INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 7601–7608

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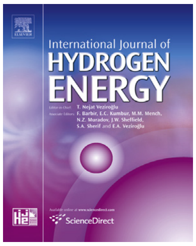

Multi-objective optimization of an ocean thermal energy conversion system for hydrogen production

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ARTICLE INFO

Article history:
Received 28 July 2014
Received in revised form
4 October 2014
Accepted 13 October 2014
Available online 14 November 2014

Keywords:
Efficiency
Electrolysis
Energy
Exergy
Hydrogen production
Ocean thermal energy conversion
Optimization

ABSTRACT

Hydrogen can be produced in a relatively environmentally benign manner (depending on the source of the input energy) via splitting water by photocatalysis, thermochemical cycles and electrolysis, and hydrogen production by proton exchange membrane (PEM) electrolysis has numerous advantages. Ocean thermal energy conversion (OTEC) usually incorporates a low-temperature Rankine cycle which boils a working fluid such as ammonia to generate a vapor which drives a turbine to generate electricity, and is then condensed back to a liquid in a continuous process. Here, a comprehensive thermodynamic analysis and multi-objective optimization are reported of an OTEC system to produce hydrogen using electrolysis. A multi-objective optimization method based on a fast and elitist non-dominated sorting genetic algorithm (NSGA-II) is applied to determine the best design parameters for the system. The total cost rate of the system is minimized while the cycle exergy efficiency is maximized using an evolutionary algorithm. To provide additional insights, the Pareto frontier is shown for the multi-objective optimization. In addition, a closed form equation for the relationship between exergy efficiency and total cost rate is derived. A sensitivity analysis is performed to assess the effects of several design parameters on the system.

Introduction

Energy usage is growing and fossil fuels like coal, petroleum, and natural gas are becoming scarcer. Fossil fuel use causes many problems. One of the major problems of using fossil fuels is the amount of greenhouse gases that are produced and released to the environment, contributing to climate change. Renewable energies, such as solar, wind, tidal, wave and geothermal, are of great importance. Hydrogen as an energy carrier can facilitate sustainable energy systems. The development of sustainable carbon-neutral energy sources is increasingly significant in the world today. Hydrogen can be produced from various energy sources using methods like biomass conversion, steam methane reforming and water splitting. Hydrogen can be produced in a relatively environmentally benign manner (depending on the source of the input energy) via splitting water by photocatalysis, thermochemical cycles and electrolysis. Currently, both thermochemical and photocatalysis hydrogen production are not economically competitive, but water electrolysis is a mature technology for large scale hydrogen production. Hydrogen production by proton exchange membrane (PEM) electrolysis has numerous advantages, such as low environmental impact and easy maintenance [1].

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http://dx.doi.org/10.1016/j.ijhydene.2014.10.056

A large amount of solar energy is stored as heat in the surface waters of the world's oceans, providing a source of renewable energy. Ocean thermal energy conversion (OTEC) is a process for harnessing this renewable energy in which a heat engine operates between the relatively warm ocean surface, which is exposed to the sunlight, and the colder (about 5 °C) water deeper in the ocean, to produce electricity. OTEC usually incorporates a low-temperature Rankine cycle engine which boils a working fluid such as ammonia to generate a vapor which turns the turbine to generate electricity, and then is condensed back into a liquid in a continuous process. 80% of the energy the Earth receives from the sun is stored in the Earth's oceans [1,2], and many regions of the world have access to this OTEC resource. OTEC can produce fuels via the product electricity including hydrogen, which can be used in hydrogen fueled cars as well as in the development of synthetic fuels. For a small city, millions of tons of CO_2 are generated annually through fossil fuel use, while with OTEC the value is near zero during the operation of devices. OTEC has a potential to replace some fossil fuel use, perhaps via OTEC ships traveling the seas of the world.

Potential markets for OTEC have been identified by various countries, most of which are in Pacific Ocean, for its implementation as a sustainable source of energy and fresh water, including India, Korea, Palau, Philippines, the U.S. and Papua New Guinea [3]. In 2001, as a result of cooperation between Japan and India a 1-MW OTEC plant was built in India [3], and others are planned to be constructed in the near future [4]. Considerable research has been devoted to the development of OTEC recently. Uehara [5–7] conducted numerous theoretical and experimental studies on the major components of an OTEC plant, and showed that ammonia is a suitable working fluid for a plant employing a closed organic Rankine cycle (ORC). The energy efficiency of the Rankine cycle in an OTEC plant is usually limited to around 5% due to the small temperature difference between surface water and deep water of the ocean. So, to improve the efficiency of OTEC, other thermodynamic cycles like the Kalina and Uehara cycles, that use an ammonia–water mixture as the working fluid, are being considered [8]; they are reported to have better energy efficiencies rather than a Rankine cycle at the same temperature difference [8]. Increasing the temperature difference between the hot heat source and the cold heat sink can improve the efficiency of OTEC plants, as can the integration of OTEC with other energy technologies. Saitoh and Yamada [9] proposed a conceptual design of a multiple Rankine-cycle system using both solar thermal energy and ocean thermal energy in order to improve the cycle efficiency. In addition, Uehara et al. [5] optimized OTEC plants using ammonia as the working fluid in closed cycles. Ahmadi et al. [1] conducted energy and exergy analyses for a solar boosted OTEC plant for hydrogen production. The results showed that the energy and exergy efficiencies of the integrated OTEC system are 3.6% and 22.7% respectively, and the exergy efficiency of the PEM electrolyzer is about 56.5% while the amount of hydrogen produced by it is 1.2 kg/h.

Although much research has been conducted on OTEC performance, there is a lack of work on multi-objective optimization for OTEC energy systems. The main reasons for using multigeneration often are to increase efficiency and sustainability and to reduce environmental impact (including global warming) and cost, and the research reported to date suggests that multigeneration can support these purposes. The primary objective of the present research is to improve understanding of multigeneration, by performing thermodynamic modeling and exergy and economic analyses of an integrated solar and OTEC based system for hydrogen production. The system consists of an OTEC cycle and a PEM electrolyzer that produces hydrogen. The specific objectives of this study are listed as follows:

- To thermodynamically model this integrated energy system.
- To conduct exergy and economic analyses of this integrated system.
- To apply a multi-objective optimization technique based on a code developed in the Matlab software program using an evolutionary algorithm.
- To propose a new closed-form expression for the exergy efficiency in terms of total cost rate at the optimal design point.
- To derive an equation for the Pareto optimal points curve that can serve as an aid for designing optimal multigeneration plants.
- To select the final optimum design point using a decision-making method.

Modeling and energy analysis

For thermodynamic modeling purposes, the integrated OTEC system for hydrogen production considered here (Fig. 1) is divided into three parts: flat plate solar collector, ocean thermal energy conversion (OTEC) unit and PEM electrolyzer. Fig. 1 shows a schematic diagram of an integrated OTEC system equipped with a flat plate solar collector and PEM electrolyzer. This integrated system uses the warm surface seawater to evaporate a working fluid like ammonia or a Freon refrigerant, which drives a turbine to produce electricity, which in turn is used to drive a PEM electrolyzer to produce hydrogen. After passing through the turbine, the vapor is condensed in a heat exchanger that is cooled by cold deep seawater. The working fluid is then pumped back through the warm seawater heat exchanger, and the cycle is repeated continuously. Energy and exergy analyses are used to determine the temperature profile in the plant, input and output enthalpy and exergy flows, exergy destructions rates and energy and exergy efficiencies. The relevant energy balances and governing equations for the main sections of the plant shown in Fig. 1 are described in the following subsections.

Energy analysis

Flat plate solar collector

As shown in Fig. 1, water enters the solar collector at point 2 and is heated by the collector. The useful heat gained by the working fluid can be written as:

$$\dot{Q}_u = \dot{m}C_p(T_3 - T_2) \tag{1}$$