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Boosting the energy output of an On-Grid solar PV system using a novel techniques

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Abstract: Two techniques have been used in this study to boost energy output of an on-grid PV system. Boosting energy output is achieved by improving the solar PV system performance parameters. Planar concentrators and cooling are two techniques used to boost energy output. The current solar PV system is placed in Baghdad/Al-Mansour corporation. This work includes improving the following performance parameters: performance ratio (PR), array efficiency, array yield, electrical energy, as well as solar irradiation. All these improvements are accomplished by increasing solar irradiance using planar concentrators (made of aluminum metal) and cooling (via water). The monthly daily average energy produced of enhanced and reference PV modules is 14.2 kWh and 11.1 kWh, respectively. The monthly daily average array yield of the enhanced PV modules and reference PV modules is 7.14 kWh/kWp and 5.61 kWh/kWp, respectively. The monthly daily average solar irradiation of the enhanced and reference PV modules is 7.71kWh/m^2 and 6.101kWh/m^2, respectively. The monthly daily average efficiency and performance ratio of the enhanced and reference PV modules are 14.3% & 93.6%, and 13.9% & 91.1%, respectively. The maximum average monthly temperatures of the enhanced and reference PV modules are 48.5°C and 57.4°C, respectively, in July, where the ambient air temperature is 42.1^{O}C. The successful optimization of the performance (PR) parameters of an on-grid PV system is the novel aspect of this work. In addition to developing a novel system to increase the performance of second-generation solar PV modules (CIGS).

Keywords: Efficiency, cooling, irradiation, planar concentrators, on-grid

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1. Introduction

Under global warming circumstances, notably in Iraq, and with a serious shortfall of power supply against demand, it is necessary to develop and utilize renewable energy resources. Solar PV system is used to reduce the gap between consumption and production to achieve a stable state in the electrical grid and to reduce the demand for fossil fuels utilized in the generation of electricity. The use of renewable energy reduces the enormous number of local diesel generators in Iraq that are used to generate electric power when the grid is cut off, which has a negative impact on human health and the quality of the air and water. Solar resources are a clean resource that can be used to meet the world's energy needs (Han et al., 2022). Solar energy reduces emissions because it emits no greenhouse gases such as carbon dioxide (Al-Shamani et al., 2016). Unlike traditional power systems such as diesel generators, solar energy may be harnessed even on the roof. It does not require its own transmission grid and can be used directly at the point of generating (Shankarappa et al., 2017). In contrast to traditional energy sources like gas and oil, which are concentrated in specific regions of the world, clean energy sources are prevalent everywhere. Rapid use of solar energy resources and energy efficiency result in climate change mitigation, significant energy security, and economic advantages (Ellabban et al., 2014; Seitel, 1975).

Ronnelid et al, studied the performance of PV solar modules equipped with solar reflectors (V-trough) at a fixed tilt angle in the Swedish climate. They demonstrated that the flat plate fixed solar reflector increases the annual power production of the PV module by 20% to 25% (Rönnelid et al., 2000). Khaled and Ali (2020) designed a hybrid photovoltaic-thermal solar collector system in Duhok city to enhance the PV module efficiency. The cooling method leads to an increase in the electrical efficiency by about 3% as compared with the PV solar collector system. Ozgorn et al, designed a cooling system to reduce PV module temperature in the Konya province (Turkey) environment. They noticed that when using water cooling, the PV module conversion efficiency increased to 10% (Ozgoren et al., 2013). Bahaidarah et al. (2015), investigated the electrical power production of the V-trough system. The results revealed that the power increase of the solar PV module when using the cooling techniques is 22.8 % and 31.5 % when using the cooling by the V-trough system. Some studies have revealed that a vertical PV module with a horizontal planar concentrator is the best position at high latitudes (Duffie et al., 2020).

Pavlov et al. (2015), revealed that using planar concentrators increased daily power by 35% during cloudless days at specified times of the year. Bahaidarah et al. (2013), developed a solar system that is cooled by the flow of water on the backside of the PV module in the Al-Dhahran (KSA) climatic condition. The results revealed that the operating temperature of the solar PV module dropped by around 20% and the electrical efficiency increased by 9%. Palaskar and Deshmukh (2015), developed a PV/T system with planar concentrators that boost solar radiation to 950W/m^2 and a water mass flow rate of 0.042 kg/sec. The results indicated a combined electrical and thermal efficiency of 71.40%, with the photovoltaic electrical efficiency at 12.40% and thermal efficiency at 59 %.

Zubeer and Ali (2022) designed a water-cooled concentrated PV system to improve the PV solar module efficiency. The practical results showed that the final module temperature of the reference PV modules, concentrated PV system, and water-cooled concentrated PV system is 57.5, 64.1, and 36.5°C, respectively. In addition, the power output of the water-cooled concentrated PV system and concentrated PV system is improved by 24.4% and 10.65%, respectively. In addition, electrical efficiency is increased from 14.2% to 17% by adding planar concentrators and water-cooling units to the PV modules (water-cooled concentrated PV system). Ahmad et al. developed multi-level fin heat sinks (MLFHS) made of an extruded aluminum material with a novel geometry attached to the back side of the PV module. At solar irradiance and ambient temperature of 941 W/m^2 and 36.17°C, respectively, a significant drop in the PV module temperature of 8.45°C is observed (Ahmad et al., 2022).

This study intends to increase energy output and thus achieve good economic feasibility while also reducing deterioration of the solar PV module by cooling, as the life of the solar PV module is inversely related to temperature. In addition to evaluating the performance of the thin film module technology and the on-grid PV system. This PV system is designed and equipped with techniques for reducing surplus heat generated by solar PV modules. Cooling reduces surplus heat, which contributes to improving the performance parameters of solar PV modules.

2. Photovoltaic solar system description

The present solar PV system is in Baghdad/Al-Mansour corporation at longitude 44.4^{O}E and latitude 33.3^{O}N. As illustrated in Figure 1 and 2, the present solar PV system consists of 30 modules designed in 5 strings of 6 series-connected PV modules. Table 1 shows the data sheet for the PV modules as well as information on the PV system.

3. Planar concentrators and solar PV modules

The solar PV system in this study is split into two groups; the first group consists of 12 PV modules and is labeled as an enhanced group, while the second group consists of 18 PV modules and is labeled as a reference group. The increment percentage (gain) in solar PV system performance parameters is then calculated by comparing the enhanced group to the reference group. The enhanced group receives greater solar radiation intensity (from the sun and planar concentrators) than the reference group. The planar concentrators are mounted in front of the enhanced group (added to 12 PV modules), as demonstrated in Figure 2, whereas the second group (18 PV modules) does not have the planar concentrators. In the present solar PV system, an inverter has two inputs: the reference group input, which contains 18 PV modules (2970 Wp), and the enhanced group input, which has 12 PV modules (1980 Wp). Data is collected via a speedwire that links the inverter to a laptop. As seen in Figure 3, an inverter displays data in two groups (A and B). The enhanced group data is represented by group (B), whereas the reference group data is represented by group (A). In the current system, an inverter is comprised of two inverters that use maximum point tracker (MPPT) technology (Yilmaz et al., 2019).

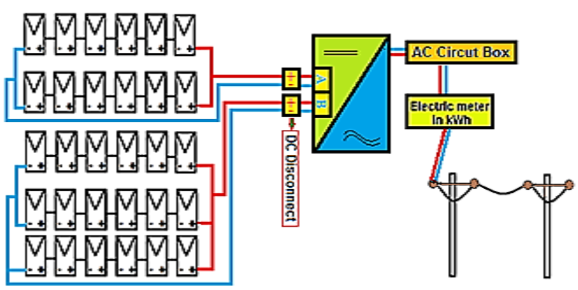

Figure 1. PV solar system block circuit.

Table 1. PV system and photovoltaic PV module information.

System Information	Value	Module Information	Value
System size.	5kWp.	Module model.	TS-165C2. CIGS.
Inverter size.	5.30kWp.	Max power. (Pmax)	165W
Inverter efficiency.	97%	Open-circuit voltage. (Voc)	88.7V
Inverter model.	SMA SB-5000T-21.	Short-circuit current. (I_{sc})	2.66A
Modules number.	30	Max power voltage. (V_{mpp})	68.5V
PV modules tilt angle.	30^{O}	Max power current. (I_{mpp})	2.41A
Temperature coefficient of Pmax.	-0.30% /^{O}C	Max reverse current. (I_R)	6.5A
Array area.	32 m^2	Operating temperature.	-40°C to 85°C.

The cooling system is illustrated in Figures 4 and 5. The cooling system, like the planar concentrators, is added to the first group (enhanced group). When the water tank faucet is opened, water flows toward the solar PV modules inside the perforated pipe that runs along the enhanced group (PV modules), then it falls on these PV modules and accumulates in the gutter, then it accumulates in underground water storage, and eventually it is returned to the tank by the water pump. This circulation repeats continuously during a certain period (cooling time). The temperature of the tank water rises due to the heat of the PV modules, as water absorbs heat from these PV modules and returns to the tank. In this experiment, water loss during the cooling process is incredibly low.

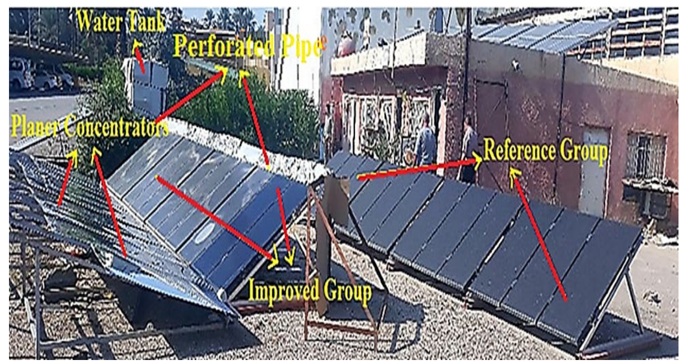

Figure 2. Reference and enhanced solar PV modules (groups).

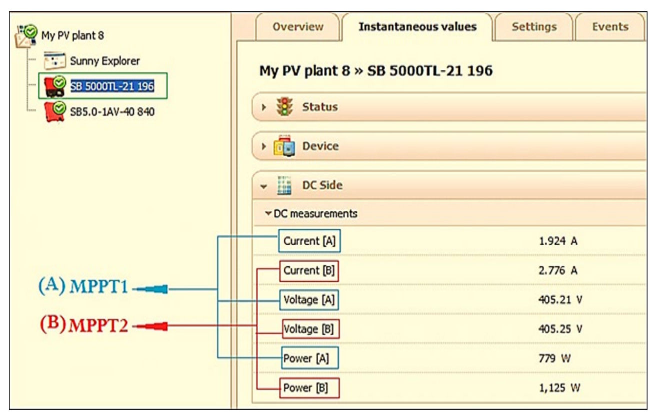

Figure 3. Snapshot of an inverter data presentation on a laptop.

4. Preparing of the study

The current experimental investigation is completed at the Baghdad/Al-Mansour corporation. Enhanced performance parameters include electrical energy, efficiency, and performance ratio (PR), as well as solar irradiation, and PV module temperature. Temperatures are recorded for the reference and enhanced PV modules.

The study runs from sunrise to sunset. On the study day, cooling runs from 10:00 pm to 12:00 pm, then stops for two hours to study the PV module temperature gradient and determine how long the cooling lasts. After two hours, the cooling process begins for an hour. This work is a sample study, which means that the days studied for performance enhancement are those in the middle of the month, such as the 13th, 14th, 15th, 17th, or even 19th in the event of cloudy months. Because cloudy days make it impossible to study performance enhancement. Because the monthly average of ambient temperature and solar radiation is in the middle of the month, this study conducted in the middle of the month.

Despite being enclosed in a cardboard box, the water tank is heated by ambient heat and solar radiation. Most of the heat is dissipated through water flow along the gutter, then to underground storage, and eventually to the tank, as illustrated in Figures 4 and 5. Figures 4 and 5 show virtual and actual cooling-planar concentrators systems, respectively. When the electricity goes off, the solenoid valve device shown in Figure 4 controls the water flow. This valve closes the water faucet when the electricity goes off. The solenoid valve is essential because without it, when the electricity goes off, the water faucet remains open, and the submersible water pump stops and no longer raises water into the tank.

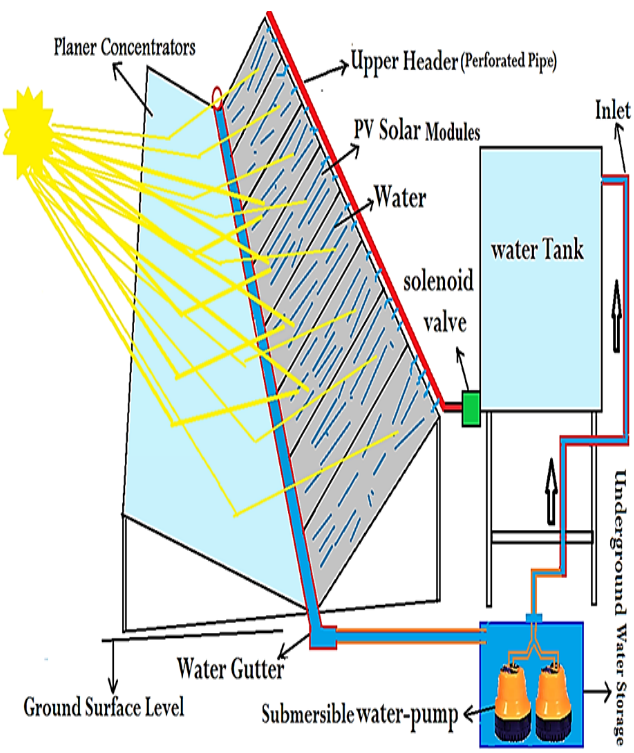

Figure 4. Virtual scheme of cooling-planar concentrators system.

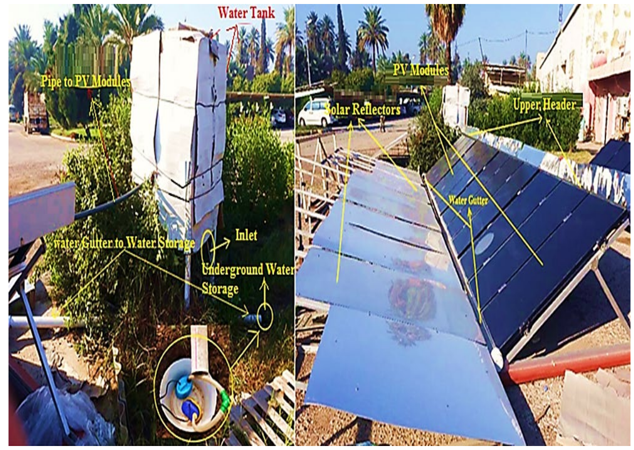

Figure 5. Actual scheme of cooling-planar concentrators system.

5. Performance parameters analysis

The performance parameters of the enhanced and referenced groups are studied in terms of efficiency, performance ratio (PR), and electrical energy, as well as solar irradiation. The energy data is obtained directly from an inverter, whereas the PR, efficiency, and solar irradiance are estimated using a set of equations. A digital thermometer is used to measure the temperatures of the ambient air and the solar PV modules.

5.1. Efficiency

Solar PV system efficiencies are classified as inverter, system, and array efficiencies. The system efficiency (η_{sys}) is based on the AC power output, while the array efficiency (η_{PV}) is based on the DC power output (Attari et al., 2016; Vikraman et al., 2020). The array efficiency is defined as the ratio of the daily, monthly, or annual average of the DC power (or energy) output to the daily, monthly, or annual average of in-plane solar insolation multiplied by the area of the solar PV array (Abed et al., 2020; de Lima et al., 2017). It is estimated as follows:

$$\eta_{PV} = \frac{E_{DC}}{H_T * A_m}\ 100\% \quad (1)$$

the system efficiency is estimated as follows:

$$\eta_{SYS} = \frac{E_{AC}}{H_t * A_m}\ 100\% \quad (2)$$

where: H_T stands for in-plane solar insolation, A_m stands for PV array area, and E_{DC} stands for DC energy. The efficiency of an inverter is estimated as follows.

$$\eta_{UNV} = \frac{E_{AC}}{E_{DC}}\ 100\% \quad (3)$$

The inverter efficiency ranged from 97%-96%. It is indoor (Vikraman et al., 2020).

5.2. Performance Ratio (PR)

The RP parameter is essential because it reveals all the negative effects (losses) of the solar PV system. The PR value indicates how near the real PV system is to ideal performance during real working time and allows comparison of PV solar systems irrespective, tilt angle, azimuth angle, solar radiation resources, and nominal power capacity (Attari et al., 2016; Khalid et al., 2016; Ozden et al., 2017). PR is calculated as follows.

$$PR = \frac{Y_F}{Y_R} \tag{4}$$

Where: Y_F is the **final yield** estimated in Equation (5), while Y_R is the **reference yield** estimated in Equation(6).Y_F is the AC energy production divided by the PV system's nominal (rated) power (Obaid et al., 2020; Sharma & Chandel, 2013). It denotes the amount of hours per day that the PV system operates at rated power. It is calculated as follows:

$$Y_F = \frac{E_{AC}}{P_{rated}} (kWh/kW_P) \tag{5}$$

where: EAC denotes the production of AC energy (kWh).

The reference yield (Y_R) is defined as the in-plane solar insolation divided by the reference irradiance of 1000 W/m^2. Equation 6 is used to estimate Y_R (Adaramola & Vågnes, 2015; Obaid et al., 2019).

$$Y_R = \frac{H_T}{H_R} \ (kWh/kW_P) \tag{6}$$

Where: H_R and H_T are the reference irradiance and in-plane solar insolation (irradiation) respectively.

Equation 7 is derived by compensating Equations 5 and 6 in Equation 4 (Rezk et al., 2019).

$$PR = \frac{E_{AC} * H_R}{P_{PV,rated} * H_T} \tag{7}$$

PR can also be calculated using Equation 8.

$$PR = \frac{\eta_{Actual}}{\eta_{ref}} \tag{8}$$

The PR and actual efficiency (η_{Actual}) are calculated using Equation 8.

The array yield(Y_A) is calculated by dividing the DC energy production by the nominal power of the solar PV system. The array yield indicates how many hours per day the PV system operates at nominal power (de Lima et al., 2017). Equation 9 gives the array yield:

$$Y_A = \frac{E_{DC}}{P_{PV.rated}} \ (kWh/kW_P) \tag{9}$$

the actual (P_{AC}) and rated (P_{rated}) power are estimated as follows:

$$P_{AC} = H_R \, \eta_{Actual} \, A_m \tag{10}$$

$$P_{rated} = H_R \ \eta_{ref} \, A_m \tag{11}$$

Equation 12 can be used to measure actual efficiency (η_{Actua}).

$$\eta_{Actual} = \eta_{ref} \, [1\text{-}\beta(T_m\text{-}T_{ref})] \tag{12}$$

Where:- η_{ref}: rated efficiency (15.2%), A_m: area of reference and enhanced groups (PV modules) (13.04 m^2 each), β: temperature coefficient (-0.3%/^{O}C), T_{ref}: reference PV modules temperature (25^{O}C), and T_m: actual PV modules temperature (Kasim et al., 2019).

Equation 13 can be derived from Equation 10 as follows:

$$H_R = \frac{P_{AC}}{A_m * \eta_{Actual}} \tag{13}$$

where: P_{AC}, A_m and η_{Actual} are the actual power, enhanced group area and actual efficiency, respectively.

Solar irradiance (H_R) and actual efficiency (η_{Actual}) are calculated using Equations 13 and 8, respectively.

The following is the formula for calculating the energy increment percentage (PINCP):

$$EINCP = (E_{im}\text{-}E_{ref})/E_{ref} * 100\% \tag{14}$$

where: E_{im} and E_{ref} are the energy of the enhanced and reference groups, respectively. EINCP is an acronym for energy increment percentage (energy gain).

Because reference group has 18 PV modules and the enhanced group has 12 PV modules, before all calculations the power of the reference group is divided by (18) and multiplied by (12), so that each group contains 12 PV modules (each group has the same power).

6. Result and discussion

Figure 6 illustrates the energy INCP and energy of the enhanced and reference PV modules. The maximum energy values correspond to the maximum solar radiation and the optimum tilt angle of solar PV modules. The maximum energy values of reference PV modules and enhanced PV modules in May are 12.9 kWh and 17 kWh, respectively, while the energy INCP (the gain) is 31% (4.011 kWh). The minimum energy values of reference PV modules and enhanced PV modules in

December are 8.28 kWh and 10.16 kWh, respectively, while the energy INCP is 22.7% (1.88 kWh). The yearly energy INCP (annual gain) is 28% (36.51 kWh). This gain (28%) has a considerable influence on the economic viability of PV solar systems. The physical explanation for May having the highest energy output compared to all other months of the year is the optimum tilt angle for solar PV modules (30^{O}), high solar radiation, and mild temperature.

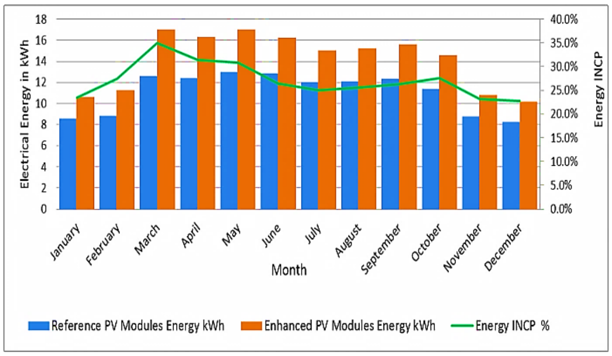

Figure 6. Energy INCP and energy of the enhanced and reference PV modules.

Figure 7 illustrates the performance ratio (PR) of the enhanced and reference PV modules. Maximum values of enhanced PV module PR and reference PV module PR are observed in December and January, at 98 % and 95.5 %, respectively. Whereas the lowest PR values are 89.7 % and 88.1 % in July, respectively. The monthly daily average performance ratios for the enhanced PV modules and reference PV modules are 93.6 % and 91.1 %, respectively. PV module performance ratio approaches ideal performance during cold months. Due to cooling, it stays excellent throughout the warmest months. Despite planar concentrators increasing the intensity of solar radiation, which raises the temperature of the PV modules, the performance ratio of the enhanced PV modules increases due to cooling. Figure 7 shows that the lowest PR values are recorded during the warmest months (June to September) because cooling efficiency decreases when the water used to cool becomes hot. It is noticed in Figure 7, the PR increases and decreases with decreasing and increasing the temperature of the PV modules, respectively.

RP is an important index because it reveals all the negative effects (losses) of the solar photovoltaic system. The PR value shows how near the real PV system is to ideal performance during real working time and allows comparison of PV solar systems regardless of location, tilt angle, azimuth angle, solar radiation resources, and nominal power capacity (Kasim et al., 2020).

Figure 8 shows the efficiency of the enhanced and reference PV modules. The maximum efficiency values of the enhanced PV modules and reference PV modules are observed in January and December (the coldest months), at 14.89% and 14.56%, respectively. Whereas the minimum of efficiency occurs in July and September at 13.6% and 13.3%, respectively. Figure 8 demonstrates that the highest efficiency value of the enhanced PV modules does not exceed the efficiency at STC (15.2%), because the temperature of the PV modules does not exceed 25℃. Planar concentrators reduce PV module efficiency slightly because they boost solar radiation, which causes the PV solar module temperature to rise, reducing efficiency. The monthly daily average efficiency for enhanced PV modules and reference PV modules is 14.23% and 13.85%, respectively.

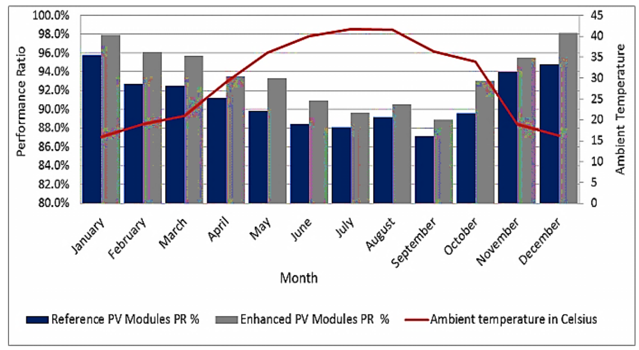

Figure 7. PR of the enhanced and reference PV modules.

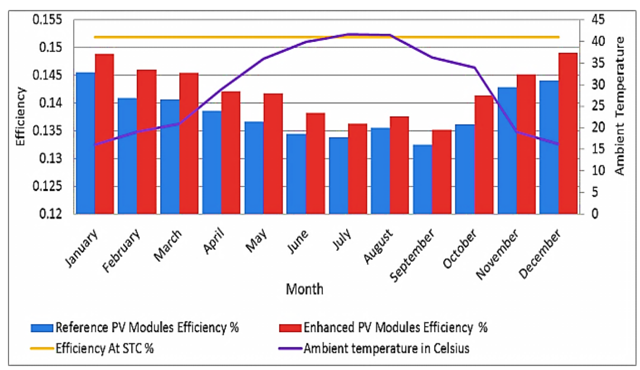

Figure 8. Efficiency of enhanced and reference PV modules.

Figure 9 illustrates solar irradiation (S.IRR) for enhanced and reference PV modules. The maximum value of enhanced PV module solar irradiation is observed in March at 780 Wh/m^2, whereas the maximum value of reference PV module solar irradiation is observed in May at 610 Wh/m^2. This is because the tilt angles of the PV modules and planar concentrators are perfect in March, but far from perfect in other months. The minimum solar irradiation values for enhanced and reference PV modules in December are 475.45 Wh/m^2 and 400.91 Wh/m^2, respectively. The greatest INCP in solar irradiation (S.IRR gain) is 30 % in March, while the lowest INCP in S.IRR is 18 % in December. These INCP values correspond to 181Wh/m^2 and 74.5 Wh/m^2, respectively.

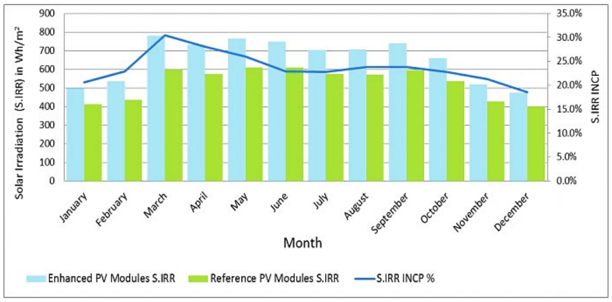

Figure 9. S.IRR INCP, enhanced and reference PV modules solar irradiance (S.IRR).

Figure 10 illustrates the temperatures of reference PV modules, enhanced PV modules, and ambient air. The maximum temperatures of reference PV modules, enhanced PV modules, and ambient air in July are 57.89°C, 48.4°C, and 41.7°C, respectively. The enhanced PV module temperature dropped by 10°C when compared to the reference PV module temperature (57.5°C). The lowest temperatures of reference PV modules, enhanced PV modules, and ambient air in January and December are 34.15°C, 29.5°C, and 16.3°C, respectively. The yearly average temperatures of reference PV modules, enhanced PV modules, and ambient air are 45.94°C, 40 °C, and 29.15°C, respectively. The temperature difference between the reference PV modules and the enhanced PV modules decreases in cold months because the temperature of the reference PV modules is low.

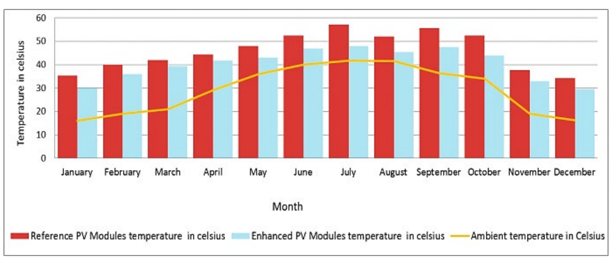

Figure 10. PV modules and ambient air temperatures.

7. Conclusions

The current study comes to the following conclusions.

- The usage of planar concentrators with cooling results in significant gains in performance parameters (electrical energy, performance ratio, and efficiency) in addition to solar irradiation.
- Energy improvement varies throughout the year based on meteorological elements such as ambient temperature and solar radiation. The energy increases at its maximum in summer months, while it begins to decrease in winter months.
- The monthly daily average energy increment percentage (EINCP) is calculated to be 28%. (36.51 kWh).
- The monthly daily average solar irradiation increment percentage (S.IIR INCP) is calculated to be 25% (127 Wh/m^2).
- The maximum energy increment percentage in March is 35%.
- The maximum solar irradiation increment percentage in March is 30%.
- The cooling effect is highly effective in removing excess heat from the PV modules.
- During the cold months, the cooling effect on losses is low because the losses are minimal, therefore the cooling only reduces a small amount of losses.
- The largest INCP in all performance parameters occurs in March and May because the ambient temperature is moderate, and the solar radiation intensity is suitable.
- When using planar concentrators with cooling, PR and efficiency increase because PV modules temperature drops; when using planar concentrators without cooling, PR and efficiency decrease because PV modules temperature increases.
- The maximum temperatures for PV modules are in July, August, and September.
- The water used for cooling contributes significantly to the cleaning of the PV modules.

Conflict of interest

The authors have no conflict of interest to declare.

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