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Analysis and Optimization of a Hybrid Solar-Ocean Powered Trigeneration System for Kish Island

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Abstract
With the depletion of fossil fuels and intensification of the environmental burdens, utilization of renewable energies are in the center of attention across the globe. In this paper, a thermodynamic analysis and optimization using MATLAB software is performed for a hybrid solar-ocean powered system to produce three goods including desalinated water, electricity and gaseous hydrogen for the Kish island in Iran. The system considered here includes a solar power tower system, molten salt thermal energy storage system, steam Rankine cycle, multi-stage flash distillation unit and an electrolyzer as the hydrogen production unit. A detailed energy and exergy analysis have been conducted to assess the exergy destructions, component efficiencies and system hotspots. Moreover, the effect of varying some of the main parameters such as solar irradiation and sea water temperature on the system outputs are considered next. For the baseline scenario of the study, it was calculated that the proposed system produces 123.27 kg/s of sanitary water, 14.02 MW of electricity and 0.185 kg/s of hydrogen. A single objective optimization was also carried out to determine the best system performance. It was concluded that the optimum energy and exergy efficiencies of the integrated system are 30.30% and 40.45%, respectively.

Keywords: Exergy, Sustainability, Renewable Energy, Optimization.

Introduction

More than 94% of the power generation in Iran is based on fossil fuels [1], but as these resources are depleting and the problems related to the environment are getting more serious every day, moving toward a more sustainable energy sector is an absolutely necessary task. Besides that, the distribution of power and the scarcity of sanitary water of the distant regions of the country such as islands are another challenge. In this between, small to medium scale renewable energy based plants can be utilize to produce various goods such as water or power to these distant regions. As Iran is placed in the subtropical zone, solar and ocean thermal energies are two of the renewable energies available here, especially in the southern parts of the country.

Many researchers across the world are investigating the use of renewable energies to produce distributed power or other goods. Alzahrani and Dincer investigated the use of solar energy coupled with carbon dioxide super critical power cycle to produce electricity for the city of Medina in Saudi Arabia. They utilized parabolic trough solar collectors integrated with CO_2 power cycle and absorption refrigeration system to produce electricity. The energy and exergy efficiencies of the proposed system was found to be 66.35% and 38.51%, respectively [2]. In another study, El-Emam and Dincer thermodynamically evaluated a solar based multigeneration system that included solar power tower, reverse osmosis unit, electrolyzer unit, Rankine cycle and absorption refrigeration system to provide various goods for the city of Aswan in Egypt. The proposed system generated 4 MW of power, 1.25 kg/h of hydrogen and 90 kg/s of fresh water [3]. The motivation of this paper is the replacement of the fossil fuel based energy systems in the Kish island with more sustainable energy resources such as solar and ocean thermal systems.

Objective here is to perform a thermodynamic analysis and optimization through energy and exergy approaches for a hybrid system using both solar and ocean thermal sources to produce clean water, power and hydrogen for the Kish island in Iran.

System Description

The configuration of the proposed system is shown in "Figure 1". The heliostats reflect the solar radiation to the top of the receiver tower to heat up the molten salt running through the receiver. When the solar radiations are higher than a certain amount, the molten salt tanks began to get charged up and while it is less than that the salts will discharge from the tanks. Two heat exchangers are placed in the way of molten salt to power a steam regenerative Rankine cycle and a multi-stage flash (MSF) unit. In the meantime, the sea surface warm water is pumped up to the coils in the MSF unit to get preheated before entering the molten salt heat exchanger. Based on the design of the MSF unit, certain amount of heat is transferred to the water stream to start the distillation process. The MSF unit consists of a series of stages in which the pressure is lowered after each stage so that the high temperature water gets instant evaporation. The temperature of water before entering each stage is higher than the evaporation temperature of water with regard to the pressure of that stage. The evaporated water condenses on the coils in the upper section of each stage and will be collected. The remaining un-evaporated brine will be released to the sea. Also, the steam entering the condenser of the regenerative Rankine cycle is cooled down by the cold deep sea water. This enables us to lower the pressure of Rankine cycle condenser to produce more power.

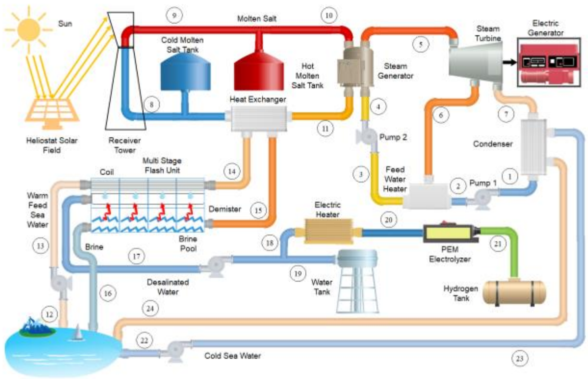

Figure 1. Schematic of the proposed system

Mathematical Modeling

Energy and exergy analysis are performed to investigate the performance of the proposed system. MATLAB software coupled with the library of REFPROP 9 was utilized here to develop the thermodynamic model and Genetic Algorithm was used to perform the optimization. It was assumed that the system operates steadily, while the potential and kinetic energy changes are negligible. Reference pressure and temperature are 101 kPa and 25 ℃. Mass, energy and exergy balances are defined as follow:

$$\sum \dot{m}_i - \sum \dot{m}_e = 0 \quad (1)$$

$$\dot{Q} - \dot{W} = \sum (\dot{m}h)_i - \sum (\dot{m}h)_e \quad (2)$$

$$\dot{Ex}_{dest} = \dot{Ex}_{heat} - \dot{W} + \sum (\dot{m}ex)_i - \sum (\dot{m}ex)_e \quad (3)$$

In the energy systems, sustainability index is defined to relate exergy with the environmental impacts. It is determined as the equation 4:

$$SI = \frac{1}{D_p} \quad (4)$$

In which D_p is the depletion number and is defined as the ratio of exergy destruction to the exergy input.

Due to the intermittent nature of solar energy, a molten salt thermal energy storage (TES) system was considered here. Here, it is assumed that solar radiation changes sinusoidally from 6 AM to 6 P.M and the TES system can store the energy for 12 hours, therefore, the system operates without intermittency. The maximum solar radiation occurs at 12 PM which is 780 w/m^2. The cold and hot seawater temperatures are assumed to be 18 and 27 ℃, respectively and the MSF unit has 20 stages.

Results and Discussion

To validate the presented model, two system components was chosen to perform the validation on them, the solar and electrolysis systems. The solar system was validated based on the study of Li et al. [4]. The efficiency of the receiver was found to be 94.6% while Li et al. [4] reported the value of 90.04%, which indicate the acceptable error of 5%. To validate the proton exchange membrane (PEM) electrolyzer, the study of Loroi et al. [5] was chosen. "Figure 2" show the voltage potential with regard to current density for the present model and that of the Loroi et al.

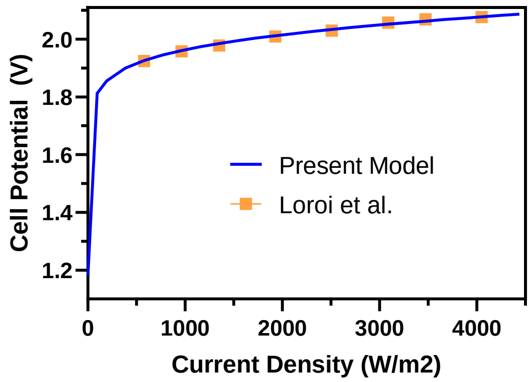

Figure 2. Validation results for the PEM electrolyzer unit for the present model and that of the Loroi et al.

Kish island has a population of 41,250 based on the data reported by the Statistical Center of Iran [6]. Based on the population of the island and also the energy and water consumption per capita, an estimation for the amount of water and power production was performed. The results indicated that for a solar power plant with 10000 heliostats mirror each with an aperture area of 140 m^2, 12 hours of molten salt thermal energy storage and the previous assumptions, 123.27 kg/s of sanitary water, 14.02 MW of electricity and 0.185 kg/s of hydrogen will be produced.

Important parameters that affect the total performance of the system was investigated here to assess the system hotspots and important factors. The effect of solar irradiation on the total hydrogen production and exergy destruction is showed in "Figure 3". As it is observable from this figure, when the intensity of solar radiation increases, both amount of produced hydrogen and sustainability index will be increased. It literally dictates that site selection will be an absolutely important factor that affect the whole system.

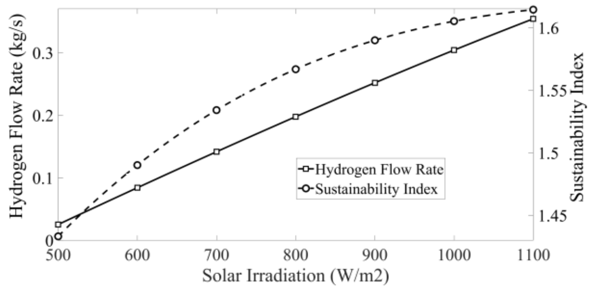

Figure 3. Variation of solar radiation and its effect on sustainability index and hydrogen flow rate

The variation of hot sea water temperature on the exergy efficiency and total exergy destruction is shown in "Figure 4". As it was predicted, the increment in the surface water temperature will increase the system performance by reducing the total exergy destruction while increasing the exergy efficiency. When the hot sea surface water temperature increases by 10 kelvin, the total exergy efficiency of the system increases to more than 5% while the exergy destruction reduces by more than 5 MW.

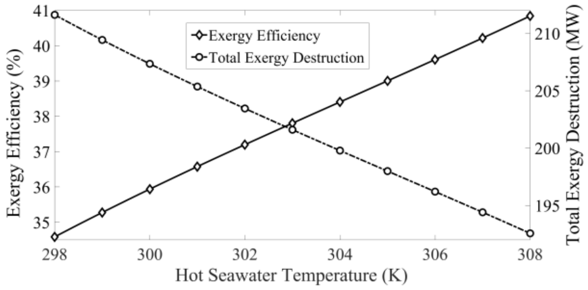

Figure 4. Variation of hot surface seawater temperature with respect to total exergy destruction and exergy efficiency

The effect of cold deep sea water temperature on both energy and exergy efficiencies are shown in "Figure 5". Cold sea water temperature serves as the coolant of the steam Rankine cycle condenser and indeed when the coolant temperature gets higher both efficiencies will be reduced.

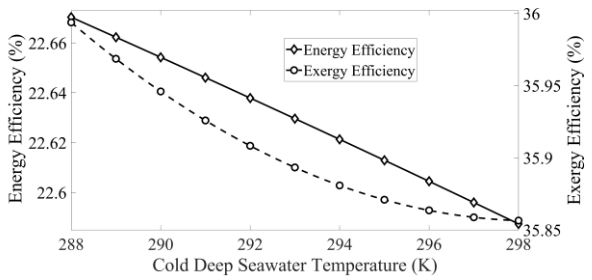

Figure 5. Variation of cold deep seawater temperature with respect to energy and exergy efficiencies

Boiler pressure is one of the other important factors that totally affect the overall system performance as it is shown in "figure 6". As it is observable by increasing the boiler pressure from 10 and doubling it, both the energy and exergy efficiencies will be increased for more than 0.5%.

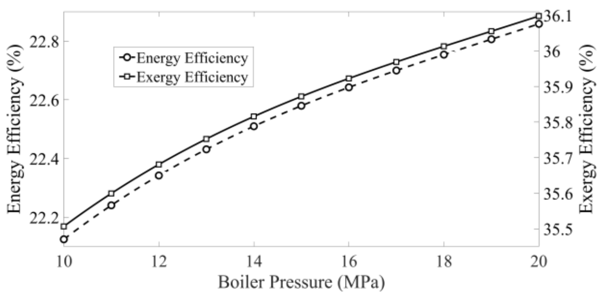

Figure 6. Variation of boiler pressure and its influence on energy and exergy efficiencies

Next but not last is the turbine bleed pressure, which is the pressures of streams number 2 and 6. The variations of this value on total exergy destruction and energy efficiency is shown in "Figure 7". As it is observable here, this parameter has a certain peak point which is located at 1.4 Mpa.

The last important parameter considered here is the pinch temperature which is defined as the minimum possible temperature between the hot stream and the cold stream in the heat exchangers. Its variation with respect to hydrogen flow rate and total exergy destruction is shown in "Figure 8". It was predictable that when the pinch temperature gets lower, system performance gets higher.

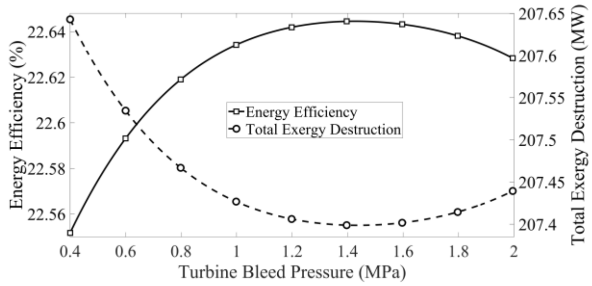

Figure 7. Variation of turbine bleed pressure with respect to energy efficiency and total exergy destruction

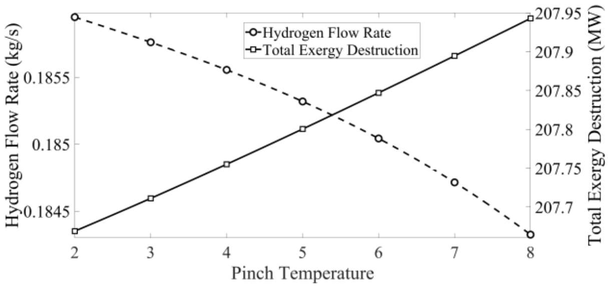

Figure 8. Variation of pinch temperature and its influence on total exergy destruction and hydrogen flow rate

In the Grassmann diagram of "Figure 9", the contribution of different sub-systems on the overall exergy destruction is shown. As it is observable, around 49% of the destroyed exergy is associated with solar field and receiver while the molten salt heat exchangers and storage are the next contributors with around 28% of the overall consumed exergy.

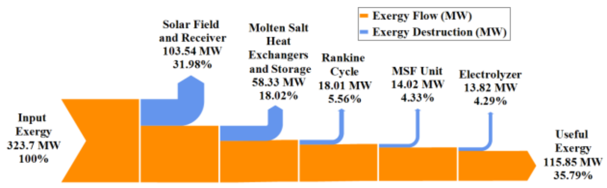

Figure 9. Grassmann diagram for the contribution of different sub-systems on overall exergy destruction of the integrated system

For the optimization in this study, genetic algorithm was utilized with the help of MATLAB software. Chosen input parameters and their ranges for optimization are shown in "Table 1".

Table 1. Chosen input variables and their ranges for the optimization analysis.

Variable	T_{HSW}	T_{CSW}	n_H	ΔT_P	$P_{2,6}$	P_4
Ranges	25-35	15-20	6000-12000	3-10	0.5-2	14-18
Unit	℃	℃	-	-	MPa	MPa

T_{HSW} and T_{CSW} represents the hot and cold seawater temperatures, respectively. n_H is the number of heliostats, ΔT_P is the pinch temperature, $P_{2,6}$ is the turbine bleed pressure and P_4 is the boiler pressure. Two objective function was considered here, energy efficiency and exergy efficiency. The optimum values for both of these functions and their variables was evaluated and are listed in "Table 2". In this table, η represents the overall efficiency of the integrated system. As it is observable from this table, the optimum energy and exergy efficiencies are evaluated to be 30.3% and 40.45%, respectively.

Table 2. Optimum values for input and output of the proposed integrated system.

Variable	Optimum energy efficiency	Optimum exergy efficiency	Unit
T_{HSW}	27.5	34.5	℃
T_{CSW}	17.4	19.8	℃
n_H	6000	9530	-
ΔT_P	3.0	4.37	℃
$P_{2,6}$	1.26	1.43	MPa
P_4	14.78	16.95	MPa
η	30.30	40.45	%

Conclusions

In this paper, by utilization of energy, exergy and optimization approaches, a thermodynamic model was developed to assess a hybrid solar-ocean powered trigeneration system for the Kish island in Iran. A comprehensive analysis was carried out to assess system performance, exergy destruction and system hotspots. The proposed renewable energy based system in this study includes various subsystems such as solar field and tower receivers, molten salt thermal energy storage system, stream regenerative Rankine cycle, multi-stage flash distillation unit and PEM electrolyzer as hydrogen production unit. Moreover, by varying important parameters such as intensity of solar beams or cold and warm seawater temperature, their influence on the overall system performance was evaluated. For the baseline scenario of the study, it was calculated that the proposed system produces 123.27 kg/s of sanitary water, 14.02 MW of electricity and 0.185 kg/s of hydrogen. A single objective optimization using Genetic Algorithm was also carried out to determine the optimum values of input parameters and hence the system outputs. It was concluded that the optimum energy and exergy efficiencies of the integrated system are 30.3% and 40.45%, respectively.

Nomenclature

$\dot{E}x$	Exergy (kW)
$\dot{Q}$	Heat rate (kW)
T_P	Pinch temperature
$\dot{W}$	Work rate (kW)
$\dot{m}$	Mass flow rate (kg/s)
n_H	Number of heliostats
h	Specific enthalpy (kJ/kg)
P	Pressure (kPa)
SI	Sustainability index
T	Temperature (K)
ex	Specific exergy (kJ/kg)
	Subscripts
CSW	Cold seawater
HSW	Hot seawater
dest	Destruction
e	Exit
i	Inlet
	Greek symbols
Δ	Difference
η	Efficiency
	Abbreviations
MSF	Multi-stage flash
PEM	Proton exchange membrane
TES	Thermal energy storage

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