. There is a rationality behind this concept that is related to lower cost of optical concentrating elements than photovoltaic cells. However, concentrator modules are exposed to a higher incident solar irradiation than flat plate module cells, and they provide excess heat and also cause more intricate assembly structure.

Multi-generation energy system based on solar spectrum splitting is an innovative solution to problem of water and energy scarcity. The proposed concept is to split the solar spectrum into spectral bands that can drive photo-quantum and photo-thermal conversion processes to produce hydrogen and distilled water, concurrently. In order to improve the overall conversion efficiency of concentrated solar energy systems, the concept of spectral selectivity is applied to design the solar-thermal or hybrid quantum systems. James et al. has analyzed the operation of multi-band gap concentrator cells at 450–525 suns with a spectrum-splitting filter [24]. A special silicon concentrator solar cell was designed and conversion efficiencies of 16.2% and 20.4% were attained at flux concentration of 455 suns and 525 suns, respectively. The application of liquid absorption and dichroic filters in beam splitters with spectral selectivity was described by Osborn et al. [25]. They concluded that a PV-thermal system with spectrally selective beam splitters has the highest electric efficiency compared to a pure PV system.

The potential application of spectrum splitting for large-scale solar concentrating system has been demonstrated by Yogev et al. [26]. They have analyzed the optics of a tower reflector comprising dielectric mirrors as reflector with a beam-splitting capability. It has been observed by Penn et al. that the sunlight to electricity conversion efficiency of 60–70% can be achieved using an optimized design [27].

In this paper, a novel multi-generation process is designed that combines a solar high temperature electrolysis (HTE) plant with a multi-stage desalination cycle. This cycle produces hydrogen and distilled water from brine water using solar energy, simultaneously. A solar spectrum splitting system is considered to provide the required thermal and electrical energy for the combined cycle. This system not only relieves the efficiency bottleneck of a solar based energy system, but also introduces a sustainable energy conversion method to produce two valuable commodities, i.e. hydrogen and water.

The present work provides a detailed assessment of the performance of a large-scale concentrating solar system with beam splitting that is integrated with hydrogen production and water desalination cycles. The analysis starts from process modeling of the integrated system and conducts to an exergy and economic analyses to proof the feasibility and suitability of the proposed cycle for concurrent solar hydrogen and water production. The integrated cycle has various applications in many industries including oil refinery and steel making plants that require considerable amount of hydrogen and distilled water. The novelty of this research lies in the thermodynamic assessment of a tri-generation process that is designed for efficient production of electricity, water and hydrogen from saline water and solar energy.

2. System description

As shown in the process flow diagram, Fig. 1, the integrated cycle mainly consists of high temperature electrolysis, multi-stage desalination, and a solar spectrum splitting system that facilitates thermal and electrical energy extraction form the incident irradiation.

In order to improve the overall conversion efficiency of a solar thermal system, the spectral selectivity concept can be applied to concentrated solar energy to produce multi commodities in a sustainable manner. This can be accomplished by separating the solar spectrum into different spectral bands that supply the energy requirements of thermochemical and photo-thermal conversion processes.

In the solar plant, a heliostat field collects solar energy. Subsequently, part of this energy at a specific band gap that is optimized for PV cells is captured by a hyperboloidal reflector and a reflective mirror. Therefore, a conversion efficiency as high as 60% can be achieved while the rest of the available energy is concentrated, using Compound Parabolic Concentrators (CPC), to supply the thermal energy requirements of chemical hydrogen production and desalination processes.

Hydrogen production process is accomplished by high temperature steam electrolysis in Solid Oxide Electrolyser (SOEC), and desalination of brine water is based on multi-stage flash distillation process. A network of heat exchangers and a double stage turbine is considered to recover the excess thermal energy from CPC and SOEC that leads to enhancement in productivity and overall conversion efficiency of the integrated cycle. The electric power generated by the double-stage turbine is delivered to the SOEC for hydrogen production.

The water desalination cycle is integrated with hydrogen production cycle to provide make-up water required for water splitting in the SOEC. The combined hydrogen production and water desalination cycle is called HW cycle, thereafter for simplicity, and the overall process that includes solar spectrum splitting is called HWS. Three main systems in the HWS process is explained in detail as follows. This system is suitable for remote applications where only sea or brackish water is available.

2.1. Solar energy harvesting system

An optical system based on solar spectrum splitting concept that consists of a heliostat field surrounding a tower equipped with a hyperboloidal reflector and a dielectric mirror is considered, with technical specifications suggested by Segal et al. [28]. The heliostat field is designed to deliver maximum power of 46 MW to the tower reflector, and it consists of 783 heliostats with net area of 95.5 m^2 each.

The tower reflector mainly consists of a hyperboloidal mirror with two focal points. It reflects the radiation from heliostat field to the lower focus at the entrance plane of a group of identical CPCs. A