# THERMODYNAMICS ANALYSIS INTEGRATION OF SOLAR HOT WATER COLLECTOR WITH AN OFF-GRID SOLAR-HYDROGEN SYSTEM FOR COMBINED HEAT AND POWER APPLICATION

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**Abstract -** Standalone solar-hydrogen systems, integrating components like PV panels, fuel cells, and hydrogen storage, offer a promising solution for off-grid power and heat generation, particularly when enhanced with heat recovery from fuel cells in combined heat and power (CHP) applications. By integrating solar thermal collectors, these systems can overcome the limitations of intermittent solar heating and potentially achieve 100% renewable heat and power supply without auxiliary energy sources. This study proposed a novel mathematical model based on the laws of thermodynamics to investigate the energy and exergy efficiency of a proposed standalone solar hydrogen integrated with solar hot water collector. The impacts of solar radiation on the performance of the main components and whole system are investigated. The results show that the energy efficiency and exergy efficiency of the proposed system is only around 12% and 9% respectively.

**Key words –** Solar hydrogen; fuel cell; solar hot water; exergy analysis; CHP

## 1. Introduction

Standalone solar-hydrogen systems comprising solar PV, fuel cells, electrolysers, and hydrogen storage - have gained significant attention for off-grid electrification in remote areas where grid access is either impractical or prohibitively costly. These systems offer several advantages over conventional power solutions, including high efficiency, zero greenhouse gas emissions, long-term autonomous operation, and low maintenance [1]. Additionally, hydrogen storage provides better long-term (seasonal) energy retention than batteries, enabling the use of smaller PV arrays without diesel backup [2]. These benefits have spurred research and deployment of standalone solar-hydrogen systems for remote power applications. For instance, Cetin et al. [3] analyzed a hybrid PV-hydrogen/fuel cell system for a residential site in Turkey. Nelson et al. [4] assessed the economics of a wind-solar-hydrogen system for a household in the Pacific Northwest, and Eroglu et al. [5] developed a wind/PV/fuel cell system for a mobile home to study its feasibility for heat and power generation.

Recovering heat from proton exchange membrane fuel cell (PEMFC) stacks for domestic uses such as water and space heating can significantly enhance overall system efficiency in combined heat and power (CHP) applications. Due to their relatively low operating temperatures (60–80 °C), PEMFC-based CHP systems are mainly suited for small-scale, low-temperature applications like homes and small buildings [6-9]. Briguglio et al. [10] demonstrated that a 5 kW PEMFC CHP system could achieve up to 85% efficiency when supplying electricity and hot water to a typical Italian household. Similarly, Hwang et al. [11, 12] reported a peak efficiency of around 82% for residential applications. Shabani and Andrews [1, 2] showed that integrating heat recovery into solar-hydrogen CHP systems can raise annual energy efficiency from 35–50% (power-only mode) to over 80%. Additionally, round-trip energy efficiency improves from ~34% (electricity only) to over 50% when heat is also utilized. However, in systems sized to meet full electrical demand, recovered heat typically covers only about 40% of domestic hot water needs (e.g., for a rural Australian household) [2]. To achieve near-zero emissions, fuel cell waste heat should be supplemented with other renewable sources, such as solar thermal collectors.

On the other hand, solar thermal collectors are widely used for domestic water and space heating, covering about 80% of the global thermal market. However, due to their intermittent nature, especially in winter and cloudy conditions, they typically meet only 60–70% of annual hot water demand, even with oversized collectors and thermal storage. To ensure reliable supply, auxiliary systems such as electric heaters, gas burners, or heat pumps are commonly integrated. Therefore, the idea of integrating solar hot water collector with solar hydrogen could be a good idea to obtain 100% both heat and power supply for standalone applications while avoiding the use of auxiliary energy sources for hot water.

## 2. System description

The proposed system by integrating solar hot water with a standalone solar hydrogen system for combining heat and power (CHP) generation is shown in Figure 1. The system consists of a solar PV array, a controller, an electrolyser (EL), a hydrogen storage tank, a PEMFC, a liquid-to-liquid heat exchanger (HE) with circulating pumps, a solar hot water collector and hot water tank.

As shown in the Figure 1 the PV array supplies renewable electricity to the load during the daytime; after meeting the load demand, surplus electricity will be used to generate hydrogen in the electrolyser. Generated hydrogen is then stored in a hydrogen tank for later use by PEMFC during low solar radiation conditions (i.e. nighttime). In the case of energy supplied from PV to electrolyser is greater than the rated power of the EL, then the addition power generated by the PV is dumped and lost. When the PV is not able to fully meet the load requirement (i.e. at night or low solar radiation), the fuel cell stack will start, using stored hydrogen from the storage tank to produce electricity and maintain the supply to the household.

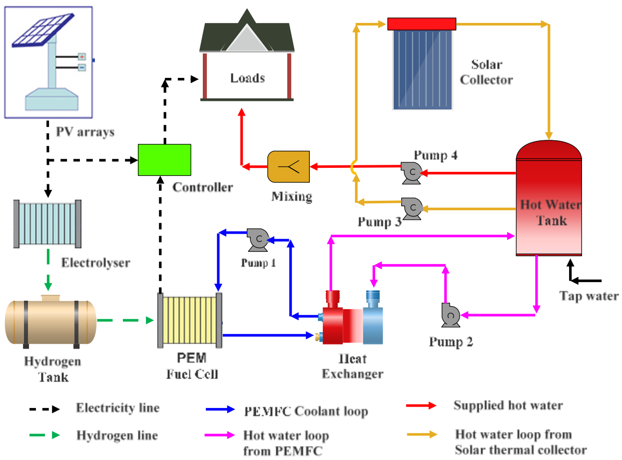


***Figure 1.*** *Schematic diagram of a standalone solar-hydrogen integrated with solar hot water for combined heat and power*

During operation, the fuel cell generates a significant amount of heat, often surpassing the electrical power it produces. Approximately 20% to 30% of this thermal energy is absorbed by the water formed during the electrochemical reactions, leading to its evaporation. A small fraction of heat is also carried away by unreacted hydrogen and air in the exhaust streams. The remaining 60% to 70% of the generated heat, commonly referred to as the "cooling load", must be managed to maintain optimal fuel cell performance. In order to increase energy efficiency of the fuel cell stack, this excess heat is captured using a heat exchanger (HE) and transferred to a domestic hot water storage tank. This process not only aids in thermal management of the fuel cell but also contributes to meeting the household's hot water requirements. However, the heat recovery from the fuel cell stack is typically covers only about 40% of domestic hot water needs. Therefore, a solar hot water collector is added into the system to cover further 60% of the total thermal demand. If the solar radiation is available, the pump 3 will start to circulate hot water through the collector to the hot water tank. Pump 4 will supply hot water to the load when needed.

## 3. Mathematical model

Solar PV convert directly the solar radiation into electricity. The exergy balance for solar PV panels can be written as follow:

$$\dot{E}_{PV,in} = I_{PV}.V_{PV} + \dot{E}_{PV,loss} + \dot{E}_{PV,des} \quad (1)$$

where, $I_{PV}$ and $V_{PV}$ are the output current (A) and voltage (V) of the PV, respectively; $\dot{E}_{PV,in}$ is the input exergy from solar radiation to PV panels (J/s); $\dot{E}_{PV,loss}$ is the exergy losses due to heat losses from the PV's surface to environment; $\dot{E}_{PV,des}$ is exergy destruction of the PV panels.

The exergy of solar radiation plays an important role in determining the performance of systems that convert sun's radiation into useful energy. The exergy of solar radiation is given by [13]:

$$\dot{E}_{PV,in} = G.A_{PV}\left[1 - \frac{4}{3}\frac{T_0}{T_{sun}} + \frac{1}{3}\left(\frac{T_0}{T_{sun}}\right)^4\right] \quad (2)$$

where, $G$ and $A_{PV}$ are the incident solar radiation on the panels (W/m$^2$) and area of PV arrays; $T_{sun}$ = 5777 K is temperature of sun; $T_0$ is environment temperature (K)

When solar radiation strikes on the panels, about 80% of total solar energy is reflected in the ambient and/or converted to thermal energy. This results in an increase in the PV's cell working temperature. Depending on the incident radiation, wind speed and ambient temperature, the PV's cell working temperature can reach up to 80 °C [14, 15]. Therefore, the energy and exergy loss due to heat transfer is considerable and needs to be considered. The exergy loss from PV panels to the environment is given by equation:

$$\dot{E}_{PV,loss} = U_{PV}.A_{PV}.(T_{PV} - T_0).\left(1 - \frac{T_0}{T_{PV}}\right) \quad (3)$$

Where $U_{PV}$ is the overall heat transfer coefficient (W/m$^2$K), $T_{PV}$ is the temperature of the PV panel.

The energy efficiency of PV is defined as the ratio of the created electricity to the incident solar radiation energy on the panels:

$$\eta_{PV} = \frac{I_{PV}.V_{PV}}{G.A_{PV}} \quad (4)$$

The exergy efficiency of the PV can be shown as the equation:

$$\psi_{PV} = \frac{I_{PV}.V_{PV}}{\dot{E}_{PV,in}} \quad (5)$$

Energy balance formulation of the solar thermal collector (STC) can be given as below:

$$GA_{STC} = \dot{Q}_{STC,gain} + \dot{Q}_{STC,loss} \quad (6)$$

where, $A_{STC}$ is area of STC (m$^2$); $\dot{Q}_{STC,gain}$ and $\dot{Q}_{STC,loss}$ are energy gained by the water stream flow through STC and heat lost to ambient, respectively (W).

Exergy balance equation for STC is given as:

$$\dot{E}_{STC,in} = \dot{E}_{STC,gain} + \dot{E}_{STC,loss} + \dot{E}_{STC,des} \quad (7)$$

Where $\dot{E}_{STC,in}$ is the exergy received by STC; $\dot{E}_{STC,gain}$, $\dot{E}_{STC,loss}$, $\dot{E}_{STC,des}$ are the exergy received by water, loss to environment and destruction respectively.

The thermal energy efficiency of STC is given by

$$\eta_{STC} = \frac{\dot{Q}_{STC,gain}}{G.A_{STC}} \quad (8)$$

Exergy efficiency of the STC is expressed as:

$$\psi_{STC} = \frac{\dot{E}_{STC,gain}}{\dot{E}_{STC,in}} \quad (9)$$

The general energy balance for a PEMFC can be expressed as:

$$\sum \dot{Q}_{FC,in} = \dot{W}_{FC} + \sum \dot{Q}_{FC,out} + \dot{Q}_{FC,heat} + \dot{Q}_{FC,loss} \quad (10)$$

where, $\dot{Q}_{FC,in}$ and $\dot{Q}_{FC,out}$ are the inlet and outlet energy transfer rates respectively (i.e. by hydrogen, air and water coolant streams in the thermodynamic system; $\dot{Q}_{FC,heat}$ is the heat energy rejected out the cell stack by water coolant stream; $\dot{Q}_{FC,loss}$ is energy of heat loss from the cell stack to environment; $\dot{W}_{FC}$ is the electricity generated by the fuel cell system.

The general exergy balance for a PEMFC is derived:

$$\sum \dot{E}_{FC,in} = \sum \dot{E}_{FC,out} + \dot{E}_{FC,loss} + \dot{W}_{FC} + \dot{E}_{FC,des} \quad (11)$$

The energy efficiency of the fuel cell can be driven as:

$$\eta_{FC} = \frac{\dot{W}_{FC}}{\dot{m}_{FC,H2\,in}.HHV_{H2}} \quad (12)$$

Exergy efficiency of PEMFC is expressed [16]:

$$\psi_{FC} = \frac{\dot{W}_{FC}}{\dot{E}_{FC,in} - \dot{E}_{FC,out}} \quad (13)$$

The energy efficiency of the fuel cell combined heat generation is calculated by:

$$\eta_{FC\_CHP} = \frac{\dot{W}_{FC} + \dot{Q}_{H2O,FC}}{\dot{m}_{FC,H2\,in}.HHV_{H2}} \quad (14)$$

Exergy efficiency of PEMFC combined hot water is expressed [16]:

$$\psi_{FC\_CHP} = \frac{\dot{W}_{FC} + \dot{E}_{H2O,FC}}{\dot{E}_{FC,in} - \dot{E}_{FC,out}} \quad (15)$$

Energy balance equation for electrolyser:

$$\dot{m}_{EL,H2O} h_{EL,H2O} + \dot{W}_{EL} = \dot{m}_{EL,H2}.h_{EL,H2} + \dot{m}_{EL,O2}.h_{EL,O2} + \dot{Q}_{EL,loss} \quad (16)$$

The mass flow balance is written as:

$$\dot{m}_{EL,H2O} = \dot{m}_{EL,H2} + \dot{m}_{EL,O2} \quad (17)$$

where, $\dot{m}_{EL,H2O}$, $\dot{m}_{EL,H2}$ and $\dot{m}_{EL,O2}$ are the mass flow rate of input water, produced hydrogen and oxygen from electrolyser, respectively; $h_{EL,H2O}$, $h_{EL,H2}$ and $h_{EL,O2}$ are enthalpy of input water, produced hydrogen and oxygen (kJ/kg); $\dot{W}_{EL}$ is electric supplied for electrolyser for hydrogen production; $\dot{Q}_{EL,loss}$ is the heat loss from electrolyser to ambient.

The energy efficiency of electrolyser is given by:

$$\eta_{EL} = \frac{\dot{m}_{EL-H2}.HHV_{H2}}{\dot{W}_{EL}} \quad (18)$$

The general exergy balance for a PEM electrolyser is derived as:

$$(\dot{m}.e)_{EL,H2O} + \dot{W}_{EL} = (\dot{m}.e)_{EL,H2} + (\dot{m}.e)_{EL,O2} + \dot{E}_{EL,loss} + \dot{E}_{EL,des} \quad (19)$$

Exergy efficiency of electrolyser is expressed as:

$$\psi_{EL} = \frac{(\dot{m}.e)_{EL,H2}}{\dot{W}_{EL}} \quad (20)$$

Overall energy efficiency of whole system is the ratio of net output energy of the system to input energy absorbed from the sun, and it is driven as below:

$$\eta_{sys} = \frac{\dot{W}_{net} + \dot{Q}_{H2O} + \dot{m}_{EL,H2}.HHV_{H2}}{G(A_{PV} + A_{STC}) + \dot{m}_{FC,H2\,in}.HHV_{H2}} \quad (21)$$

Where $\dot{W}_{net}$ is the net output electricity of the system, $\dot{Q}_{H2O}$ is the total heat energy produced by solar collector and fuel cell.

Overall exergy efficiency of the whole system is determined by equation:

$$\psi_{sys} = \frac{\dot{W}_{net} + \dot{E}_{H2O} + \dot{m}_{EL,H2}.HHV_{H2}}{\dot{E}_{STC,in} + \dot{E}_{PV,in} + \dot{m}_{FC,H2\,in}.HHV_{H2}} \quad (22)$$

## 4. Case study

A case study was conducted on a small energy-efficient home in a rural area in Victoria, Australia, with a daily electricity usage of approximately 5 kWh and the profile provided in Figure 2. This demand is based on energy consumption for main electrical and auxiliary appliances excluding heating and cooling (i.e. air conditioning). As shown in Figure 2, the average load consists of two peaks: one in the morning (at 7-8 am) and another in the evening (at 6-7 pm). This daily profile is assumed to be the same throughout the year.

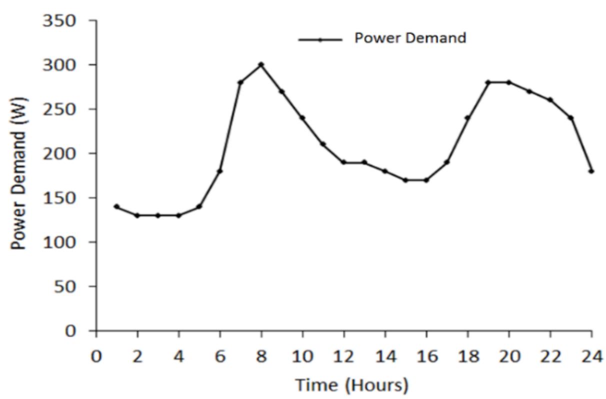


***Figure 2.*** *Load profile of a case study*

In order to meet the power demand, the size of the solar hydrogen must be large enough. The optimal size of the system had been simulated in HOMER software, assuming that the case study was conducted in Southeast Victoria, Australia. **Table 1** present the capacity of the main components:

***Table 1.*** *Optimal sizing of the solar-hydrogen system for the case study*

| **Photovoltaic array** | |
|---|---|
| Size of PV array | $n_{s,PV}$= 35; Power of PV array = 3.5 kW |
| Module area | 0.89 $m^2$ |
| | 298 K |
| **Electrolyser** | |
| Size of EL | $n_{s,EL}$= 50, $P_{r,EL}$= 2.5 kW |
| Maximum Power of one unit (StaXX7PEM electrolyser) | 50 W at 14 V DC |
| Electrode area | 16 $cm^2$ |

| **PEM fuel cell** | |
|---|---|
| Size of FC | $n_{s,FC}$ = 4; $P_{r,FC}$= 0.33 kW |
| Rated power for a single cell | 80 W |
| Electrode area | 232 $cm^2$ |
| Module short-circuit current at reference conditions | 6.5 A |
| Module open-circuit voltage at reference conditions | 21.6 V |
| **Hydrogen Storage Tank** | |
| Tank Volume | 2.5 $m^3$ at 1.5 bar |
| | |
| **Solar hot water collector** | |
| Size of collector (absorber area) | $A_{SC}$ = 2 $m^2$ |
| Flow rate at test conditions | 63 kg/hr.$m^2$ |
| Intercept efficiency ($a_0$) | 0.8 |
| Negative of first order efficiency coefficient ($a_1$) | 1.1248 W/$m^2$.K |
| Negative of second order efficiency coefficient ($a_2$) | 0.0279 W/$m^2$.K |

## 5. Results and discussion

### *5.1. Model validation*

The accuracy of key subsystem models—such as the solar PV, solar thermal collector, and fuel cell—plays a crucial role in determining the overall reliability of the proposed solar-hydrogen system. Therefore, validating these components is essential. The solar PV model is assessed by comparing its independently calculated results with the manufacturer's specifications. As illustrated in the Figure 3, the model's I-V curve under 1000 W/m² solar irradiance shows a short-circuit current of 6.5 A, an open-circuit voltage of 21.6 V, and a maximum power output of 100 W, aligning closely with the values stated in the manufacturer's datasheet.

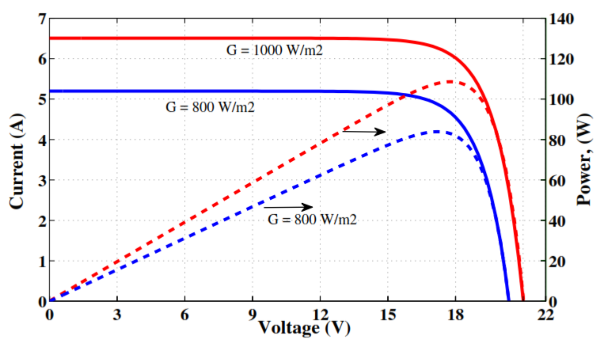


***Figure 3.*** *Validation of the solar PV subsystem in comparison with manufacture's data*

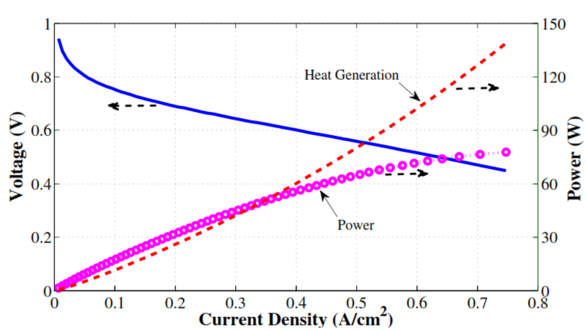


***Figure 4.*** *Validation of PEM fuel cell subsystem*

For the fuel cell system, the model is also validated by comparing the U-I curve and power profile at different current density. As shown in Figure 4, the short circuit current and open circuit voltage of the PV module at 1000 W/m2 are 6.5 A and 21.6 V respectively; and the rated power for a single cell is around 80 W, aligning closely with the values stated in the manufacturer's datasheet.

### *5.2. Effects of solar radiation on the system's performance*

The impact of solar radiation on the energy efficiency of main components including PV, fuel cell, electrolyser, solar collector and fuel cell combined heat and power only (FC-CHP) is shown in Figure 5. As shown, the fuel cell operates to meet the load demand when the solar radiation is lower than 100 W/$m^2$. If there is no sunlight the energy efficiency of the fuel cell is only around 25% and increases to 50% when solar radiation increases to 100 W/$m^2$. By recovery the waste heat from fuel cell for hot water, the overall energy efficiency of the FC–CHP improve to over 60%. The energy efficiency of the electrolyser can obtain over 60% and get higher value at lower radiation. This is due to higher radiation levels, the electrolyser works at a higher power point that results in more losses in the cells of electrolyser. The energy efficiency of solar PV is only around 12% because the PV cell in this study used the old version that was manufactured in 2010. Currently commercialized PV panels can be achieved up to 22%.

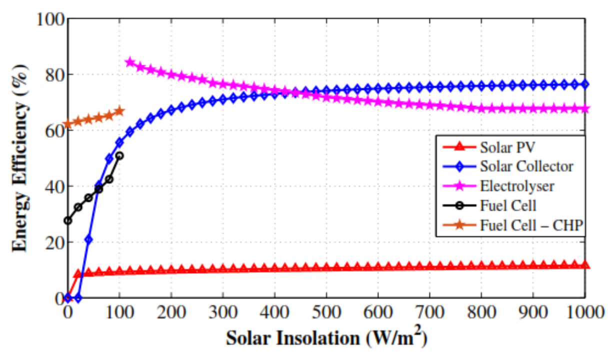


***Figure 5.*** *Effects of solar insolation on the energy efficiency of subsystems*

The exergy efficiency of the subsystems is presented in Figure 6. The exergy efficiency profiles of PV system are similar to its energy efficiency profiles, with its value only around 10-12%. This result is expected because the irreversibilities, which cause over 80% energy losses in the solar cells, such as heat generation due to the absorption shorter wavelengths energy than band gap of cell materials, thermalization, Carnot, shunts and series resistances, contribute to the remarkable destruction of exergy in PV system [17]. The energy and exergy efficiencies of the EL are the same and able to obtain approximately 70% at the rated input power. This result is in a close agreement with the results obtained by Clarke et al. [18]. Interestingly, the exergy efficiency of the solar hot water collector is very low at only 7-8% why its energy efficiency is up to 80%. This result is expected because the temperature of hot water is only 65 °C (low ability to do useful work) compared to 5500 °C temperature of the sun.

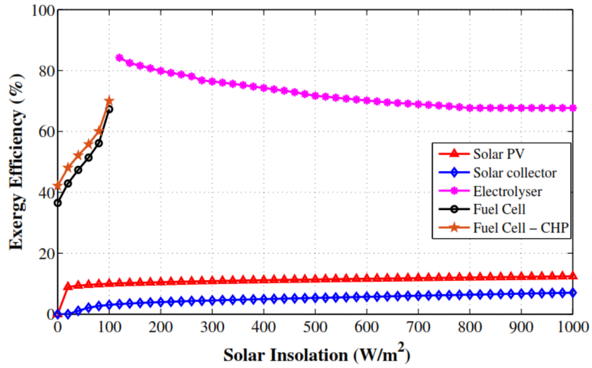


***Figure 6.*** *Effects of solar insolation on the exergy efficiency of subsystems*

**Figure 7** shows the effect of solar insolation on the energy and exergy efficiency of a standalone solar hydrogen integrated with a solar hot water system for combined heat and power applications. The energy efficiency of the system accounts for only around 10%-12% of total solar energy striking on the absorption areas of solar PV and STC. The main reason for this is that the energy efficiency of the solar PV used in this study is very low (around 12%). For second law of thermodynamics analysis the exergy efficiency of the system comes a slight lower with only 9%. This value is expected when the exergy efficiency of both solar PV and solar thermal collector is very low.

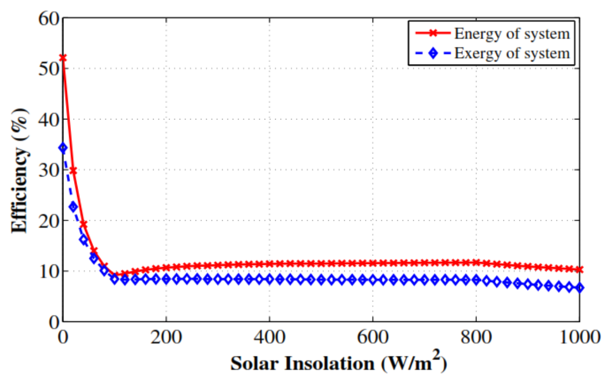


***Figure 7.*** *Effects of solar insolation on the energy and exergy efficiency of the whole system*

## 6. Conclusion

This study assessed the performance of a standalone solar-hydrogen system integrated with a solar thermal collector for combined heat and power applications under varying solar radiation. The system demonstrated energy efficiency of around 12% and exergy efficiency of about 9%, mainly limited by the low efficiency of the older PV panels and the inherently low exergy of low-temperature thermal energy. The fuel cell's efficiency improved significantly with increased solar input, and further gains were achieved through waste heat recovery in a CHP configuration. The results highlight the potential of such systems for off-grid use, while also emphasizing the need for modern PV technology and optimized integration to improve overall system performance.

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