Sustainable Cooling with Hybrid Concentrated Photovoltaic Thermal (CPVT) System and Hydrogen Energy Storage

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Abstract: Standalone power systems have vital importance as energy source for remote area. On the other hand, a significant portion of such power production is used for cooling purposes. In this scenario, renewable energy sources provide sustainable solution, especially solar energy due to its global availability. Concentrated photovoltaic (CPV) system provides highest efficiency photovoltaic technology, which can operate at x1000 concentration ratio. However, such high concentration ratio requires heat dissipation from the cell area to maintain optimum temperature. This paper discusses the size optimization algorithm of sustainable cooling system using CPVT. Based upon the CPV which is operating at x1000 concentration with back plate liquid cooling, the CPVT system size is optimized to drive a hybrid mechanical vapor compression (MVC) chiller and adsorption chiller, by utilizing both electricity and heat obtained from the solar system. The electrolysis based hydrogen is used as primary energy storage system along with the hot water storage tanks. The micro genetic algorithm (micro-GA) based optimization algorithm is developed to find the optimum size of each component of CPVT-Cooling system with uninterrupted power supply and minimum cost, according to the developed operational strategy. The hybrid system is operated with solar energy system efficiency of 71%.

Keywords: CPVT, micro-GA, Cooling, Solar Efficiency, Hybrid, Sustainable.

1 Introduction

Owing to solar intermittency [1] and prime requirement of the power supplying setups, solar energy systems need to operate in standalone configuration for steady power supply. In addition, it must be able to meet the consumer demand at any time. Current global warming situation requires the renewable energy resources to take over the conventional fossil fuels, as primary energy supply [2-4]. However, despite being the highest potential energy source [5], solar energy is intermittent in nature, which demands sustainable and sufficient energy storage for continuous power supply. Hydrogen production has proved to be the most reliable and sustainable energy storage option [6] for medium and long term operation as the conventional electrochemical energy storage i.e. batteries are only suitable for short term and small capacity systems [7].

In addition, energy conversion efficiency of the system is another important parameter that defines its overall size for specific load demand, especially in case of renewable energy resources. Concentrated photovoltaic (CPV) system, utilizing multi-junction solar cells (MJC), provides highest solar energy conversion efficiency among all of the photovoltaic technologies [8-10]. On the other hand, the entire photovoltaic market is dominated by the conventional flat plate panels
with single junction solar cells [11]. In addition, all of the theoretical studies are also focused on utilization and performance investigation of conventional flat plate panels, utilizing single junction solar cells. Despite being at the top of the solar cell efficiency chart [12], MJ based CPV systems are still lacking in the interest of customers and researchers. Moreover, none of the commercial renewable energy system simulation and optimization tools e.g. HOMER [13], iHOGA [14], TRNSYS + HYDROGEMS, HYBRIDS2, INSEL, ARES, RAPSIM, SOMES and SOLSIM [15], have provision of performance model and simulation/optimization strategy for CPV systems.

So far, the maximum efficiency of 24% has been reported [16] for Hydrogen production using CPV generated electricity at Standard Testing Conditions (STC), which is almost two to three folds higher than the efficiency of electricity production by conventional PV system alone, with 50-80% performance ratio [17]. Therefore, not only based upon the highest efficiency of CPV system alone but also CPV-hydrogen system, it can provide the most compact and efficient standalone solar energy system with steady power supply. However, the literature is lacking the detailed performance and optimization strategy of CPV-hydrogen system for standalone operation for cooling potential. In this paper, a detailed performance model and, standalone operational and optimization strategy for CPV-hydrogen system is proposed and analyzed in detail, to be coupled with mechanical vapour compression (MVC) chiller and adsorption chiller for full utilization of CPV potential with 71% efficiency. Firstly, by using the characteristics of multi-junction solar cell and optical arrangement of concentrating assembly, the model of CPV system is presented for its performance simulation. Secondly, based upon the presented performance model of each of the component of CPV-hydrogen system, mechanical vapour compression (MVC) chiller and adsorption chiller, the overall size of the system is optimized for standalone operation, with appropriate energy storage level but at minimum system cost, by using micro genetic algorithm (micro-GA).

2 Standalone CPVT-Hydrogen System

Fig. 1 shows the schematic of proposed standalone solar energy-cooling system, based upon CPV system, utilizing hydrogen production and hot water as energy storage. The main power producing unit is the concentrated photovoltaic (CPV) system that can either use lenses or reflectors as concentrators to concentrated solar radiations onto small area of multi-junction solar cell (MJC). The CPV modules are mounted onto two axis solar tracker as solar concentrators can only respond to beam part of solar radiations. Depending upon the requirement and configuration, the concentrating assembly of CPV system can be either consisting of single stage concentration, based upon Fresnel lens and homogeniser, or double stage concentration using cassegrain configuration of reflectors and homogeniser. In order to ensure the maximum output from the CPV system, the maximum power point tracking (MPPT) device is connected across it, before supplying its power output to the main DC line connection through DC/DC converter. The main DC line accepts power from all of the sources and supplies it to the main consumer load i.e. mechanical vapour compression (MVC) chiller, through DC/AC converter. It also supplies power to all of the power consuming components of CPV-hydrogen system i.e. solar tracker and gas compressor. The power converter is necessary to match the difference between voltages of generated and the required power. The hot water circuit cools the CPV systems and stores the dissipated heat into hot water storage tank. This stored heat is then used to run auxiliary adsorption chiller, to increase overall energy conversion efficiency of the system.

After covering the consumer and the system load demand, the excess produced electricity is supplied to the electrolyser to produce hydrogen and oxygen as energy storage, from electrolysis of water. However, in case of less power production by the CPV system or power supply at night time, the stored hydrogen and oxygen or ambient air, are supplied to the fuel cell to generate deficient electricity, which is then supplied to consumer load, with water production as by product. In order to lower the footprint of the energy storage, hydrogen is compressed and stored
in cylinders using mechanical compressors. However, oxygen is stored at the production pressure, to lower the cost and power consumption as it can also be obtained from ambient air, in case of deficiency. In the proposed standalone operation, all of the components operate in a cycle, without any need of external supply. Assuming zero leak loss, the water that is used for electrolysis is replenished back through hydrogen and oxygen reaction in fuel cell, during electricity is generated. Therefore, the proposed configuration is also ideal to be used in remote applications.

Figure 1. CPVT-Hydrogen System Schematic for Standalone Operation.

3 CPVT-Hydrogen System Performance Model

In order to optimize the overall size of the CPV-hydrogen system for standalone operation, but with minimum cost, first, there is a need to develop the performance model for each of the system component to simulate the performance of the entire system. Fig. 2 shows the energy management of the proposed standalone CPV-hydrogen system configuration. Weather data, in form of direct normal irradiance (DNI) of solar energy and ambient temperature, acts as the main power input for the system performance model. Depending upon the concentrating assembly configuration, either single or double stage, the concentration at the MJC area can be calculated, which in turns
give the overall power output from the CPV system by knowing the cell characteristics. Based upon the consumer electric load profile, also as input to the system performance simulation, excess or deficient power requirements are calculated, which define the power flow route, either from CPV or Fuel cell. The performance models for each of the component of CPV-Hydrogen system, are discussed further in this section.

![Energy Management Strategy for CPV-Hydrogen System](image)

**Figure 2.** Energy Management Strategy for CPV-Hydrogen System.

### 3.1 Concentrated Photovoltaic (CPV) System

In order to simulate the power output of CPV system, the performance model is based upon the characteristics of multi-junction solar cell (MJC), against concentration and temperature. By using the simple diode model for solar cell under concentration, the power output of single MJC is given by equation (1) [18].

\[
P_C = I_C V_C = V_C \left[ I_o \left( \exp \left( \frac{q V_C}{n_C k T_C} \right) - 1 \right) \right] - I_{SC}
\]  

(1)

In order to find out the diode saturation current factor ‘I_o’, the open circuit voltage condition is invoked i.e. \(I=0\) and \(V=V_{OC}\).

\[
I_o = \frac{I_{SC}}{\exp \left( \frac{q V_{OC}}{n_C k T_C} \right) - 1}
\]  

(2)

As mentioned above, the performance model of the CPV system is based upon the temperature and concentration characteristics of multi-junction solar cell (MJC). In this study, a triple junction solar cell InGaP/InGaAs/Ge is considered. By using equations (3) and (4), the open circuit voltage and the short circuit current of MJC, can be found at any cell temperature and concentration,
through the cell performance variation against concentration at 25°C, and the corresponding
temperature coefficients.

\[ V_{OC}(T_c, C_c) = V_{OC}(at\ 25^\circ C) + (T_c - 25) \left( \frac{dV_{OC}}{dT_c} \right)_{C_c} \]  
(3)

\[ I_{SC}(T_c, C_c) = I_{SC}(at\ 25^\circ C) + (T_c - 25) \left( \frac{dI_{SC}}{dT_c} \right)_{C_c} \]  
(4)

For certain area of MJC and solar concentrator, the concentration at the cell area depends upon
the DNI received and the optical efficiency of the concentrating assembly. The later depends upon
the optical efficiency of each of the optical component of the concentrating assembly, either single
stage or double stage. The concentration at the cell area is given by the equation (5).

\[ C_c = I_b \times \frac{A_{con}}{A_c} \times \eta_{OP} \]  
(5)

Based upon the single stage concentration of Fresnel lens and homogeniser, or double stage
cassegrain arrangement of primary parabolic and secondary hyperbolic reflectors with
homogeniser, the overall optical efficiency of concentrating assembly can be calculated by the
product of optical efficiency of individual component, as given by equations (6A) or (6B).

\[ \eta_{OP} = \eta_F \times \eta_H \]  
(6A)

\[ \eta_{OP} = \eta_P \times \eta_S \times \eta_H \]  
(6B)

Regarding MJC temperature, it is predicted to be 40°C higher than the ambient temperature as
the temperature difference between MJC and the back plate is approximately 10°C [20] and the
back plate temperature is assumed to be 20-30°C higher than the ambient temperature. The total
power output from the CPV system can now be calculate using equation (7).

\[ P_{CPV} = \eta_{DC/AC} \times \eta_{CDC} \times \eta_{Tr} \times \frac{P_{mpt}}{N_{CM}} \times NP_{CPV} \]  
(7)

The parameter Pmppt gives the power output from single MJC cell, but at maximum power point,
which will be discussed in the next subsection. In addition, the power consumed by the trackers
is only considered in the day time only, from sunrise to sunset, as explained in the solar geometry
[21].The values of all of the constant parameters used in current study, are summarized in table
1. For Fresnel lens, PMMA is the most commonly used material for this application, which has
transmission efficiency of around 90%. However, there is a further reflective loss of 92% at the
inlet aperture of the lens. This gives the overall optical efficiency of 72-73% for the Fresnel lens
based concentrating assembly [22]. On the other hand, the silver coated reflectors have quite high
optical efficiency of 98% [23] and with the double stage concentration, overall optical efficiency
of 85% can be assumed for cassegrain based concentrating assembly, if there is further 5% loss
in the glass cover plate and 1% loss in the homogeniser. For current study, lowest average value
of 72.5% will be used for overall optical efficiency.

In order to ensure the maximum power output from each of the solar cell, the maximum power
point tracking (MPPT) device is connected at the output of CPV module. This ensures that the
solar cell operates with maximum possible power output and efficiency, at any operating
conditions. Therefore, the MPPT can be modelled by maximizing the expression for cell power
output i.e. equation (1), for which its first derivative is equated to zero.
\[
\frac{dP_C}{dV_C} = 0 \quad (8)
\]
\[
\frac{d}{dV_C} \left[ V_C I_o \left\{ \exp \left( \frac{qV_C}{n_c kT_C} \right) - 1 \right\} - V_C I_{SC} \right] = 0 \quad (9)
\]

After simplifying the derivative, we can find out the equations for current and voltage at maximum power point and the corresponding maximum power, by using equations (10), (11) and (12).

\[
V_{mppt} = V_{OC} - \frac{n_c kT_C}{q} \ln \left[ 1 + \frac{q V_{mppt}}{n_c kT_C} \right] \quad (10)
\]
\[
I_{mppt} = I_o \left\{ \exp \left( \frac{q V_{mppt}}{n_c kT_C} \right) - 1 \right\} - I_{SC} \quad (11)
\]
\[
P_{mppt} = \eta_{mppt} \times I_{mppt} \times V_{mppt} \quad (12)
\]

### 3.2 Proton Exchange Membrane (PEM) Fuel Cell

The fuel cell model used in this study is for the proton exchange membrane (PEM) based configuration, developed by [29]. The fuel cell supplies the deficient electricity from the stored hydrogen and oxygen. The total power required, determines the total amount of current flowing through the fuel cell and the hydrogen consumption rate, given by equation (13).

\[
\dot{n}_{F,H2} = \eta_H F N_{FC} I_F = 2 \dot{n}_{F,O2} \quad (13)
\]

The faraday efficiency for considered fuel cell is taken as 0.7. In order to find the IV characteristics of the single cell of fuel cell, equation (14) can be used [29].

\[
U_F = U_o - b \log \left( \frac{I_F}{A_F} \right) - R \left( \frac{I_F}{A_F} \right) \quad (14)
\]

The most important factor in the sizing the fuel cell system, is its total number of cells that must be connected in series according to the maximum possible power deficiency i.e. the maximum consumer load requirement, given by equation (15).

\[
N_{FC} = \frac{L_{max}}{\eta_{DC} \times \eta_{DC/AC} \times P_{FC,\text{max}}} \quad (15)
\]

After knowing the total number of cells in the fuel cell system, its current flow can be determine by using equation (16), if the total power demand from the fuel cell is known.

\[
I_F = \frac{P_{req}}{\eta_{DC} \times \eta_{DC/AC} \times N_{FC} \times U_F} \quad (16)
\]

### 3.3 Alkaline Electrolyser

For electrolysis system considered in current study, the performance and characteristics of an alkaline electrolyser have been used from [29]. Similar to the fuel cell, its performance model is
also based upon knowing the IV characteristics of the single cell. Then by knowing the total number of cell required, which are based upon the maximum possible excess power available from the system, that is the difference of minimum requirement of the consumer load and the maximum power rating of the CPV, the maximum power rating of the electrolyser can be determined. So the total number of the required electrolyser cells, can be determined using equation (17).

\[
N_{EC} = \frac{\left( P_{MJC,\text{max}} \times N_{CM} \times N_{P_{CPV}} \right) - L_{\text{min}}}{V_{EC,\text{max}} \times I_{EC,\text{max}}} \tag{17}
\]

All of the electrolyser cells are considered to be connected in series and therefore, same current flows through each of the cell, given by equation (18). On the other hand, the total hydrogen and oxygen production by the electrolyser and the IV characteristics of single electrolyser cell, can be determine by equations (19) and (20), respectively.

\[
I_{E} = \eta_{\text{CDC}} \times \frac{P_{\text{excess}}}{N_{EC} \times U_{E}} \tag{18}
\]

\[
\eta_{E,H_{2}} = \eta_{E,F} \times \frac{N_{EC} I_{E}}{nF} = 2 \eta_{E,O_{2}} \tag{19}
\]

### 3.4 Hydrogen Compressor

As mentioned, the excess power produced by the CPV system is stored in form of hydrogen, by the electrolysis of water. However, in order to further have a compact and reliable hydrogen storage system, which can readily supply the stored hydrogen at any time of the year, the mechanical compression storage into gas cylinders, provides reliable and compact solution. The performance of the hydrogen compressor can be modelled using thermodynamic power equation (20) [30-31].

\[
P_{\text{com}} = \left( \eta_{E,H_{2}} \times \frac{M_{H_{2}}}{1000} \right) \times CP_{H} \times \frac{T_{\text{com}}}{\eta_{\text{DC/AC}}} \times \eta_{\text{com}} \left\{ \frac{P_{\text{in}}}{P_{E}} \right\}^{(\frac{r-1}{r})} - 1 \tag{20}
\]

### 3.5 Hydrogen Storage Cylinder

The main important parameter of interest in the model of the storage cylinder, is the cylinder pressure variation against the quantity of the gas stored. The performance model of the hydrogen storage cylinder is based upon the ideal gas equation with compressibility factor ‘Z’, as given by equation (21).

\[
P_{\text{ta}} = \eta_{\text{ta}}RT_{\text{ta}} \times Z_{H} \tag{21}
\]

### 3.6 Hot water storage tank

The transient model of hot water storage is based upon heat transfer in one-dimension, in the direction of fluid flow within the tank, due to conduction and convection. With the assumption of thermal stratification, the tank is divided into specific number of layers, under thermal uniformity. Based upon the energy balance of control volume of each layer, due to conductive and convective fluxes, the finite differential equations are developed to model the transient thermal behavior of hot water storage tank, given by equation (22).
\[ F_i = \left[ m_i C_p, (T_{1,i} - T_{2,i}) + F_{in}, \left[ m_{in} C_p, (T_{1,in} - T_{2,in}) \right] + k \frac{T_{2,in} - T_{1,in}}{\Delta h} \right] + V_{in} \rho C_p, \left[ T_{1,in} - T_{2,in} \right] \]
\[ F_i = \left[ m_i C_p, (T_{1,i} - T_{2,i}) + F_{in}, \left[ m_{in} C_p, (T_{1,in} - T_{2,in}) \right] + k \frac{T_{2,in} - T_{1,in}}{\Delta h} \right] + V_{in} \rho C_p, \left[ T_{1,in} - T_{2,in} \right] \]
\[ F_i = \left[ m_i C_p, (T_{1,i} - T_{2,i}) + F_{in}, \left[ m_{in} C_p, (T_{1,in} - T_{2,in}) \right] + k \frac{T_{2,in} - T_{1,in}}{\Delta h} \right] + V_{in} \rho C_p, \left[ T_{1,in} - T_{2,in} \right] \]
\[ F_i = \left[ m_i C_p, (T_{1,i} - T_{2,i}) + F_{in}, \left[ m_{in} C_p, (T_{1,in} - T_{2,in}) \right] + k \frac{T_{2,in} - T_{1,in}}{\Delta h} \right] + V_{in} \rho C_p, \left[ T_{1,in} - T_{2,in} \right] \]

\[ (22) \]

3.7 Adsorption Chiller

The model of adsorption chiller is based upon its COP value and chiller rating. As per optimized size of adsorption chiller, the heat utilized by adsorption chiller and corresponding hot water outlet temperatures are given by equation (23)

\[ COP_{AD} = \frac{CE_{AD}}{Q_{AD}} \]
\[ Q_{AD} = L_{cool} \times FR_{AD} \times COP_{AD} \]
\[ Q_{AD} = m_{AD} \times C_{p,w} \times (T_{AD} - T_{AD,R}) \]
\[ T_{AD,R} = T_{AD} - \frac{L_{cool} \times FR_{AD} \times COP_{AD} \times m_{AD} \times C_{p,w}}{L_{cool} \times FR_{AD}} \]

3.8 Mechanical Vapor Compression (MVC) Chiller

Similar to adsorption chiller, the performance model of mechanical vapour compression chiller is based upon its COP value. However, the load requirement of MVC chiller is based upon hot water storage temperature. If there is not enough hot water storage then the MVC chiller operates at its full capacity, as given by equation (24) and (25)

\[ if \left( T_{T,1} > T_{AD} \right) \]
\[ L_{Elect} = \frac{L_{cool} \times (1 - FR_{AD})}{COP_{CH}} \]
\[ if \left( T_{T,1} < T_{AD} \right) \]
\[ L_{Elect} = \frac{L_{cool}}{COP_{CH}} \]

4 Optimization Objective Functions and Strategy

In broader sense, the main objective of proposed system design is to have standalone operation without any external supply, except solar energy as input. Therefore, in total, three objective functions have been defined to find the optimal but cost effective size of the CPVT-hydrogen system. The CPVT-Hydrogen system is optimized for the three objective functions, equations (26-28), for uninterrupted power supply, with sufficient energy storage and minimized system cost.

\[ PSFT = \sum_{t=0}^{\infty} I_{FF} = 0 \]  \hspace{1cm} (26)
\[ L1 < STH_{H2(i)} - ST_{H2(i)} < L2 \]  \hspace{1cm} (27)
\[ C_{AT} = C_{CF} + C_{H2} + C_{FC} + C_{STH2} + C_{STO2} + C_{COP} + C_{AD} + C_{MVC} + C_{IOT} + C_{EX} \]  \hspace{1cm} (28)
After defining the objective functions and the energy management strategy based upon the proposed performance model, the optimization strategy is defined in Fig. 3 and is implemented using micro genetic algorithm (micro-GA). The optimization model for CPVT-hydrogen system is developed in FORTRAN, consisting of two parts. The first part is based upon the system simulation cycle, defined by the energy management strategy according to the performance model of each of the sub-system. However, the second part has the micro-GA code which finds out the optimal value of the optimized parameters, by meeting all of the objective functions. As input to the optimization code, only two sizing parameters are optimized by the micro-GA i.e. the initial hydrogen storage needed and the total number of the CPV panels as the other parameters are linked to them. The micro-GA is implemented with population size of 5, for maximum 200 generations. The optimization results and the discussion regarding the system performance, is presented in the next section.

![Figure 3. Optimization Strategy for CPVT-Hydrogen System using micro-GA.](image)

5 Results and Discussion

In order to analyse the performance variation of CPVT-hydrogen system with received DNI, the system performance curves for whole day operation are shown in Fig. 4. It can be seen that a maximum solar to hydrogen (STH) efficiency of 18% is recorded for the developed CPV-hydrogen system, which is about 2 times higher than the electrical efficiency of conventional PV modules. In the morning, with the increase in the DNI, the STH efficiency is increasing. However, after certain limit, further increase in DNI is cause drop in the STH efficiency. The CPV efficiency was increasing in the morning with increase in the DNI, due to increase in the concentration at the cell area. However, with further increase in the DNI, the efficiency slightly drops due to increase in the cell temperature at higher concentration [32]. The CPV efficiency stabilizes at 24-25% while STH efficiency remains steady at 15%. However, if electrolyser efficiency curve is observed, a continuous drop can be seen during first half of the day when DNI is increasing and...
a continuous increase occurs during other half of the day when DNI start to drop in the afternoon. With increase in DNI, the power output of CPV also increase as there is very slight drop in the efficiency and as a result, the electrical power delivered to the electrolyser also increases, causing increase in the voltage and current of electrolyser. With continuous increase in the operating voltage of electrolyser, its efficiency drops continuously as it is only depending upon its operating voltage. However, in the afternoon when DNI starts to drop, the CPV power and as well as the operating voltage of electrolyser also drops. This causes an increase in the efficiency of electrolyser.

![Performance Curves for CPVT-Hydrogen System](image)

**Figure 4.** Performance Curves for CPVT-Hydrogen System.

The most significant and interesting part in Fig. 4 is the solar conversion efficiency of CPV-Thermal (CPVT) system, which is recorded as 71% maximum. Such efficiency is putting a benchmark for the power producing system. Although, all of the energy cannot be utilized for high grade energy applications. However, with proper combination of energy recovery system, system potential can utilized to its maximum value. In current study for application, such CPVT system provide a sustainable solution with steady production and eliminating the solar intermittency with long term energy storage in form of hydrogen.

Based upon the proposed performance model, energy management technique, objective functions, and input weather and electrical load data, the simulation and optimization code was developed in FORTRAN using micro genetic algorithm (micro-GA). The optimization results are shown in Fig. 5. It can be seen that the solution converges for the minimum cost after around 52 generations. However, for all of the generations, the obtained solution followed the other two objective functions i.e. zero PSFT and the availability of enough hydrogen storage available at the end of the simulation cycle. This shows the capability of micro-GA in search of the global optimum in a very short time. Such proposed micro-GA optimization strategy and CPVT-Hydrogen energy management algorithm can be utilized to optimize the size of CPVT system for any cooling requirements by utilizing the maximum potential of CPVT system, the best solar energy system available so far.
6 Conclusion

We have successfully conducted the design and techno-economic optimization with CPVT-Hydrogen system energy management for a standalone operation with global minimum total annualized system cost for zero PSFT factor and optimal storage. Such a multi-objective optimization procedure was reliably implemented to uninterrupted cooling load requirement by utilizing the maximum potential of CPV-Thermal (CPVT) system with solar energy conversion energy efficiency of 71%. Such a dynamic approach not only considers the hourly load variations but also proposes the system design that is capable of handling and preparing itself for the seasonal weather variations. In addition, it can also be optimally configured to accommodate the regional variations into the system design. Furthermore, the proposed performance model can also be integrated with current commercial simulation tools to make them capable to consider CPV in their analysis.

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