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Innovative Concentrated Photovoltaic Thermal (CPV/T) System with combined Hydrogen and MgO based Storage*

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Abstract

The intermittency of renewable energy resources which only have localized availability with low energy density, is the main reasons for our reliance on conventional fossil fuels. If steady supply and high energy quality can be achieved then solar energy potential is enough to meet the global energy demand. Heat and electricity both are equally important forms of derived energies. In this paper, an innovative configuration of solar energy system for simultaneous need of electricity and high grade thermal energy, is presented and discussed along with the long term energy storage solution. The proposed CPV/T system, with hydrogen based electrical and MgO based thermal storage, can produce electricity and high-temperature thermal energies at efficiency of 30% and 70% respectively. The CPV-Hydrogen configuration achieved Solar to Hydrogen efficiency of 19%. On the other hand, the MgO based TES system obtained 80% material storage efficiency at 400^{o}C which can be easily achieved with the concentrated thermal energy density of 240 Suns.

Keywords: CPVT, Hydrogen, MgO, Solar, Collector, Sustainable.

1. Introduction

Energy is an essential need for the sustainability of the modern world. However, with the recent Paris Agreement on climate change between 192 states and European Union, the target has been set to limit the global temperature increase, below 2^{o}C through expanding the use of renewable energy resources **[1-12]**. Solar energy is considered having the highest energy potential, to meet the current global energy needs **[13-15]**. Despite its availability as low grade radiative and thermal energy, it can be easily converted into high-grade source of electrical and thermal energy by using solar cell and concentrators **[16]**. In addition, to enhance the energy density of the solar energy systems, there is a need to break the conventional photovoltaic market trend with an influx of the highest efficiency CPV system, by overcoming its design complexity and application limitations **[17,18]**.

The operating requirements and conditions of photovoltaic systems depend upon the type of technology. For example, the conventional single-junction PV systems remain stationary during their operation, while the multi-junction solar cell (MJC), 47.1% efficiency **[19,20]**, based concentrated photovoltaic systems require continuous solar tracking during whole day operation as solar concentrators can only accept direct or beam solar radiations. **[21]**. However, such solar

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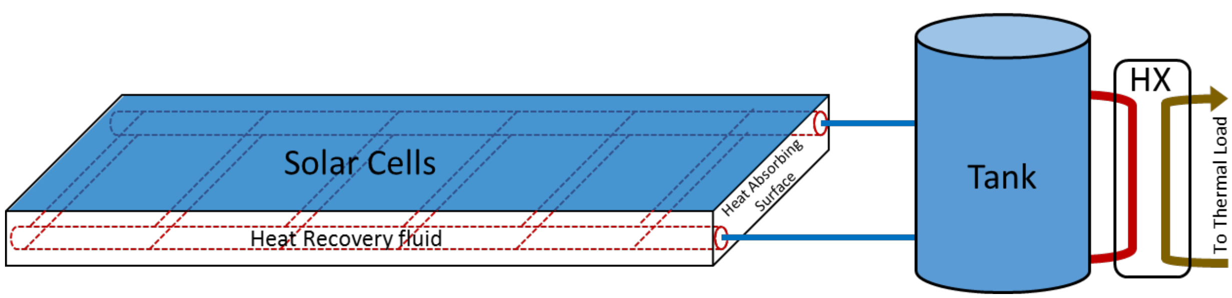
tracking must be highly accurate within the order of 0.1° as the power output of the CPV system can drop significantly with poor solar tracking **[22, 23]**. Such higher tracking accuracy can be reduced with concentrating assembly of high acceptance angle which can also save the tracker power with fewer tracking movements. The accurate and cost-effective tracking system has been developed in our previous studies **[24]** which is not only suitable for CPV tracking needs as high as 0.1° but its compact size and low-cost design will boost the CPV market with more customers and application scope, like conventional PV.

Like the importance and need for green and efficient electricity from solar energy **[25,26[**, there is a lot of application potential and need for high-grade thermal energy for industrial applications. For low grade and low-grade thermal applications, conventional flat plate and evacuated tube collectors are very common **[27]**, only for temperature range up to 90°C. For high temperature solar thermal energy, solar concentrators are used either in trough form or solar mirror field. Such configuration is suitable for a large capacity system and needs a lot of initial investment and spatial requirements. Most of the systems require both high grade thermal and electrical energy for their operation, such as MED, MD, and MSF desalination systems **[28-32]** in the GCC countries which are enriched with solar energy potential. Therefore, such a configuration of the solar energy system is needed which is capable of providing highly efficient solar electricity along with the high grade solar thermal energy. Conventionally, the thermal energy of the photovoltaic system is recovered in the form of a PV/T **[33,34]** or CPV/T **[35-37]** system. Instead of natural convection, solar cells are place on water cooled heat exchanging surface. The heat dissipated by the solar cells during their operation, is absorbed and recovered by the cooling water, as shown in Fig. 1. However, high-grade thermal energy cannot be obtained from such heat recovery schemes. In this paper, a novel CPV/T system configuration is proposed which is not capable of providing efficient electricity but high grade thermal energy can also be extracted simultaneously. Such novel configuration will be able to produce both heat and electricity using single concentrator assembly design.



Despite efficient conversion of solar energy, intermittency is still a major hindrance in its steady operation. Energy storage is needed for steady and uninterrupted solar energy supply **[38,39]**. However, solar radiation cannot be stored directly, therefore, it can be converted into other suitable energy forms such that desired energy output (heat or electricity) can be obtained at any time and capacity, without any loss.

For solar electricity, conventional electrochemical storage technique, in the form of battery, is suitable for low capacity and short period **[40,41]**. Therefore, it cannot provide a sustainable energy

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storage solution for long term solar electricity needs. However, other energy storage techniques i.e. compressed air, pumped hydro are not suitable for system level storage needs. Production of hydrogen not only provides long term energy storage options but it is also a sustainable solution as it can be easily converted back into electricity without any emission but pure water production. The hydrogen energy also can be transported over long distances without any energy loss. Such benefits make hydrogen a sustainable energy carrier and future fuel **[42]**. The most sustainable method of hydrogen production through solar energy is by splitting water **[43]** into electrolyser using photovoltaic generated electricity. However, due to low system efficiency, conventional single generation PV systems are not suitable for hydrogen production, Therefore, CPV with highly efficient solar electricity production can utilize such sustainable hydrogen storage solution to overcome solar intermittency. Moreover, it can also be utilized for both small and large capacity system needs.

For high temperature solar thermal energy storage (TES), conventional TES systems, like hot water tanks, are not suitable. However, phase change materials (PCM) such as molten salt or other suitable substances have the potential to absorb high-temperature heat energy but they have limitations in terms of system capacity, size, and period. Most of these solutions also require very high thermal insulation to avoid heat leak which becomes significant at high-temperature storage. By using the chemisorption behavior of the MgO/H_2O system, a sustainable and long term TES solution can be obtained which not only requires any thermal insulation but it can also significantly reduce the size of the TES system with its high material conversion efficiency and longer period **[44-48]**. The adsorption of water vapors to the MgO salt provides an exothermic reaction with -81.02 kJ/mol energy being released during reaction **[49,50]**. However, such MgO salt can be regenerated using high-temperature heat from solar where desorbed water vapors act as a heat source for the system needs.

In this paper, a novel configuration of CPV/T is presented which has the capability of not only generating efficient electricity but also the high-grade thermal energy using a system design with single solar concentrator. In this manuscript, firstly, the design configuration and working principle of proposed novel CPV/T will be presented and discussed, followed by the testing methodology adopted to test the performance of the proposed system. Secondly, the performance data and the detailed discussion will be presented CPV/T in terms of electricity and heat production/storage, in the results and discussion section. Lastly, the manuscript will be concluded by highlighting the key benefits and performance potential of the Proposed CPV/T system configuration.

2. System Description and Methodology

A simple illustration of the proposed CPV/T system for hydrogen and high-temperature heat production is shown in Fig. 2. The shown system has three major components: 1) CPV/T system with novel concentrating assembly to split and convert solar energy into electrical and thermal energy 2) hydrogen production and storage system and 3) MgO based TES system.

The CPV/T system considered here is based upon the novel design of the multi-leg homogenizer configuration of the concentrating assembly. The main advantage of such concentrating assembly is to have high concentrated solar radiation at its four individual outlets which can be used for

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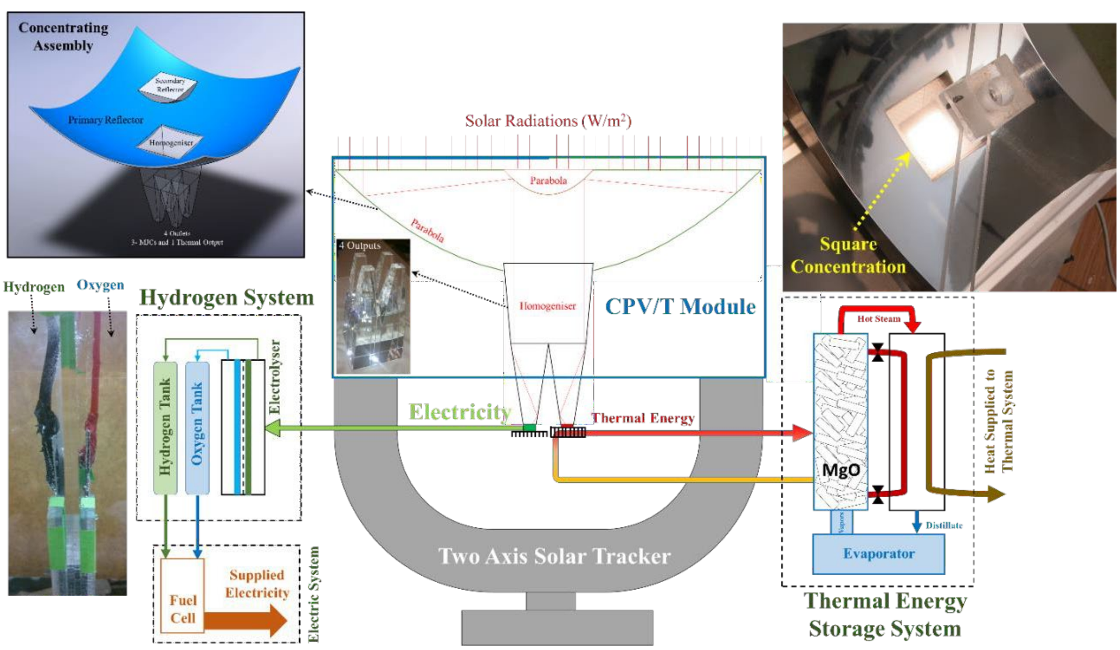
individual needs. The highlight of such design is that only a single pair of the reflector is utilized to achieve high concentration at four individual points. That is why, such a system is the only known concentrating assembly design which can provide both electricity and high-temperature heat simultaneously due to availability of concentrated rays at multiple outlet apertures. Out of four, three outlet apertures are connected to the multi-junction solar cells (MJCs) and the fourth outlet is attached to a thermal absorber that absorbs and transfers concentrated thermal energy to the working fluid circulating through the system.

The multi-leg homogenizer assembly design considered here is based upon geometric concentration factor x500. The concentrating pair of the reflector is based upon two parabolic reflectors. By using two parabolic reflectors, collimated or ray parallel to the axis of reflector, when reflected by primary and secondary reflectors, become parallel again. As a result area reflection is obtained instead of point reflection which can be seen in the top right corner of Fig. 2 where a square bright area in the middle of the primary reflector can be observed. The advantage of such are reflection is such it can be easily divided and further concentrated by the multi-leg homogenizer. Concentrated collimated rays after secondary reflector, are split into four equal parts, which are then directed to four outlet apertures of the homogenizer. A detailed description of multi-leg homogenizer and concentrating assembly design is discussed in our previous publication **[51]**. The whole CPV/T assembly is mounted onto a two-axis solar tracker to track solar beam radiations with a tracking accuracy of 0.1°.



<u>Figure 2: Illustration of Proposed CPV/T system for Hydrogen and High-Temperature Heat Production</u>

To produce hydrogen from developed CPV/T system, the electricity output from its 3 outlet ports, having MJC solar cells, is supplied to the alkaline electrolyser through maximum power point tracker (MPPT). The purpose of MPPT module is to ensure that the solar cell is operating at its maximum power point of IV curve. The electrolyser used here is alkaline-based unit, having

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Nafion membrane to keep produced hydrogen and oxygen gases separated in their compartments to ensure their maximum purity. The purity of these gases is very important as required by the fuel which is needed to convert these gases back into electricity. A flow chart for the operation of proposed CPV/T system is shown in Fig. 3.

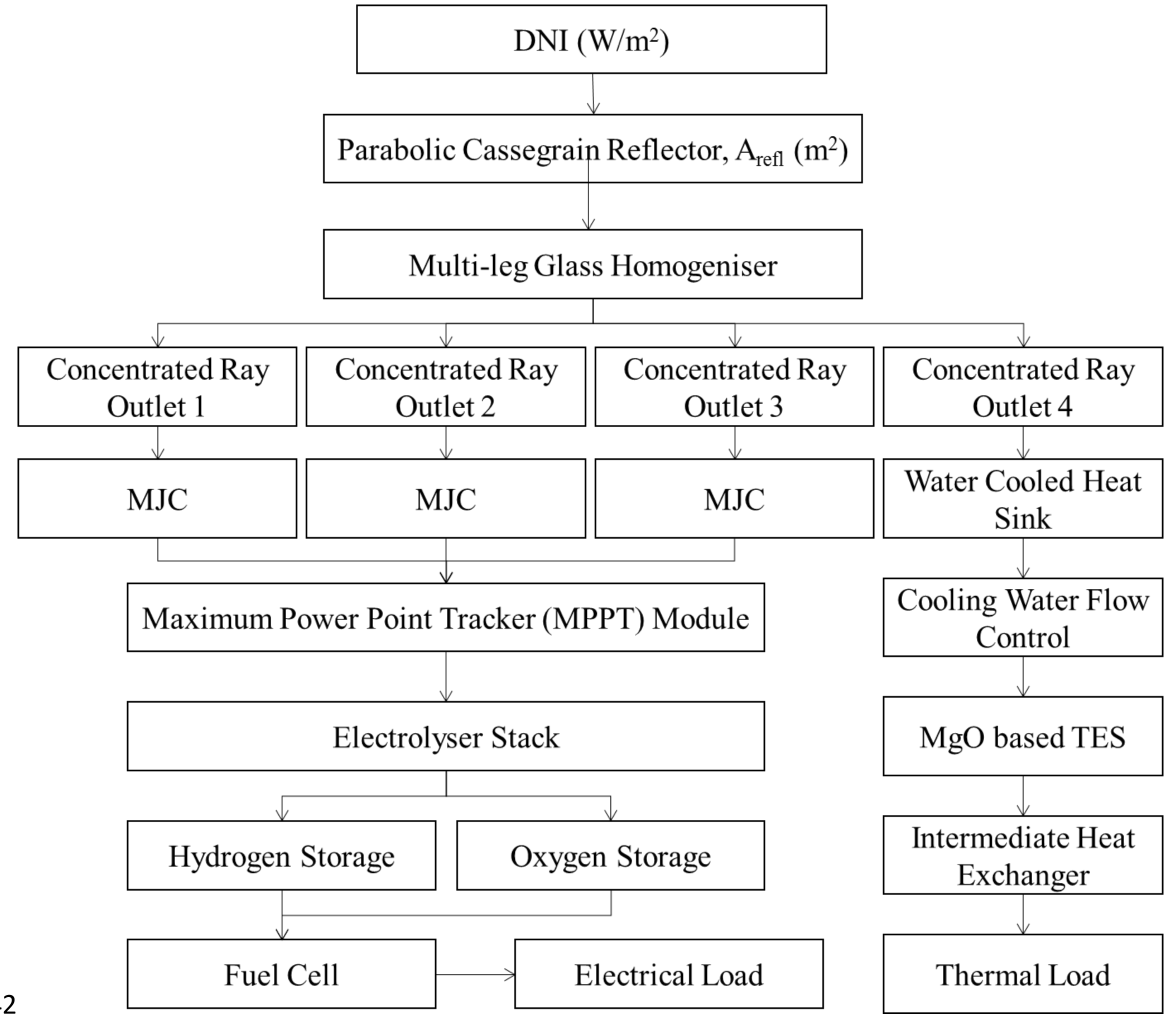

Figure 3: Flow Chart for the Operating Principle of Proposed CPV/T system

On the other hand, the high grade and concentrated thermal energy is extracted from the fourth outlet aperture of the homogenizer where heat-absorbing exchanger transfers extracted solar heat

an intermediate heat exchanger needed in-between the main thermal system and the MgO heat exchanger, which can continuously supply heat to the main thermal system during the charging and discharging process. As mentioned before, the MgO TES system is working on the chemisorption exothermic reaction of water vapors. During regeneration or charging (energy storage) process, high temperature solar thermal energy is used to dehydrate the $Mg(OH)_2$ into MgO by releasing water vapors. The heat of condensation from regenerated vapors, at the temperature same as the regeneration temperature, is used to fulfill the thermal energy needs of the load system. During discharging or adsorption (energy supply) process, which can be normally

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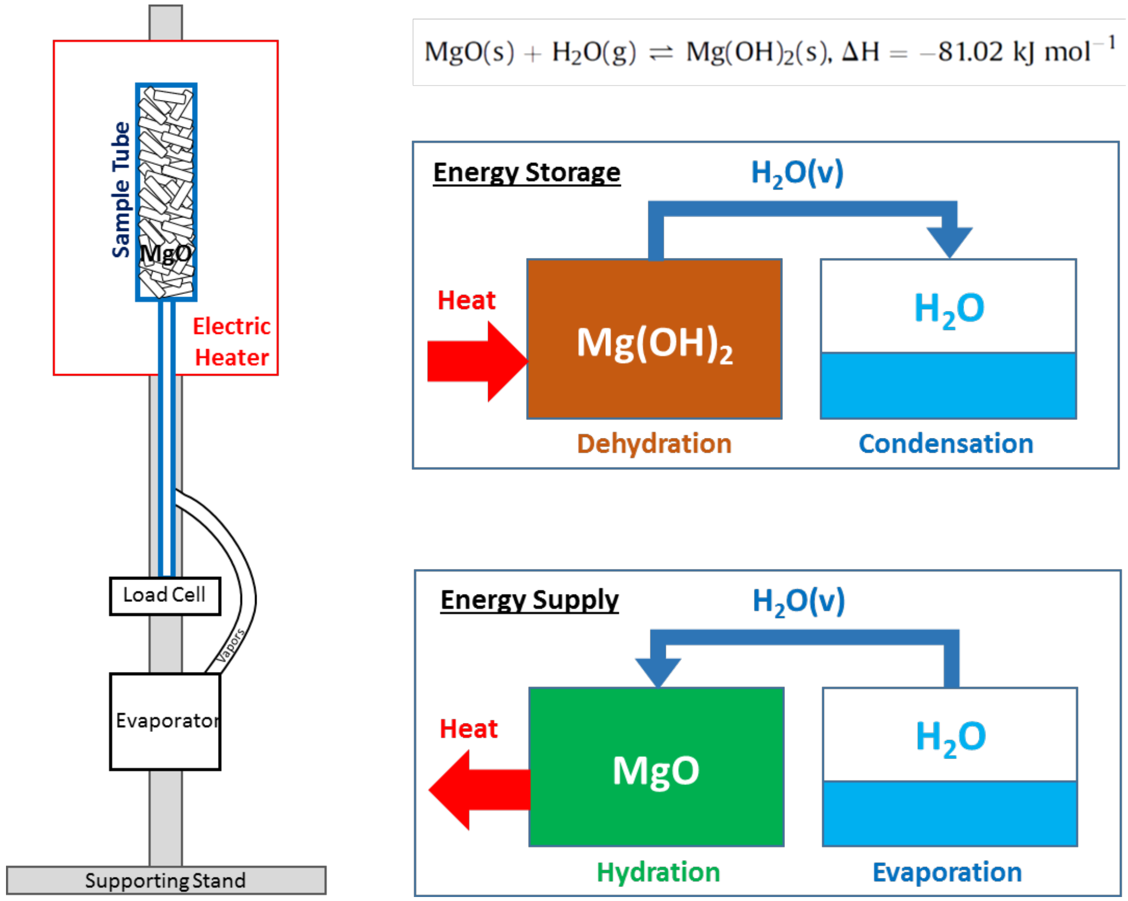
at night time, the water vapors are adsorbed by the MgO pellets and as a result of such exothermic reaction, the heat is released which is then supplied to the connected thermal load. A simple illustration of the energy storage and supply processes of MgO is shown in Fig. 4.



<u>Figure 4: MgO Performance Testing Apparatus (left) and MgO based TES Operation (right)</u>

2.1 MgO material testing methodology

Unlike the hydrogen production system, it is not simple to manufacture a working prototype of the MgO TES system. Therefore, to test and analyze the characteristics of MgO for the TES application, a simple testing apparatus was utilized as shown on the left side of Fig. 4. The MgO testing apparatus is consisting of a glass sample tube in which a certain amount of MgO is filled. The lower side of this MgO filled sample tube is resting on the top of the load cell which can measure the change in the sample weight with the change in its voltage output. The upper side of the sample tube is housed in an electric heater chamber which can be used to heat the sample for regeneration. On the other hand, for energy supply mode, a small electrically operated water evaporator is used to supply water vapors from the lower end of the sample tube. During both energy supply and storage mode, the weight of the sample tube is measured which will indicate the percentage of material used to store the thermal energy. A discussion on the performance of MgO material is provided in the next section.

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3. Results and Discussion

To analyze the performance of the proposed sustainable energy system, first, the performance of the CPV/T system is presented and analyzed. Fig. 5 shows the electrical and thermal efficiency of the CPV/T system against received DNI during full-day operation. Both CPV efficiency and thermal efficiency are obtained using equation (1) and (2).

$$\eta_{CPV} = \frac{P_{CPV}}{P_{solar}} = \frac{I_{mppt} \times V_{mppt}}{DNI \times A_{refl}} \quad (1)$$

$$\eta_{t} = \frac{P_{th}}{P_{solar}} = \frac{\dot{m} C_p \Delta T}{DNI \times A_{refl}} \quad (2)$$

Where the numerator in both of the above equations produced energy of the system either electrical or thermal, respectively. The DNI (Direct Normal Irradiance) gives solar energy in W/m^2, which was recorded using Epply Pyrheliometer as concentrator can only accept beam radiations. The subscript mppt indicate that the current and voltage recorded were from the output of MPPT module which was attached at the output of the MJC solar cells. On the other hand, the temperature of produced thermal energy was controlled by changing flow rate of cooling water.

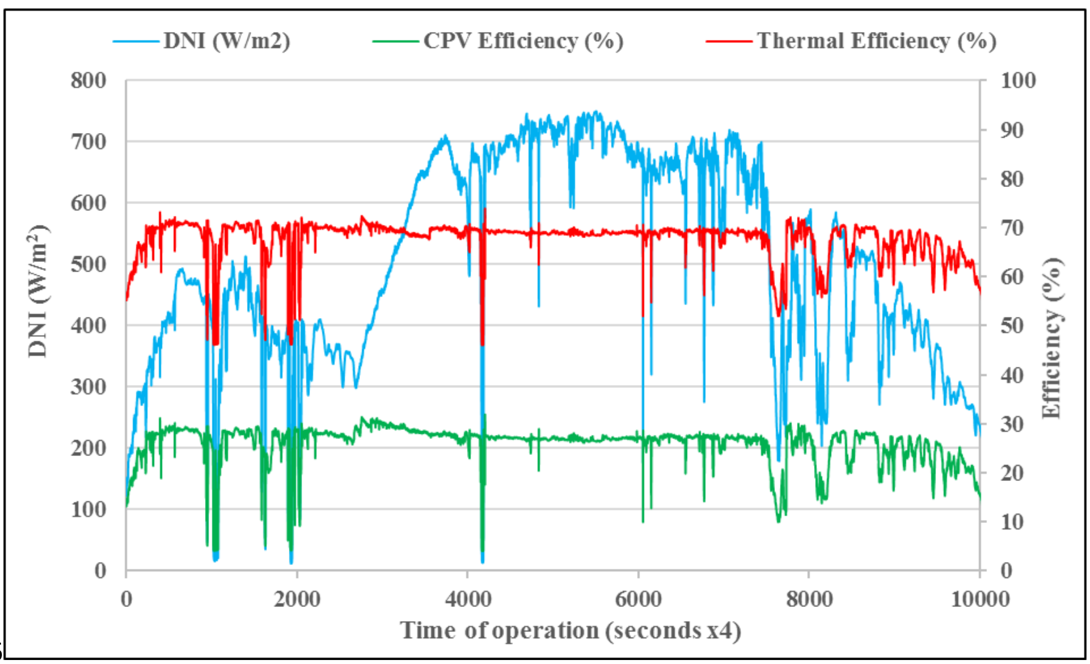

Figure 5: Electrical and Thermal Efficiency of the CPV/T System

It can be seen that the CPV system showed maximum electrical efficiency of around 30% which is about 3-4 times higher than the conventional PV systems which has maximum ranging 7-12% **[52]**. Even, such normal PV panels has marginal efficiency increase to 16% when operated under CPV configuration **[52]**. Even, CPV electrical efficiency alone is higher than the combined

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electrical and thermal efficiency of PV/T system i.e. 29% **[53]**. However, this efficiency is

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changing throughout the day as many parameters, such as temperature, solar intensity, etc. affect the performance of the system. Therefore, the important parameter to present the real electrical potential of the CPV system is its average daily efficiency which can be obtained through the ratio of total energy produced to the total solar energy received i.e. equation (3), instead of instantaneous efficiency value presented in Fig. 5.

$$\eta_{CPV,avg} = \frac{E_{CPV}\,(kWh/day)}{E_{solar}\,(kWh/day)} = \frac{\int_{o}^{24hour} \left(I_{mppt} \times V_{mppt}\right) dt}{\int_{o}^{24hour} \left(DNI \times A_{refl}\right) dt} \tag{3}$$

However, the average performance parameters will be discussed altogether later in table 1 of this section. On the other hand, the maximum thermal efficiency of CPV/T system is around 70%, as shown in Fig. 5. It is important to note here that although this maximum efficiency is almost the same as conventional solar collectors, the quality and exergy of thermal energy obtained from such a system is much higher than the conventional collectors. On the other hand, for conventional PV/T system, not only low grade heat energy is extracted but the thermal efficiency reduces further i.e. 33.8% **[54]**. To further analyze the performance and potential of CPV/T thermal energy, the density of extracted thermal energy against incident solar radiations, is shown in Fig. 6. The maximum density and concentration of thermal energy obtained by the CPV/T system is 240 suns (1 sun = 1000 W/m^2) which is having a concentration factor of x340 as compared to incident solar energy. This depicts that the current CPV/T system with a geometric concentration of x500 achieved an actual thermal concentration factor of x350 which remains almost constant throughout the whole day operation. However, actual concentrated thermal energy is obtained with a maximum intensity of 240 Suns which is changing throughout the day, depending upon the received solar intensity. Therefore, such high quality of both produced energies i.e. electricity and heat, which are from solar system, makes the proposed design configuration a competitive renewable energy system. These presented parameters are explained mathematically with following equations (4) and (5).

$$CF = GC \times \left(\eta_{op} \times \eta_{loss}\right) = GC \times \left(\eta_{th}\right) = \frac{A_{refl}}{A_o} \times \left(\frac{P_{th}}{DNI \times A_{refl}}\right) = \frac{\left(\dot{m} C_p \Delta T / A_o\right)}{DNI} \tag{4}$$

$$TC = \frac{\dot{m} C_p \Delta T}{A_o}\left(\frac{W}{m^2}\right) \times \frac{1\,Sun}{1000\left(W/m^2\right)} \tag{5}$$

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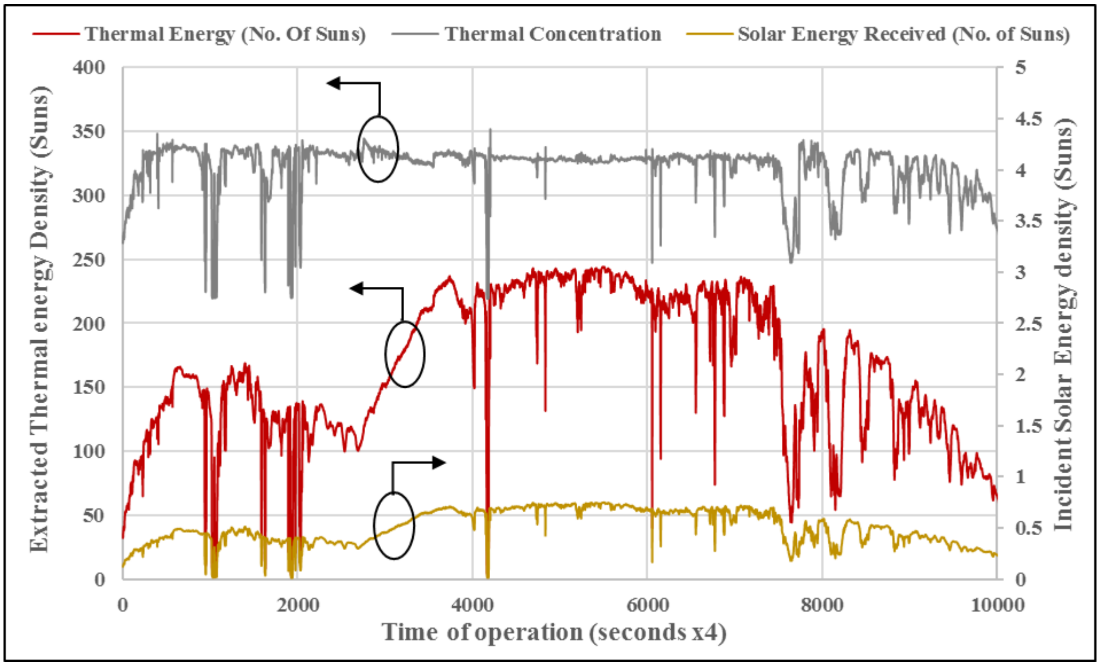

Figure 6: Density of Extracted Thermal Energy against Incident Solar Radiations

After analyzing the performance potential of the proposed CPV/T system, the storage of these derived energies in the form of hydrogen and adsorbed heat is very important, which will be further discussed in this section. Fig. 7 shows the performance and characteristic curves of alkaline electrolyser which is used in this study. Therefore, it is very important to analyze the performance of electrolyser separately before analyzing it as a combined system with CPV/T. From the IV curve, it can be seen that the electrolysis process is starting at voltage as low as 1.4 volts, and then the current and voltage are almost proportional to each other. Electrolyser efficiency is inversely proportional to the operating voltage, which is decreasing with the increase in electrolyser voltage, as given by equation (6).

$$\eta_{EL} = \frac{P_h}{P_{CPV}} = \frac{\dot{n}_{E,H2} \times 237200}{I_E \times U_E} = \frac{\eta_F \times 1.23}{U_E} \qquad (6)$$

The thermoneutral voltage for the electrolysis of water is 1.23V. However, the actual minimum voltage in current experiment is measured as 1.4V, slightly higher than the theoretical voltage as it includes practical losses which are neglected in the ideal case of thermoneutral voltage. Any voltage value lower than minimum voltage will result in no electrolysis reaction and Hydrogen production. However, the electrolyser efficiency is maximum at this point due to lowest operating voltage. But there is almost negligible production at this point. The Faraday efficiency on average is 98.5% which is almost constant throughout the operating voltage range. As the hydrogen production of electrolyser is directly proportional to its operating current, therefore, a straight line trend is also obtained for the H_2 flow rate against operating voltage. To get the best performance, the electrolyser should have high current density with minimum operating voltage.

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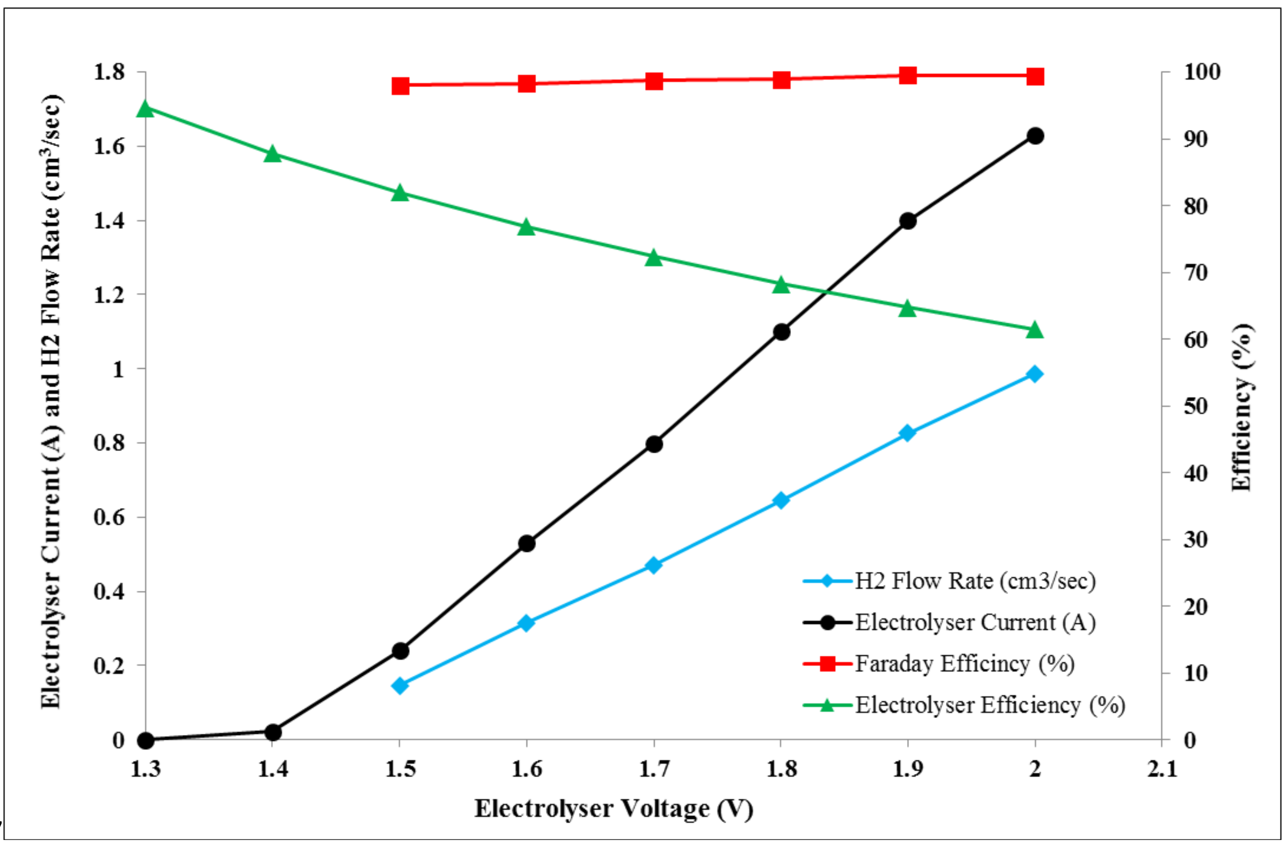
To analyze the true potential of electrolytic hydrogen production using CPV/T system, a summary of the performance data of the CPV-Hydrogen is presented in Table 1. It can be seen that although the maximum electrical efficiency of the CPV system is around 29-30%, however, the daily average efficiency is around 23%. On the other hand, maximum sunlight to hydrogen (STH) efficiency of 19.8% is recorded with the proposed CPV-Hydrogen system which is around 2 times higher than the other PV-Hydrogen and CPV-Hydrogen systems which reported maximum value of 12% **[55]**. As electrolyser efficiency depends upon its operating voltage which changes throughout the day with change in CPV power output, therefore, the sunlight to hydrogen (STH) efficiency is also changing throughout the day. To represent the meaningful performance of the CPV-Hydrogen system, daily average STH efficiency is also presented for each day, as defined by equation (7).

$$\eta_{STH} = \frac{P_h}{P_{solar}} = \frac{\dot{n}_{E,H2} \times 237200}{DNI \times A_{refl}} \qquad (7)$$

It must be noted that maximum CPV and hydrogen efficiency are not obtained at the same point of operation. However, they are just presenting the maximum value of these parameters which was recorded during the operation. Therefore, the true performance parameter to consider is the average STH efficiency with value around 16% for the proposed system.



<u>Figure 7: Characteristic Curves of Alkaline Electrolyser</u>

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Table 1: Daily Performance Data of CPV-Hydrogen System

Sr. No	Electrolyser Energy Consumed	Solar Energy Received	CPV average efficiency	CPV maximum efficiency	Electrolyser average Performance		STH Maximum Efficiency	STH average Performance	
	kWh/day	kWh/day	%/day	%	%/day	kWh/kg	%	%/day	kWh/kg
1	0.0466	0.209	22.9	29.2	69.5	48.97	19.4	15.9	219.61
2	0.0462	0.201	23.5	30.1	70.2	48.72	19.6	16.5	211.97
3	0.0401	0.187	22.7	28.6	67.9	48.33	18.2	15.4	225.37
4	0.0467	0.203	23.3	29.9	71.5	48.81	19.8	16.7	212.18
5	0.0490	0.214	23.1	29.5	70.4	49.73	19.1	16.3	217.44
6	0.0412	0.186	23.0	29.1	69.2	48.45	18.9	15.9	218.72
7	0.0419	0.189	22.9	28.9	68.4	48.05	18.4	15.7	216.76
8	0.0471	0.211	23.4	29.8	71.4	48.89	19.7	16.7	219.02

After analyzing the potential of CPV for hydrogen production, the performance of MgO material is analyzed here for a high temperature TES system. As mentioned before, the characteristics of the MgO material is analyzed through a small testing apparatus as shown in Fig. 4. During testing, the material was undergoing processes of adsorption and regeneration. Fig. 8 shows the real-time performance curves of MgO material at a regeneration temperature of 350^{o}C. One cycle is designed to last for four hours with enough time for each process. Adsorption is lasting for almost 2.5 hours while regeneration process lasts for remaining 1.5 hours. The higher time period for adsorption does not define the difference in the kinetics of adsorption and regeneration reactions. However, the higher time period is only dedicated to compensate any delay due to resistance in the mass transport of the water vapors. However, with proper system design, such losses can be minimized.

The evaporator temperature was set at 120^{o}C throughout the test. However, the rest of the parameters changed accordingly throughout the test. It can be seen in Fig. 8 that the test starts with the adsorption cycle when water vapors are adsorbed by the MgO sample material. In the meantime, the electrical heater temperature was kept at 140^{o}C just to avoid condensation as the testing apparatus was placed inside the lab with an air-conditioned environment. The weight of the sample starts increasing gradually, which indicates the adsorption of water vapors by the MgO material. The percentage change in the sample mass can be traced by the weight change curve in Fig. 8. After the end of the adsorption cycle, the regeneration starts, and the electrical heater temperature, in which the sample tube is enclosed, is changed to 350^{o}C. At the start of regeneration, the previously happening adsorption process continues till it reaches the maximum capacity of the system as the sample takes time to reach to regeneration temperature and the vapor supply is kept on. After reaching its maximum capacity, the sample weight starts to drop and reaches to its initial value. It can be seen that the MgO system achieved maximum weight change of 60% throughout the process with a regeneration temperature of 350^{o}C.

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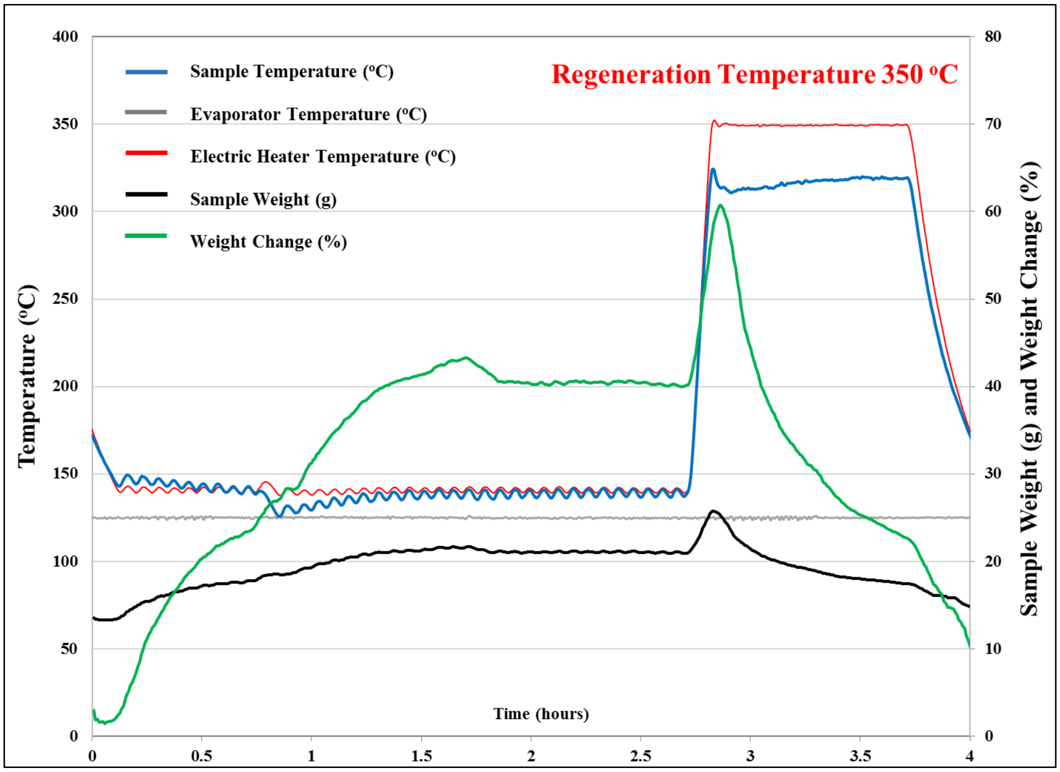

Figure 8: Real Time Performance Curves of MgO material at Regeneration Temp. of 350°C

To compare the performance of MgO material at higher regeneration temperature, the same test was repeated but this time with the regeneration of electric heater temperature of 400°C and the results are shown in Fig. 9. It can be seen that the material followed a similar trend which is explained in the above paragraph of Fig. 8. However, at higher regeneration, the material achieved a higher conversion ratio of 80% which can be observed by the peak of the percentage weight change curve. This shows that the higher regeneration is very important to achieve higher conversion ratio of the MgO material which will not only result in more energy storage but it will also ensure smaller storage footprint and such high temperature can be easily achieved through the concentrated solar thermal energy system, as proposed in this paper. To ensure the repeatability of the results, the same MgO material was tested for repeated cycles of adsorption and regeneration at both temperatures of 350°C and 400°C and the summary of the Cycle Performance Data of the MgO material is shown in Table 2. It can be seen that the performance of the MgO material is consistent for both regeneration temperatures i.e. 59% and 79% for 350°C and 400°C regeneration temperatures respectively.

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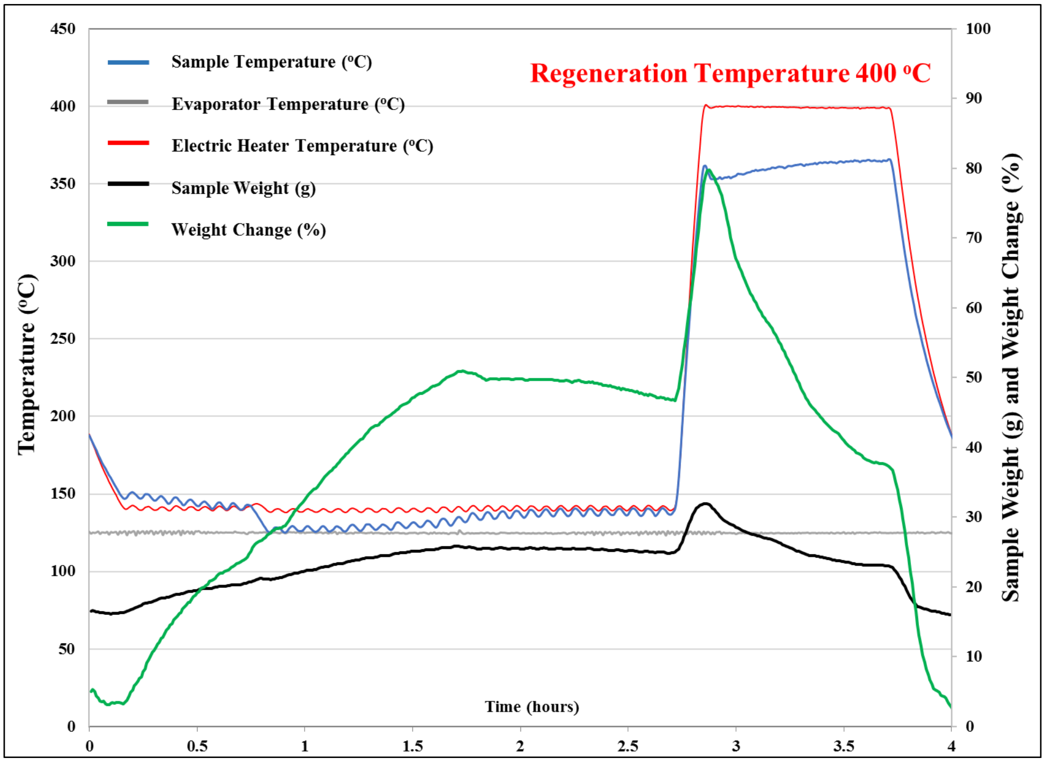

Figure 9: Real Time Performance Curves of MgO material at Regeneration Temp. of 400°C

Table 2: Conversion ratio of MgO as TES System against different Regeneration Temperatures.

Cycles	Regeneration / Conversion Ratio	
	Regeneration Temp. 350°C	Regeneration Temp. 400°C
1	0.614	0.812
2	0.576	0.781
3	0.590	0.775
4	0.581	0.802
Average Conversion Ratio	**0.59**	**0.793**

4. Conclusion

In this paper, a novel CPV/T system is proposed and presented which is capable of providing both electricity and high grade simultaneously, from single unit. The unique optical design of the concentrating assembly can provide concentrated radiations at its multiple outlet, but received by single reflective concentrator. With concentration factor of x340, the system was able to provide thermal energy with intensity of 240 Suns and 70% efficiency. On the other hand, the system showed electricity efficiency of 30%. The produced electrical and thermal energies were then

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stored into hydrogen and MgO material, respectively for uninterrupted energy supply from the solar energy system. The sunlight to hydrogen efficiency of 19% was achieved with the CPV-hydrogen system, which is 3-4 times higher than conventional. While for the high grade thermal energy storage, MgO material with chemi-sorption reaction was used, which significantly showed 80% conversion ratio at 400ºC regeneration temperature. The proposed solar energy system has eliminated the conventional categorization of solar thermal or electrical system as single system is now capable of producing high efficiency and steady electrical and thermal energies as required by most of the systems and industries.

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Nomenclature

DNI	Direct Normal Irradiance, (W/m^2)	A_{reft}	Area of Primary Solar Concentrator/Reflector (m^2)
A_O	Area of one of the outlet aperture of Homogeniser (m^2)	η_{OP}	Optical Efficiency of Concentrating Assembly (%)
I_{mppt}	CPV Current after MPPT Module (A)	V_{CPV}	CPV Voltage after MPPT Module (V)
P_{solar}	Received Solar Power (W)	P_{CPV}	CPV Electrical Power output (W)
η_{CPV}	CPV Electrical Efficiency (%)	η_{OP}	CPV Thermal Efficiency (%)
P_{th}	CPV Thermal Power output (W)	$\eta_{CPV,avg}$	CPV Electrical Daily Average Efficiency (%/day)
P_{solar}	Total Daily Received Solar Energy (kWh/day)	P_{CPV}	Total Daily CPV Electrical Energy output (kWh/day)
CF	Concentration Factor	GC	Geometric Concentration
C_p	Specific heat of Cooling media (J/kg.K)	η_{loss}	Unaccounted radiative loss (%)
TC	Thermal Concentration (Suns)	ΔT	Temperature Difference of Cooling media (K)
I_E	Electrolyser Current (A)	η_{EL}	Electrolyser Efficiency (%)
$\dot{n}_{E,H2}$	Hydrogen Production Flow Rate from Electrolyser (mol/s)	η_F	Faraday Efficiency of Electrolyser (%)

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U iciency (%)

E $\dot{m}$ Electrolyser Cell Voltage (V) P_{CPV} Hydrogen Power output (W)

Flow rate of Cooling media (Kg/s) η_{STH} Solar to Hydrogen Eff

6. References

[1] Boudries R. Analysis of solar hydrogen production in Algeria: Case of an electrolyzer-concentrating photovoltaic system. *International Journal of Hydrogen Energy* 2013, **38(26)**, 11507-11518. https://doi.org/10.1016/j.ijhydene.2013.04.136

[2] Kyoto protocol to the United Nations framework, convention on climate change. United Nations; 1998.

* This paper is an extended and revised article presented at the International Conference on Sustainable Energy and Green Technology 2019 (SEGT 2019) on 11-14 December 2019 in Bangkok, Thailand

[3] Fthenakis V, Mason JE, Zweibel K. The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US. *Energy Policy* 2009, **37(2)**, 387-399. https://doi.org/10.1016/j.enpol.2008.08.011

[4] IPCC, Renewable Energy Sources and Climate Change Mitigation. Special Report of the Intergovernmental Panel on Climate Change. 2012.

[5] Chen H, Yang C, Deng K, Zhou N, Wu H. Multi-objective optimization of the hybrid wind/solar/fuel cell distributed generation system using Hammersley Sequence Sampling. *International Journal of Hydrogen Energy* 2017. http://dx.doi.org/10.1016/j.ijhydene.2017.01.202.

[6] Apak S, Atay E, Tuncer G. Renewable hydrogen energy and energy efficiency in Turkey in the 21st century. *International Journal of Hydrogen Energy* 2016. http://dx.doi.org/10.1016/j.ijhydene.2016.05.043.

[7] Burhan M, Oh SJ, Chua KJ, Ng KC. Solar to hydrogen: Compact and cost effective CPV field for rooftop operation and hydrogen production. *Applied energy* 2017, **194**, 255-66. https://doi.org/10.1016/j.apenergy.2016.11.062

[8] Burhan M, Shahzad MW, Ng KC. Optimization Strategy of Sustainable Concentrated Photovoltaic Thermal (CPVT) System for Cooling. In*Energy Sustainability in Built and Urban Environments* 2019 (pp. 255-275). Springer, Singapore.

[9] Uyar TS, Beşikci D. Integration of hydrogen energy systems into renewable energy systems for better design of 100% renewable energy communities. *International Journal of Hydrogen Energy* 2016. http://dx.doi.org/10.1016/j.ijhydene.2016.09.086.

[10] Burhan M, Shahzad MW, Ng KC. Development of performance model and optimization strategy for standalone operation of CPV-hydrogen system utilizing multi-junction solar cell. *International Journal of Hydrogen Energy* 2017, **42(43)**, 26789-803. https://doi.org/10.1016/j.ijhydene.2017.08.186

[11] Rahmouni S, Negrou B, Settou N, Dominguez J, Gouareh A. Prospects of hydrogen production potential from renewable resources in Algeria. *International Journal of Hydrogen Energy* 2016. https://doi.org/10.1016/j.ijhydene.2016.07.214

[12] Sheu EJ, Mokheimer EM, Ghoniem AF. A review of solar methane reforming systems. *International Journal of Hydrogen Energy* 2015, **40(38)**, 12929-55. https://doi.org/10.1016/j.ijhydene.2015.08.005

[13] Saadi A, Becherif M, Ramadan HS. Hydrogen production horizon using solar energy in Biskra, Algeria. *International Journal of Hydrogen Energy* 2016, **41(47)**, 21899-912. https://doi.org/10.1016/j.ijhydene.2016.08.224

* This paper is an extended and revised article presented at the International Conference on Sustainable Energy and Green Technology 2019 (SEGT 2019) on 11-14 December 2019 in Bangkok, Thailand

[14] Burhan M, Shahzad MW, Oh SJ, Ng KC. A pathway for sustainable conversion of sunlight to hydrogen using proposed compact CPV system. *Energy conversion and management* 2018, **165**, 102-12. https://doi.org/10.1016/j.enconman.2018.03.027

[15] Burhan M, Shahzad MW, Ng KC. Optimization Strategy of Sustainable Concentrated Photovoltaic Thermal (CPVT) System for Cooling. InEnergy Sustainability in Built and Urban Environments 2019 (pp. 255-275). Springer, Singapore.

[16] Akrami E, Nemati A, Nami H, Ranjbar F. Exergy and exergoeconomic assessment of hydrogen and cooling production from concentrated PVT equipped with PEM electrolyzer and LiBr-H2O absorption chiller. *International Journal of Hydrogen Energy* 2018, **43(2)**, 622-33. https://doi.org/10.1016/j.ijhydene.2017.11.007

[17] Burhan M, Shahzad MW, Ng KC. Concentrated Photovoltaic (CPV) for Rooftop—Compact System Approach. InAdvances in Solar Energy Research 2019 (pp. 157-174). Springer, Singapore. https://doi.org/10.1007/978-981-13-3302-6_6

[18] Burhan M, Shahzad MW, Ng KC. Concentrated Photovoltaic (CPV): From Deserts to Rooftops. InAdvances in Sustainable Energy 2019 (pp. 93-111). Springer, Cham. https://doi.org/10.1007/978-3-030-05636-0_5

[19] National Renewable Energy Laboratory (NREL). https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.20200406.pdf. Date retrieved: 15-06-2020.

[20]Cherucheril G, March S, Verma A. Multijunction Solar Cells. Department of Electrical Engineering. Iowa State University. 2011.

[21] Burhan M, Chua KJ, Ng KC. Sunlight to hydrogen conversion: Design optimization and energy management of concentrated photovoltaic (CPV-Hydrogen) system using micro genetic algorithm. *Energy* 2016, **99**, 115-28. https://doi.org/10.1016/j.energy.2016.01.048

[22] Oh SJ, Burhan M, Ng KC, Kim Y, Chun W. Development and performance analysis of a two-axis solar tracker for concentrated photovoltaics. International Journal of Energy Research. 2015, **39(7)**, 965-76. https://doi.org/10.1002/er.3306

[23] Muhammad B, Seung JO, Ng KC, Chun WO. Experimental investigation of multijunction solar cell using two axis solar tracker. InApplied mechanics and materials 2016 (Vol. 818, pp. 213-218). Trans Tech Publications Ltd. https://doi.org/10.4028/www.scientific.net/AMM.818.213

[24] Burhan M, Oh SJ, Chua KJ, Ng KC. Double lens collimator solar feedback sensor and master slave configuration: Development of compact and low cost two axis solar tracking system for CPV applications. *Solar Energy* 2016, **137**, 352-63. https://doi.org/10.1016/j.solener.2016.08.035

[25] Nazir CP. Solar energy for traction of high speed rail transportation: a techno-economic analysis. *Civil Engineering Journal* 2019, **5(7)**, 1566-76. http://dx.doi.org/10.28991/cej-2019-03091353

* This paper is an extended and revised article presented at the International Conference on Sustainable Energy and Green Technology 2019 (SEGT 2019) on 11-14 December 2019 in Bangkok, Thailand

[26] Ahmed BM, ALhialy NF. Optimum Efficiency of PV Panel Using Genetic Algorithms to Touch Proximate Zero Energy House (NZEH). Civil Engineering Journal. 2019 Aug 25;5(8):1832-40. http://dx.doi.org/10.28991/cej-2019-03091375

[27] Sabiha MA, Saidur R, Mekhilef S, Mahian O. Progress and latest developments of evacuated tube solar collectors. *Renewable and Sustainable Energy Reviews* 2015, **51**, 1038-54. https://doi.org/10.1016/j.rser.2015.07.016

[28] Chen Q, Muhammad B, Akhtar FH, Ybyraiymkul D, Muhammad WS, Li Y, Ng KC. Thermo-economic analysis and optimization of a vacuum multi-effect membrane distillation system. *Desalination* 2020, 483, 114413. https://doi.org/10.1016/j.desal.2020.114413

[29] Qian C, Alrowais R, Burhan M, Ybyraiymkul D, Shahzad MW, Yong L, Ng KC. A self-sustainable solar desalination system using direct spray technology. Energy. 2020 Jun 7:118037. https://doi.org/10.1016/j.energy.2020.118037

[30] Shahzad MW, Burhan M, Ybyraiymkul D, Ng KC. Desalination processes' efficiency and future roadmap. *Entropy* 2019, **21(1)**, 84. https://doi.org/10.3390/e21010084

[31] Burhan M, Shahzad MW, Ybyraiymkul D, Oh SJ, Ghaffour N, Ng KC. Performance investigation of MEMSYS vacuum membrane distillation system in single effect and multi-effect mode. *Sustainable Energy Technologies and Assessments* 2019, 34, 9-15. https://doi.org/10.1016/j.seta.2019.04.003

[32] Shahzad MW, Burhan M, Ng KC. A standard primary energy approach for comparing desalination processes. *npj Clean Water* 2019, **2(1)**, 1-7. https://doi.org/10.1038/s41545-018-0028-4

[33] Akrami E, Nemati A, Nami H, Ranjbar F. Exergy and exergoeconomic assessment of hydrogen and cooling production from concentrated PVT equipped with PEM electrolyzer and LiBr-H2O absorption chiller. *International Journal of Hydrogen Energy* 2018. **43(2)**, 622-33. https://doi.org/10.1016/j.ijhydene.2017.11.007

[34] Rabady RI. Solar spectrum management for effective hydrogen production by hybrid thermo-photovoltaic water electrolysis. *International journal of hydrogen energy* 2014. **39(13)**, 6827-36. https://doi.org/10.1016/j.ijhydene.2014.02.074

[35] Bamisile O, Huang Q, Dagbasi M, Adebayo V, Okonkwo EC, Ayambire P, Al-Ansari T, Ratlamwala TA. Thermo-environ study of a concentrated photovoltaic thermal system integrated with Kalina cycle for multigeneration and hydrogen production. *International Journal of Hydrogen Energy* 2020 Aug 9. https://doi.org/10.1016/j.ijhydene.2020.07.029

[36] Kurşun B, Ökten K. Thermodynamic analysis of a Rankine cycle coupled with a concentrated photovoltaic thermal system for hydrogen production by a proton exchange membrane electrolyzer

* This paper is an extended and revised article presented at the International Conference on Sustainable Energy and Green Technology 2019 (SEGT 2019) on 11-14 December 2019 in Bangkok, Thailand

plant. *International Journal of Hydrogen Energy* 2019. **44(41)**, 22863-75. https://doi.org/10.1016/j.ijhydene.2019.07.003

[37] Khan SA, Bicer Y, Koç M. Design and analysis of a multigeneration system with concentrating photovoltaic thermal (CPV/T) and hydrogen storage. *International Journal of Hydrogen Energy* 2020. **45(5)**, 3484-98. https://doi.org/10.1016/j.ijhydene.2018.12.047

[38] Wang Z, Mori M, Araki T. Steam electrolysis performance of intermediate-temperature solid oxide electrolysis cell and efficiency of hydrogen production system at 300 Nm3 h−1. *International journal of hydrogen energy* 2010, **35(10)**, 4451-4458. https://doi.org/10.1016/j.ijhydene.2010.02.058

[39] Burhan M, Shahzad MW, Ng KC. Concentrated photovoltaic (CPV): Hydrogen design methodology and optimization. In*Advances In Hydrogen Generation Technologies* 2018 Aug 22. IntechOpen. DOI: 10.5772/intechopen.78055

[40] Agbossou, K., Kolhe, M., Hamelin, J., & Bose, T. K. (2004). Performance of a stand-alone renewable energy system based on energy storage as hydrogen. *Energy Conversion, IEEE Transactions on*, **19(3)**, 633-640. DOI: 10.1109/TEC.2004.827719

[41] Burhan M, Shahzad MW, Ng KC. Hydrogen at the rooftop: compact CPV-hydrogen system to convert sunlight to hydrogen. *Applied Thermal Engineering* 2018, **132**, 154-64. https://doi.org/10.1016/j.applthermaleng.2017.12.094

[42] Burhan M, Chua KJ, Ng KC. Long term hydrogen production potential of concentrated photovoltaic (CPV) system in tropical weather of Singapore. *International Journal of Hydrogen Energy* 2016, **41(38)**, 16729-42. https://doi.org/10.1016/j.ijhydene.2016.07.183

[43] Scharnberg AR, de Loreto AC, Alves AK. Optical and structural characterization of Bi2FexNbO7 nanoparticles for environmental applications. Emerg Sci J. 2020 Feb 1;4:11-7. http://dx.doi.org/10.28991/esj-2020-01205

[44] Ervin G. Solar heat storage using chemical reactions. Journal of solid state chemistry 1977, **22(1)**, 51-61. https://doi.org/10.1016/0022-4596(77)90188-8

[45] Garg HP, Mullick SC, Bhargava VK. Solar thermal energy storage. Springer Science & Business Media 2012.

[46] Ng KC, Burhan M, Shahzad MW, Ismail AB. A universal isotherm model to capture adsorption uptake and energy distribution of porous heterogeneous surface. *Scientific reports* 2017, **7(1)**, 1-1. https://doi.org/10.1038/s41598-017-11156-6

[47] Burhan M, Shahzad MW, Ng KC. Energy distribution function based universal adsorption isotherm model for all types of isotherm. *International Journal of Low-Carbon Technologies* 2018, **13(3)**, 292-7. https://doi.org/10.1093/ijlct/cty031

* This paper is an extended and revised article presented at the International Conference on Sustainable Energy and Green Technology 2019 (SEGT 2019) on 11-14 December 2019 in Bangkok, Thailand

[48] Brown DR, La Marche JL, Spanner GE. Chemical energy storage system for solar electric generating system (SEGS) solar thermal power plant. Journal of solar energy engineering 1992, **114(4)**, 212-8. https://doi.org/10.1115/1.2930008

[49] Pan Z, Zhao CY. Dehydration/hydration of MgO/H2O chemical thermal storage system. *Energy* 2015, **82**, 611-8. https://doi.org/10.1016/j.energy.2015.01.070

[50] Burhan M, Shahzad MW, Ng KC. A Universal theoretical Framework in Material Characterization for tailored porous surface Design. *Scientific reports* 2019, **9(1)**, 1-7. https://doi.org/10.1038/s41598-019-45350-5

[51] Burhan M, Chua KJ, Ng KC. Simulation and development of a multi-leg homogeniser concentrating assembly for concentrated photovoltaic (CPV) system with electrical rating analysis. *Energy conversion and management* 2016, **116**, 58-71. https://doi.org/10.1016/j.enconman.2016.02.060

[52] Bicer Y, Dincer I. Experimental investigation of a PV-Coupled photoelectrochemical hydrogen production system. *International Journal of Hydrogen Energy* 2017, **42(4)**, 2512-21. https://doi.org/10.1016/j.ijhydene.2016.02.098

[53] Cilogulları M, Erden M, Karakilcik M, Dincer I. Investigation of hydrogen production performance of a Photovoltaic and Thermal System. I*nternational journal of hydrogen energy* 2017, **42(4)**, 2547-52. https://doi.org/10.1016/j.ijhydene.2016.10.118

[54] Senthilraja S, Gangadevi R, Marimuthu R, Baskaran M. Performance evaluation of water and air based PVT solar collector for hydrogen production application. *International Journal of Hydrogen Energy* 2020, **45(13)**, 7498-507. https://doi.org/10.1016/j.ijhydene.2019.02.223

[55] Gibson TL, Kelly NA. Predicting efficiency of solar powered hydrogen generation using photovoltaic-electrolysis devices. *International journal of hydrogen energy* 2010. **35(3)**, 900-11. https://doi:10.1016/j.ijhydene.2009.11.074

* This paper is an extended and revised article presented at the International Conference on Sustainable Energy and Green Technology 2019 (SEGT 2019) on 11-14 December 2019 in Bangkok, Thailand