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Article

Simulation and modeling of the possibility of implementing solar high-concentrating photovoltaic in Libya

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ABSTRACT

Concentrating photovoltaics is a type of solar photovoltaic technology that relies on sunlight concentrating to produce electrical energy. In this regard, high-efficiency solar cells comprise many different materials cells, and energy band gaps are stacked respectively on top of each other. This technology, depending on a large portion of the solar spectrum component, which absorbed by the triple-junction solar cell; the consequence is a rise in the device's conversion efficiency. The layers of semiconductor materials, including GaInP/GaInAs/Ge, are coupled in series to gain high efficiency. Besides, an accurate assessment of the energy yield from a concentrating photovoltaic (CPV) device throughout its lifetime and the electrical performance characteristics in different operating environments is required. Hence, an MSCS-1D: V-2 solar cell simulator tool and a system advisor model (SAM) are used to model and simulate performance behavior. In this paper, we modeled and simulated mini solar concentrating photovoltaics. Based on that, solar CPV technology can be implemented in such regions to generate electricity and heat. Moreover, the selected region has a great potential for direct normal irradiations (DNI) annually. In addition, that encourages further study via applying large-scale in the form of CPV power plants.

1. Introduction

The need for energy has been growing recently, and supplies that depend primarily on fossil fuels are utilized to supply home and industrial demands. However, it's also commonly known that fossil fuels are the main contributors to environmental pollution, which leads to global warming issues, and their availability is constrained. Based on that, people worldwide look forward to developing renewable energy technology for environmental friends [1]. Also, the development of solar energy technology can play a significant role in fulfilling sustainable development shortly [2]. Over the years, scholars have become increasingly interested in solar energy or solar photovoltaic (PV) technologies. However, conventional PV cells have a large module area and limited conversion efficiency. The solar-concentrating photovoltaics have attracted attention from scholars and manufacturers over the past few decades to address the constraint. Therefore, using specific concentrators and lenses or mirrors, the incident solar radiations are focused on smaller scales; this results in electrically more effective photovoltaic cells through CPV devices [3, 4]. The concentrating photovoltaic technology can be utilized to generate electricity in space and on Earth. It is important to mention that about 46% of incident solar energy can be converted to electricity by CPV cells, with the remaining energy being lost as heat [5]. A different materials energy band gap is used in the technology of the third generation of photovoltaic solar cells, which are stacked on top of each other, and the yield is highly efficient solar cells. A concentrating PV module typically comprises a high-efficiency solar cell and a light concentrator, which can be manufactured from a mirror, a parabolic dish, or lenses [6-8]. The operating evaluation of CPV modules is essential for performance evaluation and rated power estimation, which may also result in design enhancements to the solar cell assembly, packaging of the optics concentrating, or the need for thermal management [9]. Due to its high energy yield, the high-concentrating photovoltaics HCPV technique is widely utilized in electrical energy generation. However, in high-concentrating PV technology, as a consequence of optic concentration, the cell operating temperature rises to more than 120°C. Nevertheless, for higher operating performance, longevity, and reliability aspect, it is always advised to keep cell/module temperature equal to or less than 80°C [6, 10]. The energy band gap of the semiconductor materials restricts the theoretical efficiency of the single solar cell. Based on that, the Shockley Queisser efficiency constraint, which caps the single cell's efficiency at 31%, is an important loss factor to consider [11]. So, that leads to thinking about finding advanced ways to develop solar cell efficiency above those limited values. Hence, different energy band gaps of semiconductor materials are utilized to decrease thermalization losses and boost conversion efficiency [12, 13]. It is worth mentioning that Saudi Arabia is one of the meddle-east countries with harsh environments and has implemented many applications of HCPV systems since the 1980s. The designed system operated at a concentration ratio of 1400 X; as reported in the system operating performance, it worked well and was harmonious with the environment [14]. Therefore, this work modeling and simulates the performance behavior of a triple-junction solar cell/modules and mini CPV. This gives an idea of the cell's behavior to improve the design and enhance performance. The consequences are drawn through performance analysis and prediction of energy yield. This work is a primary study towered large-scale, and in the future, we look forward to seeing that implementation on the ground.

2. Modeling Approach

In this work, we set up one triple-junction solar cell using the so-called MSCS-1D: V-2, Solar Cell Simulator. It characterized electrical performance under a concentration ratio from 1 to 1000 X and estimated cell efficiency. Based on that, in doing so, we set up a module/array of triple-junction using so-called the System Advisor Model (SAM), owner of the International Renewable Energy Laboratory (NREL). Subsequently, it estimated annual module efficiency during the daytime. Therefore, the environmental data of Sebha city, located in southwest Libya, is considered in the characterization of performance behavior analysis. That depends on the National Solar Radiation Database (NSRDB), which includes the parameters of DNI, wind speed, ambient temperature, and air mass. Furthermore, the integration of overall power produced also predicts yearly energy yield. Hence, the tools used in this study are due to their powerful tools, accuracy, and accessibility of software; for that reason, we used them for the simulation. Moreover, the performance analysis of solar cells and module takes place by quantifying the conversion efficiency. Figure 1 shows the proposed flowchart of the predicted modeling/simulation approach. The three layers of cell behavior under sunlight are described in detail. Therefore, the ultraviolet and visible portions of the solar spectrum are absorbed by the GaInP top one-layer cell. Its response to wavelengths between 300 and 700 nm with an energy band gap Eg = 1.8 eV. The infrared spectrum portions are absorbed by the GaInAs middle layer cell. It responds to wavelengths between roughly 700 and 900 nm with an energy band gap Eg =1.4 eV. Finally, the bottom layer cell Ge responds to wavelengths between 900 and 1800 nm and absorbs lower energy photons in the infrared portion of the solar spectrum with an energy band gap Eg = 0.7 eV.

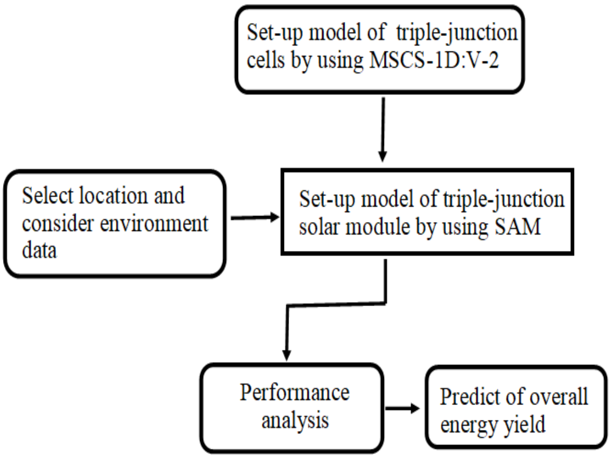

Figure 1. Flowchart of predicted modeling/simulation approaches.

It's important to give some theoretical equations utilized in the model of triple-junction solar cells. The key to the solar cell electrical performance parameters can be quantified using the equations (1-5) respectively [15].

$$J_{sc,i} = CR.\int_{\lambda 1}^{\lambda 2} SR_{i(\lambda)}.\eta_{opt(\lambda)}.G_{(\lambda)}.d\lambda \quad (1)$$

$$J_i = J_{o,i}\left(exp\frac{q(V+J_i.R_s}{n.K_b.T_c} - 1\right) - J_{sc,i} \quad (2)$$

$$V_{oc,i} = \frac{n.K_b.T_c}{q} ln\left(\frac{J_{sc,i}}{J_{0,i}} + 1\right) \quad (3)$$

$$FF = \frac{P_{max}}{V_{OC}.J_{SC}} = \frac{J_{max}.V_{max}}{V_{OC}.J_{SC}} \quad (4)$$

$$\eta_{el} = \frac{P_{max}}{P_{in}} = \frac{J_{SC}.V_{OC}.FF}{p_{in}} \quad (5)$$

From the modeling/simulation results, the maximum module power was about 596 W, and the average conversion efficiency was approximately 30%. Table 1 lists the key specification details of the simulation parameters of concentrating photovoltaic module.

Table 1. The characteristic of a high -concentring photovoltaic

Parameters	Values
Number of cells	20
Concentration ratio	1-1000 X
Area of module	2 m^2
Optical efficiency	90 %

The concentration is used to evaluate an electrical performance perspective. Since the concentration ratio rises, it will lead to more energy of photons absorbed by the cell, for example, via 500 or 1000 times, i.e., equal to 500 X or 1000 X; it depends on how much light is available. Also, it is worth noting that the one sun or (X) is equal to 1000 W/m^2. Thus, the short-circuit current intensity (J_{sc}) is increased proportionally to calculate the concentration ratio. So, the generated photo-current is directly proportional to the concentration rations due to the absorption of photon flux.

Consequently, the following is the concentration ratio described in terms of the electric perspective.

$$CR = \frac{J_{sc,X}}{J_{sc}} \quad (6)$$

In multi-junction solar cells, the p-n junctions also facilitate a PV conversion. Hence, these p-n junctions are electrically coupled in series in most devices. Therefore, a tunnel junction is needed between two p-n junctions to guarantee low resistance to electricity between the two junctions' various energy band gaps due to doping in every junction. In the application of triple-junction solar cell assembly, due to the series connection, the combined three layers' overall current density is limited by a lower current density, as given by the relationship (7).

$$J_{total} = min\ (J_1, J_2, J_3\ ) \quad (7)$$

3. Results and Discussions

3.1 Triple-junction solar cell

The amount of incident sunlight energy converted to electrical energy is known as conversion efficiency. From the modeling results of (10 mm x 10 mm) dimensions, one cell of triple-junction solar cell assembly under variation of concentration ratio from (1 to 1000 X). The efficiency was logarithmic increases as the results of light rose. In order to comprehend the performance behavior of solar cells, a characterization of the cell takes place by determining the efficiency. The expense of solar energy can be indirectly reduced by attaining high efficiency. Higher efficiency helps boost power production and lower the overall system cost, even though the cells are expensive; meanwhile, several cost elements of a power plant and photovoltaic system are associated. As shown in Figure 2, the concentration ratio versus cell efficiency simulation results; also show a typical solar receiver assembly, including a solar cell example.

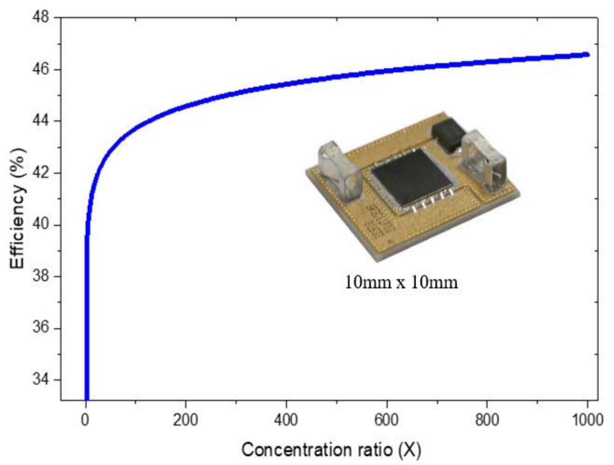

Figure 2. The efficiency of triple-junction solar cells versus various concentrating ratios

It is important to be mentioned that in high efficiency, III-V materials with certain band gap energies and approximately the same lattice constant must be taken into while developing the semiconductor materials of assembly. For the overall energy prediction of the solar HCPV systems or for enhancing module designs, the electrical characterization of solar HCPV modules is an important step. While the technology of multi-junction solar cells is used, and there are more components in the structure, the electrical characterization of ultra-high concentration photovoltaics (UHCPV) is different and more challenging than that of traditional solar PV in terms of heat removal devices and optical [16].

3.2 Triple-junction solar module

Many factors are to be considered to determine solar cell/module efficiency, e.g., the quantum efficiency, internal resistances, the maximum power point, the limitation of thermodynamic efficiency, the reflectance efficiency of the cell's surface, and the type of solar cell [17]. The module assembly consists of several solar cells linked to gain a high energy yield. The annual module conversion efficiency was estimated from January- December. The average module efficiency is 30%, and the maximum module power is 596 W. The simulation results are based on the normal reference irradiance of 1000 W/m^2; the environment temperature is 25^{o}C, the wind speed is about 4 m/s, and the air mass of 1.5. Figure 3 illustrates approximates of yearly module conversion efficiency during the daytime.

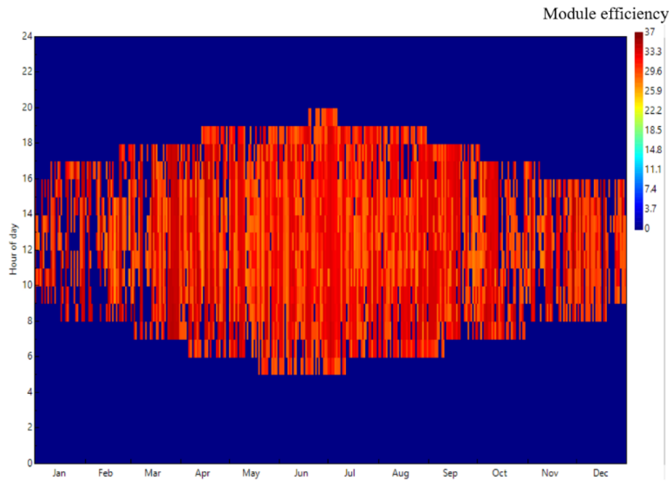

Figure 3. Estimation of annual module conversion efficiency during daytime

4. Prediction of annual energy yield

Predicting energy yield is an important task involving the determined characteristics of PV devices under various conditions and weather information from the investigation region. To build up a solar CPV power plant, direct normal irradiance (DNI) is one important parameter to consider in designing. Therefore, the area of study is very rich in the high potential of DNI annually. The daily average of DNI is approximately 3.99 kWh/m^2 daily, and the wind speed is 3.4 m/s. Hence, the typical meteorological year (TMY) data which contains a weather file, is used for a selected area of study. The sum accumulation of monthly energy depends on the hours of operation, so during the summer season is more time for daylight in contrast to other seasons. Therefore, there are rarely scattering clouds reported in the region. Also, consider the dusty windstorms in such a harsh environment, which leads to dust accumulation on the top module surface; a clean/washing strategy can highly alleviate this. Figure 4 presents the direct normal irradiance of the selected area.

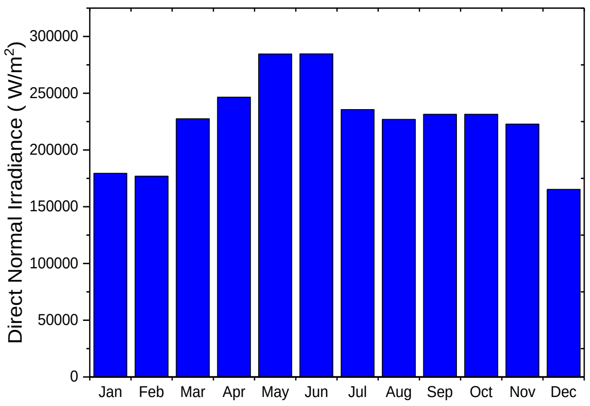

Figure 4. The monthly sum of accumulation of the solar radiation DNI

Although other design elements have an impact, the behavior of an HCPV module is significantly reliant on the solar cells' behavior. In the solar HCPV modules, the most significant environmental parameter is DNI; also, the temperature of the solar cells and the spectrum of direct sunlight. The behavior of the multi-junction or triple-junction solar cells must be well designed, which is important to actually estimate how much energy high-concentrating photovoltaic HCPV modules will produce. The daily energy produced (E_p) for each day is calculated via the integration of the output power per hour, which is given in equation (8).

$$E_p = \int_{t1}^{t2} P(t).dt \qquad (8)$$

where P(t) represents the mean power as a function of the time of the triple-junction module at every time step, and t_1 and t_2 are the times of sunrise and sunset, respectively. The energy production viewpoint showed that the typical solar modules produce more energy during the summer since there is a huge amount of DNI available. The seasons of Autumn, Winter, and Summer are different from one another because Summer has the most sunshine while Winter and Autumn have the least. Figure 5 represents the prediction of annual solar energy production. Energy yield estimates and models energy production in a certain location over time to provide the full view of the amount of energy by (kWh).

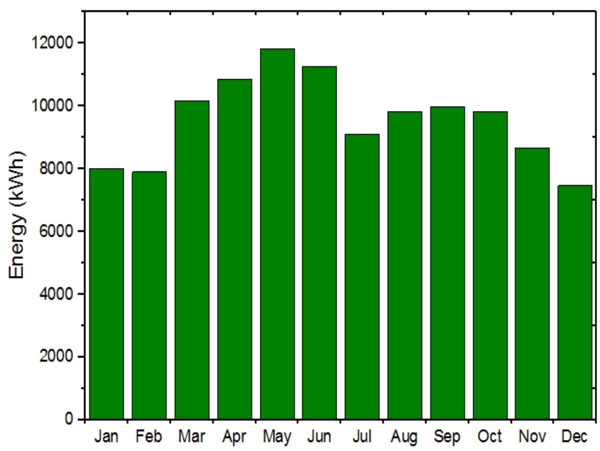

Figure 5. Prediction of annual solar energy production.

The expense can be significantly reduced by maximizing yearly energy yield during the stage of designing and implementing a photovoltaic system. Furthermore, since the modeling can predict how the solar modules and other assembly components of the system will perform in relation to energy production estimates, they also impact system cost by lowering overall expenses.

5. Conclusion

This work presented a simulation of a mini solar CPV application; this technology can benefit by generating electricity and heat. Hence the heat might be used for other purposes, e.g., water heating, desalination, or heating systems. Furthermore, the development of modeling techniques for the electrical characterization of these devices is improved through developments in our understanding of the behavior of high-concentrating photovoltaics HCPV modules. From simulation analysis, electrical characterization of CPV devices and module energy yield of the mini plant. Furthermore, the solar CPV technology needs attachment equipment on the rear side for either active or passive cooling technology to keep the cell temperature working at an acceptable degree. In Libya, the solar radiation intensity is almost similar across the country in terms of the DNI and other environmental parameters, which encourages implementing CPV technology anywhere. It is important to mention that no scattering clouds obstacle is available in the region. Further work we suggested includes a techno-economics study and the prospect of implementing a large-scale in form of a CPV power plant.

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Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Conflict of interest

The author declares no potential conflict of interest.

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