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Increasing the Energy Output of Solar Hydrogen Power System by Heat Extraction and High Temperature Electrolysis

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Abstract- The paper is about increasing the output from the Solar Hydrogen Power System (SHPS) by heat extraction method from heat loop pipes and through high temperature electrolysis. The paper deals in great detail about the effects of temperature rise on the performance of a (SHPS) on a hot sunny day and then tries to find a methodology by which its overall performance is made better by increasing its system efficiency. Heat loop pipes are employed beneath the panel surface that effectively extract the panel heat thus restoring their efficiency. This heat along with environmental heat is utilized in hot water electrolysis to reduce the electrical energy input given to the electrolyser. The results derived show a clear demarcation of the difference between the output given by a conventional SHPS and that of a modified SHPS.

Index Terms- PEM, electrolysis, heat loop pipes, Solar Hydrogen Power System, GHI

I. Introduction

The global awareness and concern about the greenhouse effect and global warming has led the scientists of the world towards developing new technologies that are environment friendly. The development of hydrogen economy* in this area has stimulated widespread attention towards utilizing hydrogen as a future fuel. Solar energy has the potential to meet the present day Worlds demand many times over. 1% of solar energy falling on Earth could provide energy equivalent to run each and every household. But the way to implementation of these technologies require huge capital investments and the results given especially by solar panels do not match up with the investments. Our this work tries to improve the energy output of Solar Hydrogen Power System in two stages i.e. by extracting heat through heat loop pipes from PV panels and by high temperature electrolysis. Regarding feasibility of the work we need not mention that most parts of India have Global Horizontal Irradiance (GHI) for as many as 300 days, thus the proposed methodology by our estimation can improve PV output by 17% and electrolyser output by 4%.

II. SOLAR HYDROGEN POWER SYSTEMS

The existing SHPS consist of following main components PV panels, PEM electrolysers, Hydrogen tanks & PEM fuel cells. The PV panels harness the solar energy & convert it into electrical energy. This energy so generated is utilised in two ways. A fraction of energy that is equal to the load requirement is transferred directly to the load that caters to the instantaneous energy requirements while the surplus energy that is left is used in electrolyser to evolve out H_2 which eventually serves as a fuel to give electrical energy when primary source is out of fuel thus serving electricity round the year.

III. PHOTOVOLTAIC TECHNOLOGY

We have focussed on the **Flat Plate Mono crystalline technology** used for development of solar cells. Mono-Crystalline Silicon cells are produced by growing high purity, single crystal Si rods and slicing them into thin wafers. The amount of current generated by a PV cell depends on its efficiency, its size (surface area) and the intensity of sunlight striking the surface. The ideal commercial efficiency of mono-crystalline silicon cells remains between 14-16 % because of the purity level. (Jayakumar, 2009)

Under illumination when photons of enough energy are incident on a semiconductor, they create e-h pair.
When a photon with an energy greater than the band gap is incident on a semiconductor, it gives an electron in the valence band enough energy to move to the conduction band. Both the electron in the conduction band and the hole that has been created in the valence band can be involved in the conduction of a current under an electric field.
When an illuminated solar cell is short-circuited, a current flows through the circuit in the opposite direction of the diode current.

$$\mathbf{I} = \boldsymbol{I_{ph}} - \boldsymbol{I_o}\ (\boldsymbol{e^{eV/kT}} - 1) \qquad \text{(i)}$$

Where I_{ph}: photocurrent

$I_o\ (e^{eV/kT} - 1)$: Current due to applied bias.

The Fill Factor (ff) of a solar cell is a measure of the quality of the cell. It is defined as:

$$\mathbf{ff} = \boldsymbol{I_{mp}} \times \boldsymbol{V_{mp}} / \boldsymbol{I_{sc}} \times \boldsymbol{V_{sc}}$$

where I_{mp} & V_{mp} are maximum power points

The efficiency of a cell is the ratio of the maximum converted power Pc to the input

Power Pi:

η= Pc / Pi ________(ii)

η= (*ff* x Isc x Voc) / Pi_______(iii)

From above equation we can see that efficiency is depending on short circuit as well as open circuit voltage.

3.1 Effect on short circuit current: An increase in the temperature of a solar cell results in a slight increase in the short circuit current.
By equation (iv), we can see that short circuit current has direct proportionality with the square of intrinsic carrier concentration which can be given as:

$$ni^2 = 4(2\pi kT / h^2)^3 \, (me^* mh^*)^{3/2} \, e^{-Ego/kT} \quad \text{\_\_\_\_\_\_\_\_(iv)}$$

Where symbols have their usual meaning

With an increase in temperature band gap Ego decreases .Due to which there is an increase in intrinsic carrier concentration which directly results in the slight increase of short circuit current. Standard results shows that for mono crystalline silicon cell short circuit current increases by
0.06 % .per ℃ rise in temperature.

3.2 Effect on open circuit voltage: We have seen that increase in temperature results in the increase of short circuit as well as Io .Therefore because of following relation,

$$Voc= \frac{kT}{q} \ln\left(\frac{Isc}{Io}\right) \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_(v)}$$

Open circuit voltage decreases typically by 2.2mV per ℃ increase of temperature.**The effect of decrease of open circuit voltage is more dominant than increase of short circuit current**

3.3 Effect on fill factor: Due to combined effect of Voc and Isc, fill factor decrease typically by 0.0015 per ℃ rise in temperature.

3.4 Effect of Temperature on Solar Panel Efficiency
25℃ , 10 watt/100 cm2 solar power (STC condition),
100 cm2 or 0.01 m2 solar cell

Voc = 600 mV = 0.6 V*
Isc = 3.0 A*
Vmp = 500 mV = 0.5 V*
Imp = 2.7 A*
ff = ImpVmp/IscVoc = (2.7× 0.5) / (0.6 × 3.0) = 0.75*

*{data taken from the specification sheet of mono crystalline solar cell of PV panel}

Table 1: Temperature and Solar Panel Parameters of hot sunny day in Jaipur (Source NREL)

Ambient Temperature (C)	Temperature of cell (C)	Voc(V)	Isc(A)	ff	Pi(watt)	P max(watt)	Efficiency(%)
42	55	0.534	3.018	0.705	10	1.136	11.36
43	65	0.512	3.024	0.69	10	1.0683	10.68
46	70	0.501	3.027	0.683	10	1.036	10.36
44	68	0.497	3.026	0.686	10	1.032	10.32
43	67	0.494	3.025	0.688	10	1.028	10.28

IV. PROPOSED METHODOLOGY

In the present paper attempt has been made to extract the excess heat produced in the solar panels due to which its efficiency goes down considerably and later on it is shown how the efficiency of electrolysis is improved if temperature is high. Then these two effects are separately dealt with and taken into account to improve the overall performance of Solar Hydrogen Power System. The proposed methodology is shown in the figure below

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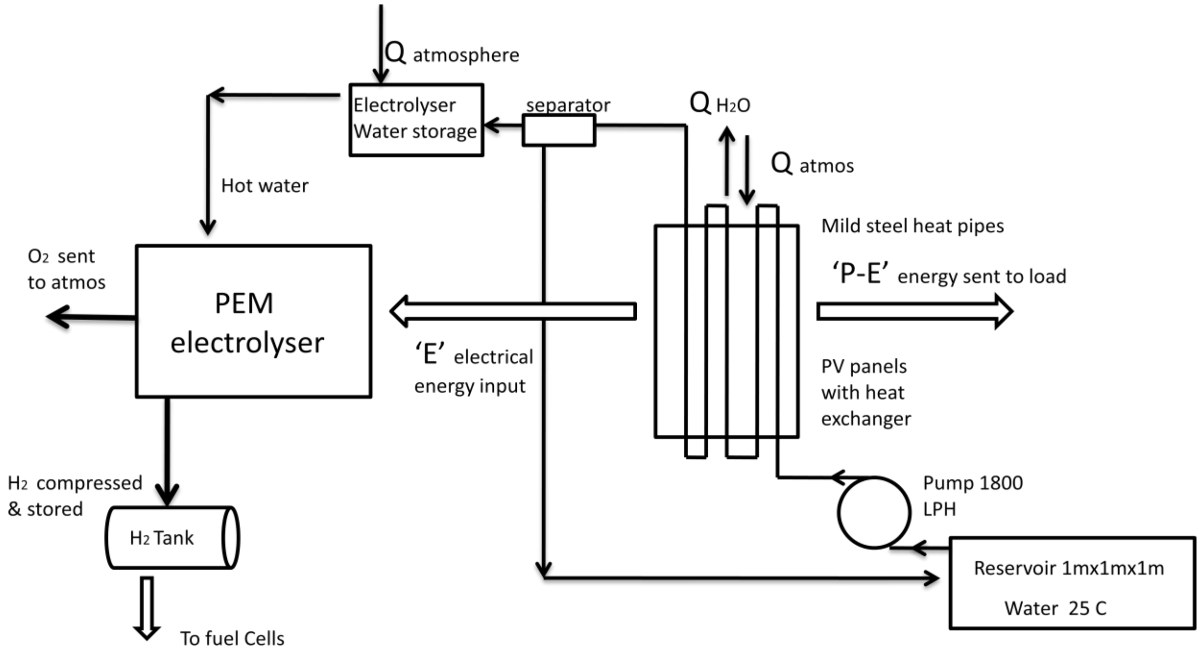

Fig 1: Schematic diagram of modified Solar Hydrogen Power System

4.1 Heat extraction from Solar Panels:

We have considered solar panels spread in an area of $20m^2$ on a hot sunny day in the areas of Jaipur the ambient temperature data is taken from NREL. Solar panels are inclined at 5° to the ground, and for practical purpose inclination is neglected. The GHI is considered in calculating incident energy falling from the sun. Due to high heat capacity of Si and ambient conditions the cell temperature rises to about 70°C due to which its efficiency goes down considerably. To restore the efficiency of Panels heat loop pipes are installed beneath the panel surface making a line contact with it. Water is continuously pumped through a pump from a reservoir 1m x1m x1m made of bricks having optimum insulation and in complete shade so that the water of the reservoir does not rise above 30°C. Pumped water circulates in the mild steel pipes that effectively removes heat of the cell. A part of this water is then diverted towards another reservoir kept directly in the sun with large surface area to enable the water to gain as much heat as possible, rest of the water is pumped back into the reservoir.

In practical use solar panels does not only constitute Silicon cell but the cell is sandwiched between different layers for protection against mechanical injury. The different layers of PV panels include a the layer of glass with an anti reflecting coating, a layer of EVA (ethylene vinyl acetate) then is a thin layer of Si layer with a very thin n side and a thin p side so that the light energy readily reach the junction area where electron hole pairs are created. Below Si cell is another layer of EVA so as to absorb moisture and protection against environmental damage. These layers are then framed under Aluminium frame with Al contacts provided for electrical connections. The cross section of a solar cell in a PV panel is given below along with a table that shows the thickness and thermal conductivity of various layers of Solar Panel.

Table 2: Thickness & thermal conductivity of different layers of Solar Panel

No.	Layer	Thickness (mm)	Thermal Conductivity ($W\ m^{-1}.K^{-1}$)
1	Glass	3.0	0.98
2	EVA	0.5	0.23
3	ARC	$(0.08)x10^{-3}$	
4	Si	0.3	148
5	EVA	0.5	2.6*

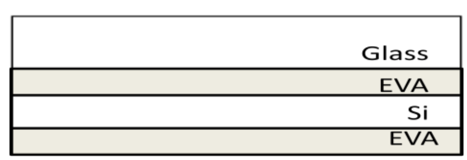

Fig 2: Cross section of a solar cell in a solar panel

Here EVA: ethylene vinyl acetate
(Encapsulation for protection against mechanical injury & moisture)
ARC: Anti reflecting coating
** To improve the thermal conductivity of EVA some filler elements are added like SiC (60% volume) (Lee, 2008)*

For efficient dissipation of heat from a solar panel the encapsulation must have a lower electrical conductivity to prevent leakage currents and must have a higher thermal conductivity. Earlier works on cooling solar panels through natural or forced air cooling has resulted in the restoring of efficiency by 2-3%. The following calculations are done in accordance to cool the solar panel by heat loop pipes.

From the National Renewable Energy Laboratory the GHI (Global Horizontal Irradiance) falling on a metre square area in Jaipur on a hot sunny day is as listed below

Table 3: Temperature and GHI of Jaipur for a particular day (source NREL)

Time	Ambient Temperature	Cell Temperature	GHI (W/m^2)
11:00 am	42	55	913
12:00 noon	43	65	977
01:00 pm	46	70	1005
02:00 pm	44	78	965
03:00 pm	43	67	869

Experiments suggest that cell temperature can rise to even higher values even if the ambient temperature is 38 deg C

4.2 Heat absorption rate by the solar cell Q = GHI x A

Where

GHI: Global Horizontal Irradiance =1000 W/m^2; A: Area of PV panel = 20 m^2

$Q_{apparent}$= 20KW

Since this is the total heat power falling on PV panel. We make a valid assumption that 50% of this solar power is radiated through glass coating and through protective covering therefore the heat absorption rate of the solar cell would not exceed 10KW,

Q=10KW

hence we design the heat exchanger to extract this amount of heat power so that the temperature of Si would remain as per its specifications.

4.3 Design of heat exchanger

The heat exchanger has a plate of mild steel of thickness 12.7mm for increasing contact surface area and for maintaining uniform heat transfer rate to water. It has semi circular grooves on its surface for pipe fixation We choose mild steel pipes of diameter 25.4 mm which are suitable for handling pressure head by the flow of water in the pipes because mild steel has good tensile strength and it is cost effective.

Below is the CAD design of heat loop pipes aligned with PV panels.

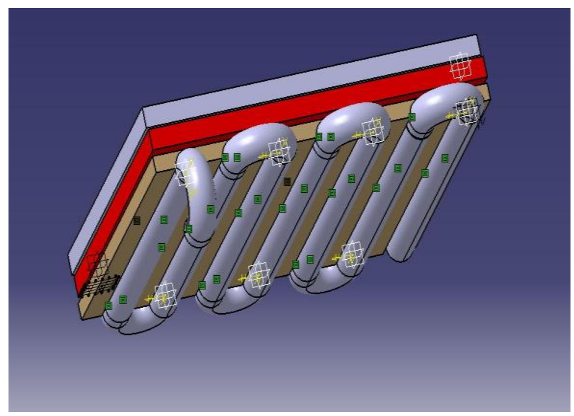

Fig 3: CAD design of heat exchanger pipes (Red colour: EVA layer, grey colour: cell layer)

4.4 Heat transfer rate by EVA and mild steel pipe to water

$$Q^0 = \frac{\Delta T}{\frac{x_{EVA}}{K_{EVA} \times A_{EVA}} + \frac{x_{ms}}{K_{ms} \times A_{ms}}} \quad \text{(vi)}$$

Where

K_{EVA}: thermal conductivity of EVA= 2.6 W/m K , ΔT: temperature difference=5K, x_{EVA}: thickness of EVA= 0.5mm A_{EVA}: Area of EVA= 20m^2, x_{ms}: max. thickness of mild steel pipe with grooving plate=12.7mm, K_{ms}: thermal conductivity of ms pipe=51 W/m K A_{ms}: area of ms pipe= 15.70m^2

Q^0 = 170 KW

Since the heat transfer rate > heat production rate, therefore there is no restriction in heat transfer.

4.5 Heat loop pipe specifications: We have taken heat extraction pipes of mild steel of effective bore 21.4mm and thickness 2mm aligned together in the form of loops with a spacing of 25.4mm between them for bends.

Therefore effective diameter of pipes including clearance space d_0= 50.8mm

Number of pipes required to cover 20 m^2= l/d_0 = 88 pipes

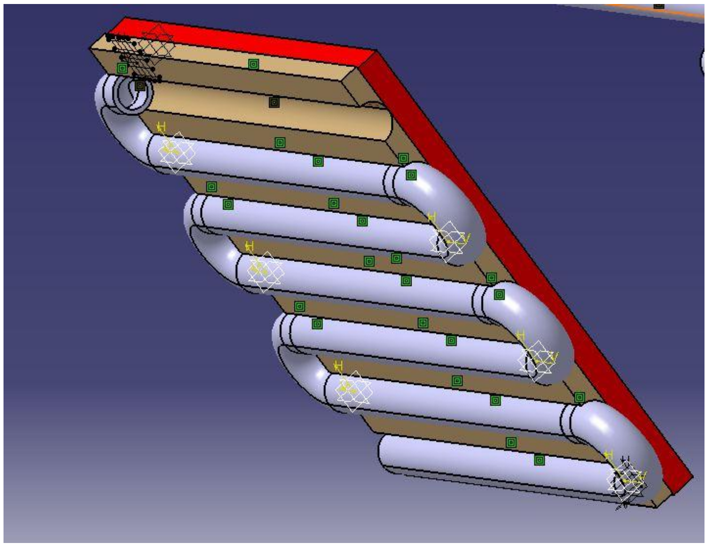

Fig 4: Arrangement of heat pipes in grooves

4.6 Flow rate of water required for heat transfer For heat transfer from solar panels to water in mild steel pipes we pump water from the reservoir kept in insulation and away from sun rays so that water temperature does not go beyond 25℃. Water is pumped through a pump to heat loop pipes so as to reduce the temperature of PV panels.

Heat production $Q' = m_w \times C_w \times T$___________(vii)

Where m_w: mass of water, C_w: specific heat capacity of water= 4200J/Kg K
Since we require that water temperature does not exceed 5°C in Cu pipes we take T= 5℃ and then equating Q′ with Q we get
m_w=0.46 Kg/sec
Now volume flow rate of water q = m_w/ρ_w
q=0.46 l/sec
If all this methodology is applied to PV panels the cell temperature would drop down to 30℃
And its efficiency would be restored to 15% as claimed by manufacturer.

4.7 Pump specifications:
To circulate the water in mild steel pipes we need a water pump of flow rate 1800 lph at 1 m head.
For the purpose we chose the Aquaris Universal 2000lph water pump with maximum 65W power at 3m head

4.8 Calculations of energy output and comparison for 2 cases

Table 4: depicting temperature and GHI of Jaipur

Date	Time	DNI	Temperature	GHI (W/m^2)
05/31/2012	07:00	262	36	49
05/31/2012	08:00	322	37	174
05/31/2012	09:00	393	39	540
05/31/2012	10:00	470	38	731
05/31/2012	11:00	548	42	883
05/31/2012	12:00	621	43	977
05/31/2012	13:00	686	46	1005
05/31/2012	14:00	736	44	965
05/31/2012	15:00	769	43	859
05/31/2012	16:00	783	39	697
05/31/2012	17:00	776	38	500
05/31/2012	18:00	749	36	278
05/31/2012	19:00	705	35	14
				Total 7672

As it has been established that efficiency drops to 10.5% (avg) in the hours between 11am-3pm
We take total energy falling on solar panel = 7.672×20 = 153.44KWh
Total GHI when efficiency is taken to be 15% = 2.983 ×20= 59.66KWh
Total GHI when efficiency is taken to be 10.5%= 4.689 × 20=93.78KWh
Electrical energy produced when efficiency is 15% = 8.949KWh
Electrical energy produced when efficiency is 10.5%=9.84KWh
Total energy produced =18.80KWh

Now total electrical energy produced when modified system is employed=23.016KWh
Total amount of this energy which goes in pumping for 5 hours= 65W x 5hr = 0.325KWh
Effective energy left=22.69KWh
Percentage electrical energy increment =
17.1% _________________(viii)

V. Electrolysis

For the purpose of producing hydrogen, PEM electrolyser is employed due to its following advantages

- ability to cope with a variable power input
- a higher purity level of the produced hydrogen
- higher rates of hydrogen production per unit mass and volume of the electrolyser unit
- an option of getting compressed hydrogen directly delivered without the requirement of a mechanical compressor

Working:
In a PEM electrolyser, a solid polymer membrane acts as the ion-conducting electrolyte, in place of the aqueous solution of an alkaline electrolyser. The polymer membrane conducts the flow

of H^+ ions from the anode to cathode where formation of hydrogen molecules occurs (Barbir 2005).
The cell reactions are

Anode : $2H_2O \rightarrow 4H^+ + O_2 + 4e^-$
Cathode : $4H^+ + 4e^- \rightarrow 2H_2$
Cell : $2H_2O \rightarrow H_2 + O_2 \quad \Delta g_f > 0$

Where Δg_f is the Gibb's free energy of the water decomposition. The positive sign of Δg_f suggest that reaction is endothermic.

5.1 The effect of temperature on electrolysis

Theoretically not all energy required for splitting of water molecule is electrical energy. Empirical relations suggest that at room temperature about 25% energy required for production of hydrogen is given by environment.

It is significant to note that the environmental heat can be supplied to the PEM electrolyser so that this heat can be directly used the water splitting reactions and hence the electrical energy input required to maintain high operating temperature is reduced.

H_2O + heat + electricity $\rightarrow 0.5O_2$. The total energy required for electrolytic hydrogen production

$\Delta H(T)$ =**Q(T) + ΔG(T),**________________(ix)

where
Q(T) = TΔS(T) is the thermal energy demand ΔS(T) is the entropy change in the water splitting reaction process and T is the operating temperature of the electrolyser
If Q(T) is increased further then automatically G(T) is reduced because the total energy required for hydrogen production is constant , which is shown in the graph below

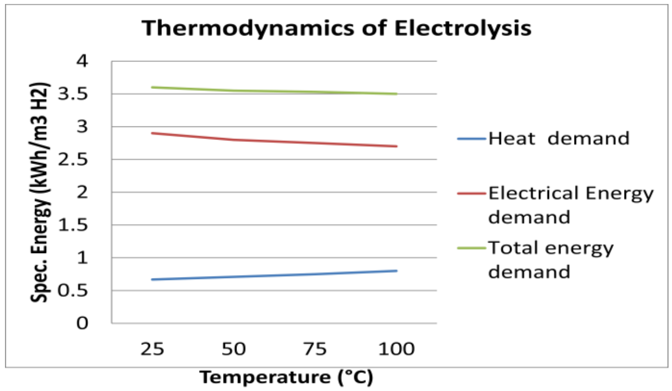

Fig 5: Thermodynamics of Electrolysis

The graph clearly indicates that at high temperatures electrical energy demand for splitting of water is reduced.

The energy efficiency of an electrolyser is the ratio of the energy content of the hydrogen produced per sec to the power consumed. Hence in terms of the higher heating value of hydrogen (HHV)

$\eta = \frac{E_{\text{hydrogen}}}{P_s} = \frac{H_E \times HHV_{H2}}{P_s}$___________(x)

HHV_{H2} is the higher heating value of hydrogen, P_s: Electrical energy demand.

To supply energy to load requiring 5KWh daily we choose specifications of EL 30 PEM electrolyser.
EL30 PEM electrolyser gives H_2 at the rate of 0.33 m^3/h at 1.8KW rated power at 25°C.
Assuming that it runs for 9 hours in sunlight, it requires 16.2KWh electrical energy to produce $3m^3$ hydrogen per day.

But from the thermodynamics of electrolysis curve it is clear that from 25°C to 50°C electrical energy requirement dips by 5.17% and so for producing same quantity of hydrogen under ambient conditions the electrical energy requirement would be 15.36 KWh or for same electricity input, 3.14 m^3 hydrogen would be produced

Table 5: interpolation and extrapolation values of H_2 production by EL 30 electrolyser

hours	Electrical energy at 25°C	Electrical energy at 50°C	H_2 production(m^3/d)
8	14.4	13.65	2.64
9	16.2	15.36	2.97
interpolation	17.1	16.2	3.14*
10	18	17.1	3.33
extrapolation	18.9	18	3.46*

Thus putting the values in eq (x) we get

$\eta = \frac{E_{\text{hydrogen}}}{P_s} = \frac{0.33 \times 3.55 \times 9}{16.2} = 65.0\%$ at 25°C

$\boldsymbol{\eta = \frac{E_{\text{hydrogen}}}{P_s} = \frac{3.14 \times 3.55}{16.2} = 68.8\%}$ **at 50°C**

The results depicted here show that if PEM electrolysers are made to operate at temperatures around 50°C the efficiency improves by about 4%.

steps to publish the research paper in a journal.

VI. CONCLUSION

Through this paper, we tried to increase the energy output of SHPS mainly through heat extraction from PV panels and through high temperature electrolysis. Though calculations above suggest that there is about 17% increment in Solar output and about 4% in electrolysis. But we must mention that these are theoretical stats and are prepared by some assumptions, approximations and by neglecting or assuming some data that can only be obtained through experiments. Like data for Q_{PEM}, energy absorbed by solar cell etc. At the same time it is also just to mention that if experimentally results prove positive for this methodology then it can prove beneficial in achieving higher efficiencies especially for PV panels. Therefore research should be done in this field to improve efficiency of solar cells and also to increase energy output from SHPS because as we are surrounded with issues like Global Warming & Green House effect, gradually shifting to green energies is the way ahead. The capital cost of such SHPS is a major issue that also needs a greater consideration to make such a modified SHPS available to mankind at affordable rates.

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