Overheating in Residential Solar Systems: Towards Efficient Cooling Solution

Ahmad Al Takash[1*], Razan El Kassar[2], Adie Msadi[2], Assadour Khanajian[2], Youssef Abbani[1]

[1] Energy and Thermo-Fluid Group, The International University of Beirut BIU, Beirut P.O. Box 146404, Lebanon.

[2] Energy and Thermo-Fluid Group, Lebanese International University, LIU, Bekaa P.O. Box 146404, Lebanon.

* Corresponding author. email: ahmad.takash@b-iu.edu.lb (A.A.T.)

Manuscript submitted March 10, 2024; revised April 18, 2024; accepted May 13, 2024; published August 30, 2024.
doi: 10.12720/sgce.13.3.94-104

Abstract: As the worldwide demand for solar renewable energy continues to rise, researchers have consistently aimed to create cost-effective, high-efficiency solar cells. They are aware that elevated panel temperatures can result in reduced conversion efficiency and diminished long-term dependability, presenting a familiar challenge within the photovoltaics industry. This project is divided into two main studies related to Photovoltaic (PV) panels overheating and cooling systems. The first study focused on investigating the effect of high ambient temperature on the efficiency of solar system, theoretically using MATLAB, AutoCAD and Helioscope, and computationally using PVsyst Software. Results showed that up to 11% of energy output is being lost due to temperature, and error of 2% was detected between theoretical and computational simulations. The findings indicate that computational modeling can be a trustworthy means of forecasting the performance of solar cells and solar systems. Following the identification of the problem, an already modeled and designed radiative cooling system using a combination of nano and micro structuring glass was simulated using PVsyst and theoretical equations to illustrate the output energy of the residential solar system, where results showed that adding one more panel can result in energy output higher by 2% than using the proposed cooling system.

Keywords: Solar energy, photovoltaic, computational modeling, energy efficiency, cooling systems

1. Introduction

The global demand for electricity is on a trajectory of rapid escalation, driven by the growing needs of the expanding global population. Projections indicate a substantial increase in electricity demand, with non-renewable sources, particularly coal-fired power plants, currently dominating the global energy landscape [1]. This reliance on non-renewables contributes to environmental challenges such as CO_2, NO_x, and SO_x emissions, exacerbating global warming [2]. Addressing this challenge is critical, especially with the anticipated surge in global energy consumption by 2050, requiring the generation of an additional 20 terawatts of fresh energy [3]. In response, renewable resources, notably solar energy, emerge as a key solution [4]. Solar energy, harnessed since the seventh century, offers numerous advantages, including energy security, reduced conventional energy costs, market competitiveness, economic stimulation, job creation, and environmental sustainability [5]. Given its abundance and capacity for off-grid electrification, solar energy is projected to be the leading electricity source by 2050 [2]. Moreover, the utilization of solar energy involves various technologies, including solar water heaters [6], concentrated solar power systems [7], and Photovoltaic (PV) systems [8]. Among these, PV power conversion stands out as a well-established technology that directly converts solar energy into electricity [9]. However, despite their efficiency, PV cells face challenges that impact their performance, particularly overheating due to environmental factors [10].

The temperature coefficient plays a crucial role in understanding the impact of temperature on PV panels [11]. A rise in temperature results in a decrease in maximum power, with efficiency reductions for different types of cells [12]. Excessive temperatures, such as those nearing 70 °C, can lead to local hotspots and poor currents, degrading electrical performance and panel life [12]. This underscores the importance of addressing overheating issues to ensure optimal performance and longevity. Where to enhance the efficiency of PV panels, various cooling strategies have been developed to mitigate the adverse effects of temperature [13], such as Air-based cooling, either passive or active, liquid-based cooling strategies include forced water circulation, liquid immersion cooling, water spraying, and natural water cooling, Phase Change Materials (PCMs), Heat Pipe Cooling Systems, heat fins, radiative sky cooling, Nano-fluid-based, Thermo-Electric (Peltier), Spectrum Filter Cooling [14]. Ongoing research explores Hybrid Multi-Concept Cooling Systems, combining different techniques for potential cost benefits in diverse applications with high energy requirements.

One effective method recommended is radiative cooling, where PV panels release additional heat by radiating it away in the atmospheric transparency window at 8–13 μm. This method allows the panel to radiate heat energy into the surrounding environment, improving overall efficiency [15].

The radiative procedure can be summarized in a Eq. (1) including all dependent parameters where In this equation, Prad represents the thermal radiation power released from the radiative cooling system surface, P_{atm} represents the absorbed atmospheric radiation power by the radiative cooling system, P_{sun} represents the absorbed solar radiation power by the radiative cooling surface, and finally, $P_{non\text{-}rad}$ represents the conductive and convective heat transfer between the radiative cooling surface and ambient space, where they are all measure in W/m^2 [15].

$$P_{net,\,rad} = P_{rad} - P_{atm} - P_{sun} - P_{non-rad} \tag{1}$$

2. Residential Solar System Specifications

The purpose of this study is to investigate the influence of high temperatures on the performance of residential solar systems. The main goal is to quantify the percentage of temperature-related losses encountered by these systems by comparing computational simulations utilizing PVsyst software with theoretical calculations based on relevant equations. The simulation is to be performed is an off-grid system located in Mount Lebanon Governorate, Chouf District, Barja Village. Details of the solar system are provided in Table 1.

Moreover, for the cooling study, the radiative cooling system that will be used for the comparative study on the residential solar system is a combination of Nano and micro structuring glass used for radiative cooling that is based on increasing the emissivity and efficiency of the PV panel by modifying the glass structure rather than the glass material, with the updated structure being placed above the panel's glass. Moreover, this system also focused on improving the amount of heat transmission by convection through the structure used, where an efficiency improvement of 3.0%, with the design being appropriate for all devices impacted by photon management at different wavelength ranges/scales was found.

Table 1. Solar System Details on Which the Study was Done

Specification	Related Information
Solar system tilt angle (°)	45
Solar system azimuth angle (°)	180
Number of panels used	6
Type of panels connection	In series
Type of panels used	JKM540M-72HL4-V
Maximum power per panel (W)	540
Open circuit voltage per panel (V)	49.42
Short circuit current per panel (A)	13.85
Temperature coefficient of maximum power per panel (%) at STC conditions	−0.35% / °C
Number of inverters	1
Inverter type	SUNON PRO 3.5 kW
Cell area (cm^2)	165.6
Module area (m^2)	2.579
Peak sun hours during june 2023 (h)	6.55

3. Computational Modeling

In this study, PV syst software is employed to computationally investigate the influence of high ambient temperatures on residential solar systems. The software provides crucial information for theoretical analysis through its reliable weather forecast database, supplying monthly, daily, or hourly temperatures and irradiance values. Moreover, PVsyst bridges the temperature gap between ambient and cell temperatures, offering the array temperature directly after considering all relevant details based on the provided ambient temperatures.

First of all, the location is chosen through the PVsyst, after selecting the exact location of the residential system, PVsyst provides all the weather forecasts needed through Metronome 8.1 database. Furthermore, as illustrated in Fig. 2, the PVsyst software requires the panels' field type, plane tilt, and azimuth angle as input. Also, it is necessary to specify the season for which the design is intended, such as yearly, monthly, or hourly.

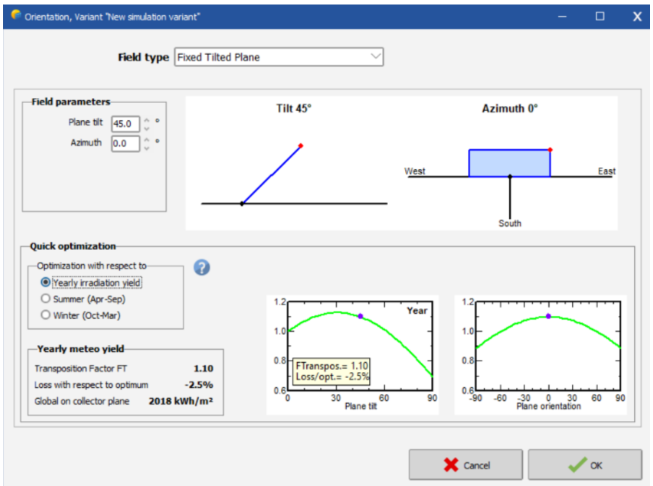

Fig.1. PVsyst Software panel specifications.

Fig. 1 illustrates the system's losses as a result of not orienting it optimally, as well as the average global irradiance received on the array plane. Following the completion of all system specifics for weather and implementation conditions, technical information about the panels, batteries, inverters, and home load hourly distribution is requested. Now it is necessary to define the panel specifications for PVsyst, the PV array orientation, PV module type, control mode, and controller type. The design requirements for the number of modules and strings are also supplied.

4. Theoretical study Modeling

In this section, the solar system studied was simulated on Helioscope software in order to determine the percentage of power losses of this system. In addition to the location details, system details including panels type, mounting structure, azimuth, and tilt angle were also inserted into the helioscope software. Finally, after setting all the conditions related to the location and its specifications, the system was sketched in detail on Helioscope. The blue region in the solar system helioscope design, which shows the number of panels, orientation, and design, symbolizes the region in which the panels are mounted, while the orange region depicts the region to keep out because this region the designed system may experience shading losses. After the design was completed, the simulation was conducted, and a report on the system's monthly output was delivered in addition to the sources of losses percentages that are shown in Fig. 2.

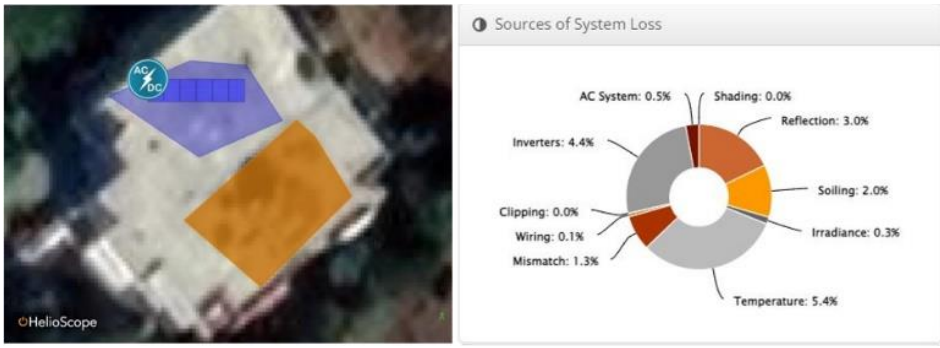

Fig. 2. Helioscope design and losses simulations.

This system's losses are classified as losses caused by the AC system, inverters, wiring, mismatch, soiling, irradiance, reflection, and temperature. Where the entire proportion of energy losses excluding temperature losses is expressed in percent, this is a key factor in distinguishing between energy lost due to temperature and energy lost owing to other sources. However, because the analysis is based on the net energy at the array's output, the AC system losses and inverter losses were eliminated. Furthermore, reflection losses were eliminated because the irradiance considered is the incident irradiance inside the panel including reflections.

5. Mathematical Analysis

First of all, the total cell area is calculated using the number of modules used in the project, where A_{total} is total cell's area (m^2)

$$A_{total} = Cell\ area\ x\ Number\ of\ modules \tag{2}$$

After that, the amount of energy converted is calculated, where $E_{converted}$ is array output energy excluding losses (kWh/day), Ginc is the global incident irradiance (kWh/m^2/day), and η_{panel} is panel's efficiency (%):

$$E_{converted} = G_{inc}\ x\ A_{total} x\ \eta_{panel} \tag{3}$$

However, this obtained value is without losses, in order to get the net energy output from the system after losses due to system and location losses, excluding temperature losses, reflection losses, AC systems losses, and inverters losses, the following equation is used where $E_{daily\ net}$ is array output energy including all losses except temperature losses (kWh/day)

$$E_{daily\ net} = E_{converted} \times (1 - Losses\ \%) \quad (4)$$

Finally, the last used equation which shows the direct relationship between the system's daily energy output and the array temperature theoretically, is shown below, where Edaily out is the array output energy including all losses, CT is the panel temperature coefficient (%/°C), T_{array} is the array temperature (°C) and Tref is the reference baseline temperature of 25 °C:

$$E_{daily\ out} = E_{dailynet}\left[1 - C_T\left(T_{array} - T_{ref}\right)\right] \quad (5)$$

Moving on, the following equations were also employed in MATLAB to complete the study and examine the theoretical and computational effects of overheating on residential solar systems. The below equation is used to determine the percentage of temperature losses using the data provided by PVsyst, where Templss are temperature losses (%) provided by PVsyst software:

$$\%Temperature\ losses = \frac{Templss \times 100}{Templss + Earray}(\%) \quad (6)$$

After calculating the %Temperature losses for the PVsyst computational study, it is needed to calculate this percentage for the theoretical study using the following rule

$$\%Temperature\ losses = \frac{\left(E_{daily\ net} - E_{daily\ out}\right) \times 100}{E_{daily\ net}} \quad (7)$$

Finally, to find the value of the error between theoretical and computational studies, the percentage of error between the energy output of each system was calculated:

$$\%error = \frac{\left(E_{daily\ out} - E_{array}\right) \times 100}{E_{daily\ out}}(\%) \quad (8)$$

6. Implementation and Results

The following section will display the main data received after performing the simulation using the PVsyst software along with the results achieved after completing the calculations using the MATLAB code. The dates (per day), ambient temperature (°C), array temperature (°C), global horizontal irradiation (kWh/m^2/day), and global incidence in the collector plane (kWh/m^2/day) were the useful data in the study collected from PVsyst, these gathered data are significant since they were employed in theoretical and computational simulations.

Shown in Fig. 3 are the ambient and array temperatures (°C) where the ambient temperature is the temperature of the surrounding air where the PV system is located. The array temperature, on the other hand, represents the temperature of the PV module or the array itself during operation. It is controlled by a variety of parameters such as ambient temperature, solar irradiation, wind speed, and the heat dissipation characteristics of the PV system. It is an important parameter for estimating the electrical output of PV modules since it impacts their operational efficiency.

As shown in Fig. 3, the ambient temperature varies throughout the month in values ranging from 20 to 30 °C, whereas the array temperature varies between 40 and 50 °C, indicating, as shown in the third graph, that the difference between the ambient temperature and the array temperature ranges between 15 and 20 °C.

The variation of the percentages of temperature losses with respect to the days of June is illustrated in Fig. 4, where the percentages of temperature losses using PVsyst and theoretically are presented, as well as the array temperature during these days. According to the graph, temperature losses from both PVsyst and theoretically range between 8 and 11% when the array temperature fluctuates between 39 and 47 °C.

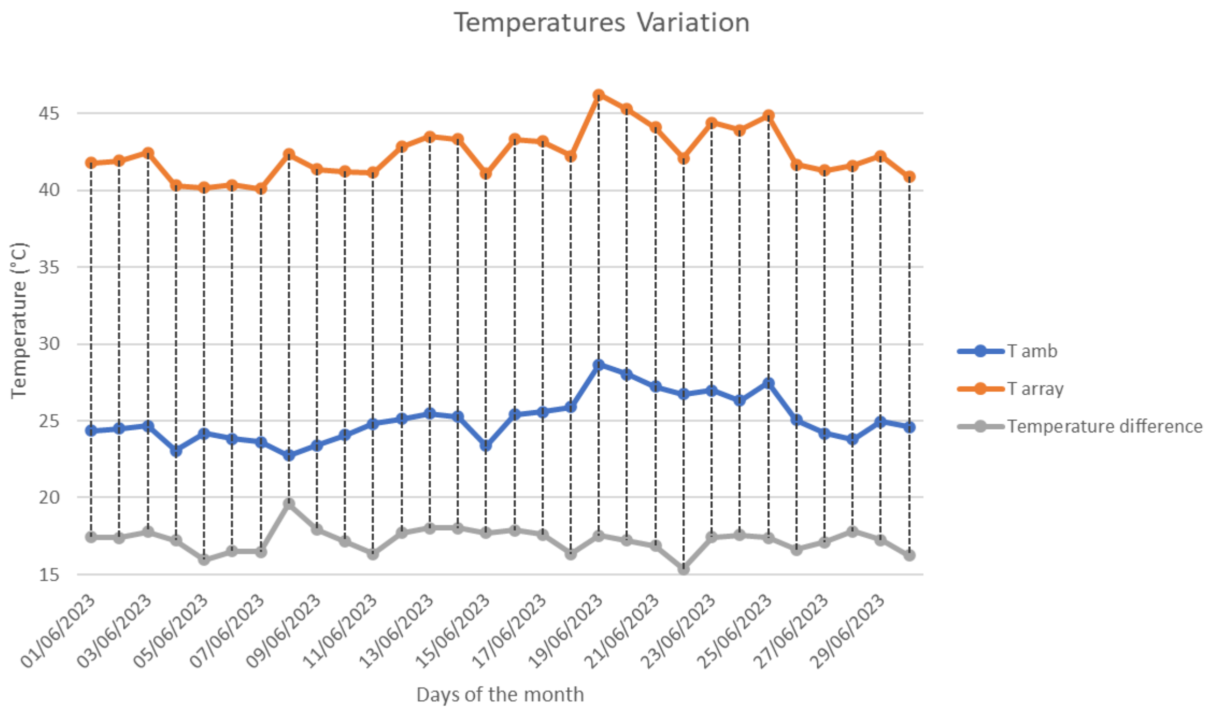

Fig. 3. Temperatures variations on June 2023.

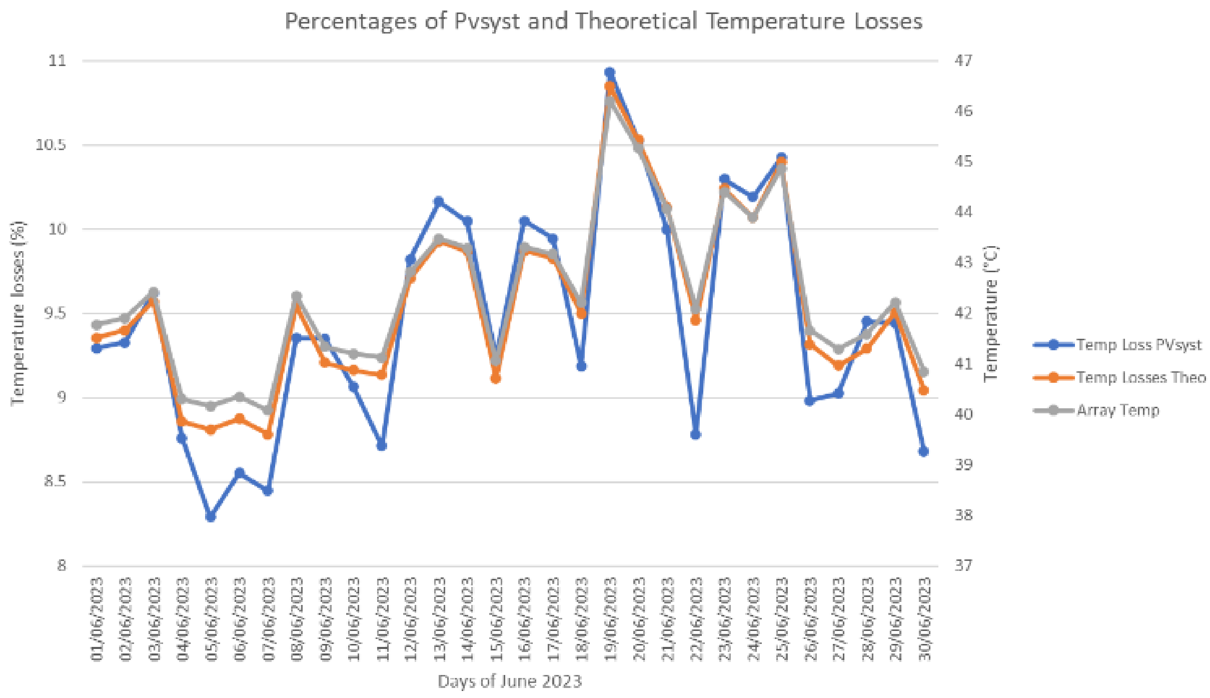

Fig. 4. Percentages of temperature losses during June 2023.

Furthermore, both the temperature losses using PVsyst and theoretically fluctuate together and are proportional to the array temperature, where they increase with increasing temperature, for example, when the temperature reached its maximum on June 19, at a temperature of 46 °C, the losses were between 10.5% and 11% for both theoretical and software studies. Moreover, at a minimum temperature of 38 °C in June 5, the losses were between 8 °C and 8.5 °C.

The graph in Fig. 5 shows the variation of the energy output calculated theoretically and the energy output obtained using PVsyst software with respect to the days of the month of June. Additionally, the graph shows the variation of the array temperature during the month of June in order to have an accurate comparison and analysis between the different parameters; especially to compare the effect of array temperature on the residential solar system and compare the difference of results between theoretical and computational study.

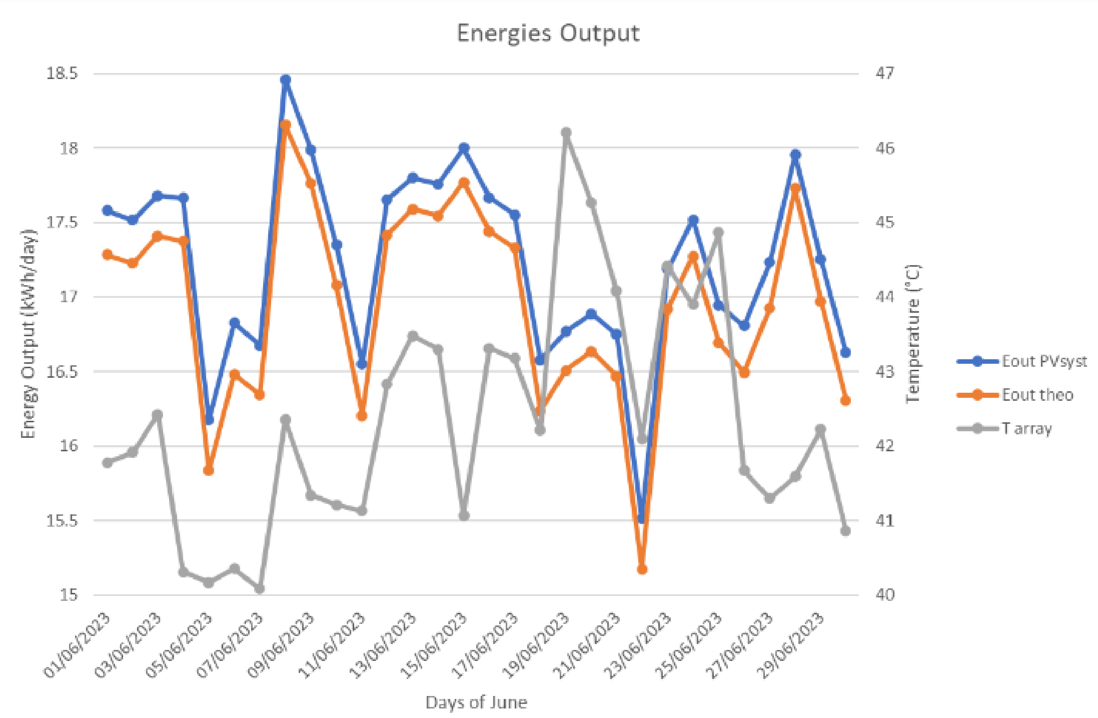

Fig. 5. Theoretical and computational output energies in addition to array temperature variations during June 2023.

The graph reveals a minor divergence between the computational and theoretical energy studies, but they increase and decrease in parallel during the month. When the computational output energy reaches a maximum of 18.5 kWh/day, the theoretical output energy reaches a value of around 18.2 kWh/day, and when it reaches a minimum of 15.5 kWh/day, the theoretical output energy reaches a value of around 15.3 kWh/day. In addition, both theoretical and computational output energies change inversely with array temperature; when the array temperature rises, both energy outputs drop, and when the array temperature drops, both output energies rise.

The percentage of errors achieved from this experiment between theoretical and computational studies for the output array energy in kWh/day is shown in Fig. 6. The errors obtained between the computational and theoretical energy values varied between 1.2% and 2.2%; these small error values between the theoretical and computational methods confirmed the validity of the computational model and the accuracy of PVsyst on simulating the output of residential solar systems and performing research studies on overheating of residential solar systems using the mentioned software.

Two simulations were run, using PVsyst software to determine the system and weather conditions, and using PVsyst or theoretical equation to determine system energy output including cooling system and extra panels as shown in Fig. 7.

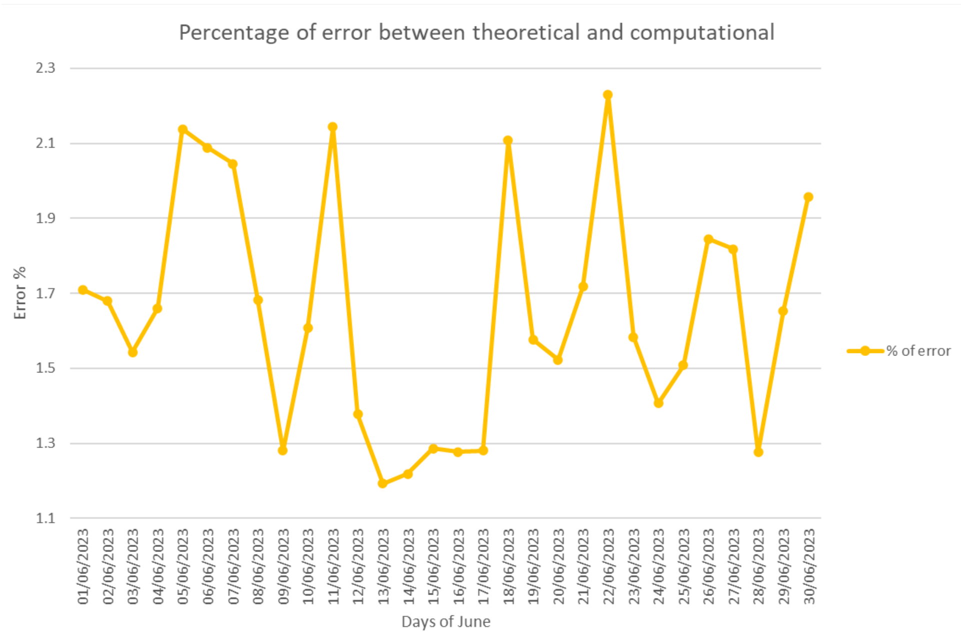

Fig. 6. Percentage of error between the output energy using PVsyst and theoretically (kWh/day) during June 2023.

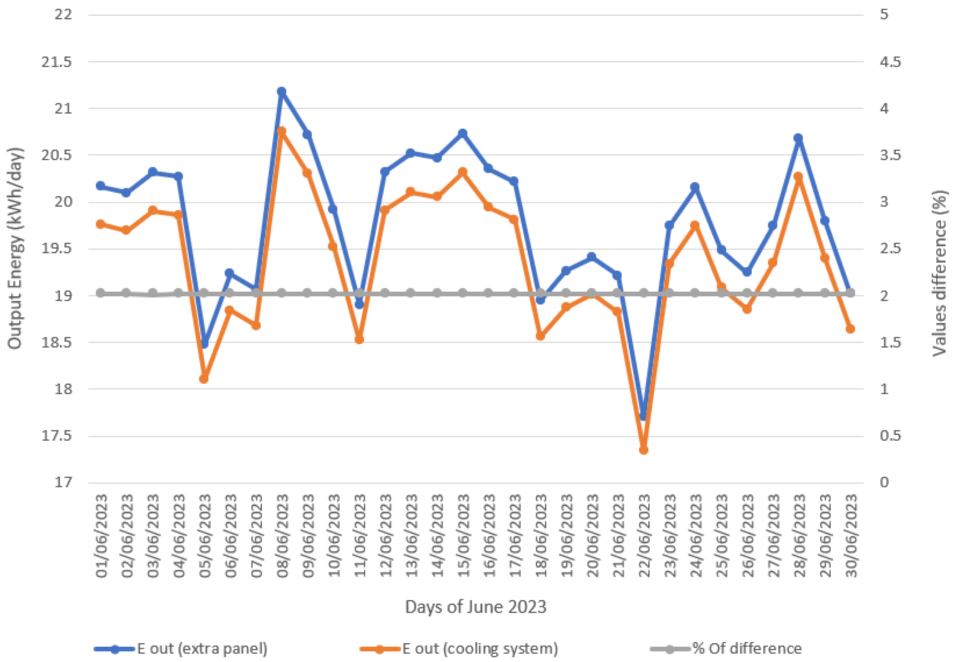

Fig. 7. Output energy using extra panel and cooling system's variation with respect to the days of June 2023.

The first study was taking into account the improved efficiency obtained from the previous research of value of 23.97% with a fixed number of six panels, and the second including an extra panel where the panels number became 7 while maintaining the system's original efficiency of 20.97%. Both energy outputs change proportionately, fluctuate concurrently and reach maximum and lowest levels at the same moment. This variation is caused due to changing only the necessary parameter (efficiency / number of panels) while maintaining all other factors (losses, irradiance, etc...) fixed.

However, the chosen residential solar system was sketched using SketchUp software, with the 6 already available PV panels, as shown in Fig. 8, based on the map and location provided using the exact dimensions of the building, including relevant details that affect PV panels' performance. Adding one extra panel, the structure's additional cost should also be taken into consideration, the available space to add one more panel, in addition to other factors such as the staircase and water storage tanks that would affect the panel's performance through shadings that will take place, which will affect the overall output of the system and results in decreasing system's efficiency.

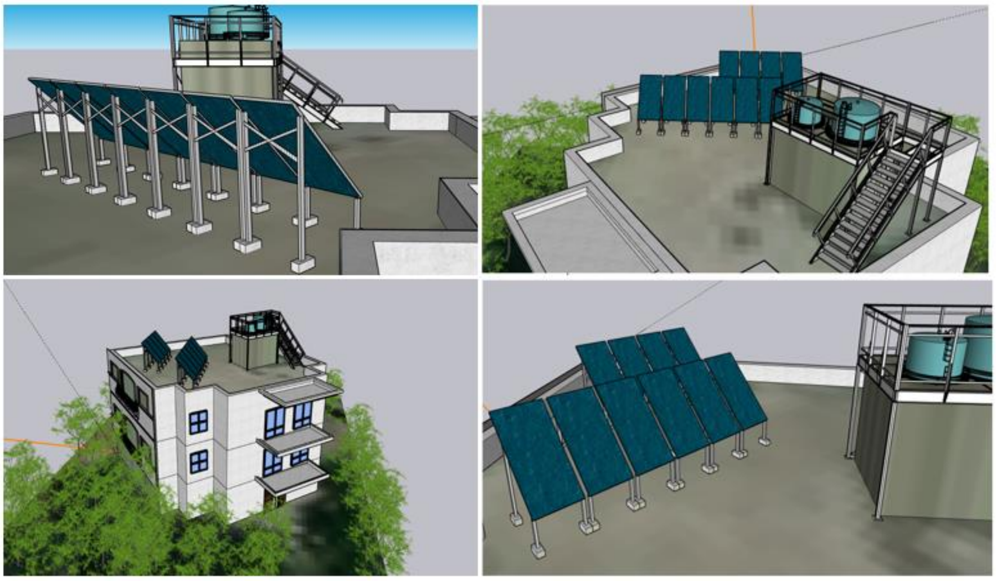

Fig. 8. Sketch up residential building design.

7. Conclusion and Future Works

- The relationship between the ambient temperature and the array temperature is proportional; they fluctuate simultaneously, this demonstrates that the ambient temperature has the greatest influence on the array temperature.
- Wind speed, incident irradiance, and heat dissipation have less of an effect on the array temperature than the ambient temperature.
- Temperature losses have significance and drop a remarkable amount of PV output energy daily, as demonstrated theoretically and computationally.
- Temperature losses are proportionate and directly related to array temperature.
- Up to 11% of the energy output of a residential solar system is being lost due to temperature
- An error of 2% was detected between theoretical and computational simulations
- Overheating research and studies may be conducted using computational techniques like PVsyst, because the computational approaches demonstrated acceptable error levels when compared to theoretical methods.
- Adding one more panel was 2% more efficient than adopting the proposed radiative cooling technique.
- When adding an extra panel, for example, other losses owing to shadings may result in a smaller and smaller energy output difference.
- An enhanced radiative cooling system may be developed so that the cooling system can be used more efficiently production taking into consideration cost and lifetime, since temperature losses are crucial and significant

Conflict of Interest

The authors state that they have no known conflicts of interest or personal relationships that might appear to have influenced the findings presented in this paper.

Author Contributions

Ahmad Al Takash: Responsible for data curation, formal analysis, investigation, methodology, validation, and writing the original draft. Razan El Kassar: Handled writing—review & editing, supervision, methodology, investigation, formal analysis, and conceptualization. Adie Msadi: Contributed to conceptualization, formal analysis, investigation, methodology, supervision, and writing—review & editing. Assadour Khanajian: Took on roles in writing—review & editing, supervision, project administration, methodology, investigation, formal analysis, and conceptualization. Youssef Abbani: Engaged in conceptualization, formal analysis, investigation, and writing—review & editing. All authors had approved the final version.

References

[1] Dinçer, H., Yüksel, S., Çağlayan, Ç., Yavuz, D., & Kararoğlu, D. (2023). Can Renewable Energy Investments Be a Solution to the Energy-Sourced High Inflation Problem? *Managing Inflation and Supply Chain Disruptions in the Global Economy*, 19.

[2] Kassar, R. E., Takash, A. A., Msadi, A., Salameh, W., & Khanjian, A. (2023). Modeling Solar cell performance at high temperatures: A validation study of theoretical equations and computational simulations. *Proceedings of 2023 Fifth International Conference on Advances in Computational Tools for Engineering Applications (ACTEA)*, Zouk Mosbeh, Lebanon.

[3] Enabling SDGs through Inclusive, Just Energy Transitions, *Towards the Achievement of SDG 7 and Net-Zero Emissions*. United Nations, 2021.

[4] Tavakoli, M., & Soufivand, M. R. (2023). Investigation of entropy generation, PEC, and efficiency of parabolic solar collector containing water/Al2O3−MWCNT hybrid nanofluid in the presence of finned and perforated twisted tape turbulators using a two-phase flow scheme. *Engineering Analysis with Boundary Elements*, pp. 324-335.

[5] Obaideen, K., Olabi, A., Swailmeen, Y. A., Shehata, N., Abdelkareem, M., Alami, A., Rodriguez, C., & Sayed, E. (2023). Solar Energy: Applications, Trends Analysis, Bibliometric Analysis and Research Contribution to Sustainable Development Goals (SDGs). *Sustainability*.

[6] Patel, K. (2023). Comparative analysis of solar heaters and heat exchangers in residential water. *International Journal of Science and Research Archive*.

[7] Wang, G., Pang, S., & Jiang, T. (2023). A brief review of liquid heat transfer materials used in concentrated solar power systems and thermal energy storage devices of concentrated solar power systems. *Natural Science Foundation of Jilin Province*.

[8] Wu, P., Ma, X., Ji, J., & Ma, Y. (2017). Review on life cycle assessment of energy payback of solar photovoltaic systems and a case study. *Energy Procedia*.

[9] Mohammad, A., & Mahjabeen, F. (2023). Revolutionizing solar energy: The impact of artificial intelligence on photovoltaic systems. *International Journal of Multidisciplinary Sciences and Arts*.

[10] Imad, L., Ziani, S., & Benami., A. (2023). Solar panels overheating protection: A review. *Indonesian Journal of Electrical Engineering and Computer Science*, pp. 49-55.

[11] Amran, N. M. H. N., Hassan, S. L. M., Halim, I. S. A., Sulaiman, N., & Abdullah, N. E. (2023). Effect of water cooling and dust removal on solar photovoltaic module efficiency. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*.

[12] Mehdi, M., Ammari, N., Merrouni, A. A., Benazzouz, A., & Dahmani, M. (2023). Experimental investigation on the effect of wind as a natural cooling agent for photovoltaic power plants in desert locations. *Case Studies in Thermal Engineering*.

[13] Bilen, K., & Erdoğan, İ., (2023). Effects of cooling on performance of photovoltaic/thermal (PV/T) solar panels: A comprehensive review. *Solar Energy*.

[14] Verma, S., Mohapatra, S., Chowdhury, S., & Dwivedi, G. (2021). Cooling techniques of the PV module: A review. *Proceedings of Materials Today*.

[15] Perrakis, G., Tasolamprou, A. C., Kenanakis, G., & Economou, E. N. (2021). Combined nano and micro structuring for enhanced radiative cooling and efficiency of photovoltaic cells. *Nature*.