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Enhancing Solar Cell Efficiency via Nanotechnology: A CFD-Driven Comparison with Conventional Models

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ABSTRACT

This investigation aims to study efficiency improvements in solar cells compared to conventional and nanoscale solar panels using computational fluid dynamics (CFD) performed in PHOENICS software. The simulation results showed that at temperatures ranging from 33 to 48℃, the nanoscale solar panels performed against the backdrop of conventional panels at temperatures of between 54 to 60℃, which had lower heat losses and 22% electrical conversion gain in efficiency. Simulations indicated that the cooling of the nanoscale panels was improved with pressure reduction from 854 Pa to 421 Pa and an increased velocity from 21 to 36 m/s. Application of perovskite nanocrystals in nanoscale solar cells enables the rate to exceed 25%, having traditional solar panels reach their maximum efficiency only at 20%. While concrete economic figures are not presented, simulation results and previous research indicate that the use of nanomaterials to produce solar cells could yield permanent cost savings. These results support how nanotechnology is being used to make solar energy more efficient and sustainable.

1. INTRODUCTION

Solar technology holds great promise as a renewable avenue towards addressing the developed world's energy shortages and reducing fossil fuel consumption. Nevertheless, the application of photovoltaic technology (PV) is hindered by the high production cost and low energy efficiency, particularly in conventional crystalline silicon-based cells [1]. The sector has rapidly expanded because sustainable technologies have become essential for climate change solutions. The present solar power systems cannot satisfy widespread electricity generation requirements because they possess low overall performance while being expensive to produce. Nanotechnology enables scientists to develop new solar cells that provide superior performance and affordable production costs. Quantum dots demonstrate exceptional capabilities for efficient solar device design thanks to their ability to create powerful cells that adapt to biological systems [2, 3]. Nanotechnology contributes to two main objectives in this field: improved efficiency and the development of simplified manufacturing methods through novel organic materials used in photovoltaic systems, even if durability and efficiency make slight concessions. Computational fluid dynamics (CFD) simulations provide research data for evaluating nano-fabricated solar cell performance versus traditional cells by exploring nanoparticle impacts on solar cell absorption efficiency and optimized atomic placements for more efficient energy conversion. Scientific investigations assess solar cell technologies, including classical, organic, and nano-fabricated cells, by examining their quality features and efficiency rate, cost, and environmental impact factors. The advancement of nanotechnology enabled sustainable, inexpensive solar cells to be manufactured while fighting against fossil fuels and toxic emissions and reaching industrial and economic balance. Gives us a clear picture of the great difference between different types of solar cells [1, 4, 5].

The existing literature has explored the ability of nanotechnology to improve the efficiency and price-effectiveness of solar cell production. Previous research has established the unique properties of nanomaterials, including quantum dots, that can enhance the mild absorption and conversion competencies of solar cells [2, 3, 6]. However, those studies have in general focused on the theoretical or laboratory-scale performance of nanostructured solar cells, without imparting a comprehensive assessment to the real-global performance of traditional solar technologies [7-9]. The modern-day studies target to address this knowledge hole by way of using superior simulation equipment, which include Phoenician software, to at once compare the performance of solar cells produced the use of nanotechnology as opposed to conventional crystalline silicon solar panels [10-13]. This technique allows for a greater realistic evaluation of the capability benefits of incorporating nanoparticles into solar cell manufacturing processes. Furthermore, this examination delves deeper into the underlying mechanisms using the improved performance of nanostructured solar cells. It examines the chemical composition of sun cellular materials, the position of atomic-scale preparations, and the way those elements have an effect on the general electricity conversion performance [1, 4, 5]. Recent advances in nanotechnology have led to an increase in solar cell research, providing materials with improved optical and electronic properties. The application of nanomaterials, such as quantum dots and plasmonic nanoparticles, holds great potential for improving light harvesting and charge transport, two important criteria for improving the energy conversion performance of solar cells. Many researchers have documented the benefits of nanoscale solar cells on paper and in laboratory settings [3, 6], but few have tested their performance in real-world applications, which is closer to that of conventional solar technology [7-9]. These gaps make it impossible to comprehensively evaluate the practical performance of nanoscale solar panels.

Applications of nanomaterials, including perovskite crystals and quantum dots, have been shown to strengthen solar cells' ability to absorb light by a great deal. For example, current research demonstrates that perovskite crystals provide a possible solution for improving the efficacy of solar cells because they trap a wide range of light. However, continued issues concerning the stability of these materials when exposed to high temperatures and even humidity limited their long-term use [14].

Ultraviolet light is absorbed better by the quantum dots, improving the performance at varying lighting conditions. The most problematic is achieving enduring stability and a functional performance in routine settings over time [15]. Although efficiency gains with nanomaterials have been significant, manufacturing processes have been truly difficult. It is difficult to close the gap between the manufacturing of nanocrystals and regular cells because intricate materials and methods are required, thus driving up manufacturing costs. Nanocrystals are in a position to accomplish higher energy conversion efficiencies, although the sophisticated manufacturing processes involved may limit their cost-effectiveness in an industrial setting [16]. The gain in efficiency gained by the application of nanomaterials in solar cells has to be weighed against the high additional cost. Achieving long-term sustainability in nanomaterial-based applications also relies on the improvement of their stability. The current research has attested to significant improvements in increasing the stability of perovskite crystals, which led to the broader use of such crystals in commercial solar cells. Scientists have introduced sophisticated materials processing to reduce the adverse effects on performance when solar cells are in heated and humid conditions [17].

However, a significant portion of CFD research has focused on assessing the behavior of solar panels independently in terms of their thermal or aerodynamic properties, rather than integrating the results to conduct a comprehensive evaluation between conventional and nanoscale solar technologies. This study departs from previous techniques by using PHOENICS software for an applied CFD analysis, where both panels are subject to homogeneous environmental and engineering parameters. By adding variables such as temperature, pressure, airflow velocity, and kinetic energy, this research provides a more detailed overview of the thermal and aerodynamic effects on panel performance. By adding variables such as temperature, pressure, airflow velocity, and kinetic energy, this research provides a more detailed overview of the thermal and aerodynamic effects on panel performance. By adopting this combined approach, this study not only reveals improved results from nanoscale panels but also reveals new details about how environmental influences influence the behavior of nanomaterials. These findings aim to help materials scientists, engineers, and energy policymakers evaluate the practical benefits that could accrue from the use of nanotechnology in solar energy systems.

2. USE OF NANO-PLASMON CAVITY

Solar cell energy conversion efficiency improves because of utilizing structures combined with metallic cavities. Nanocavity surfaces receive a semiconductor layer no thicker than 100 nm, per research, which enables nanostructured solar cell manufacturing [1]. The cell performance shows a significant boost because better light energy absorption, along with enhanced carrier transport, develops from the designed structure [7, 8]. The study of nan engineering allowed scientists to create techniques that regulate material behavior during solar cell work for better light-matter interactions and thus develop more affordable and powerful solar energy solutions.

Figure 1(a) is the schematic representation of the optimal unit cell of the absorber, which is composed of a gold back-reflector, a SiO_2 spacer layer, and a front gold nano-pattern.

Figure 1(b) shows the spectrum of the sun (black curve) and the measured absorbed part (red area).

In Figure 2, the left panel shows the simulation results of light absorption as a function of both wavelength (λ) and geometric parameter (ΔR), which reflects the closeness of adjacent triangles in the nanostructure. It is observed that the absorption bandwidth is very large when ΔR values are positive and small. And the right panel presents the comparison of the calculated (left column) and experimentally measured (right column) absorption spectra for different values of ΔR. The scanning electron microscopy (SEM) images on the right show the building blocks of the fabricated structure for each case, with the scale of the figure shown being 200 nm [7, 8].

This analysis highlights how subtle geometric modifications (such as changing ΔR) affect the light absorption behavior of nanostructures, supporting the design of solar cells with a broad wavelength response and thus enhancing the overall efficiency.

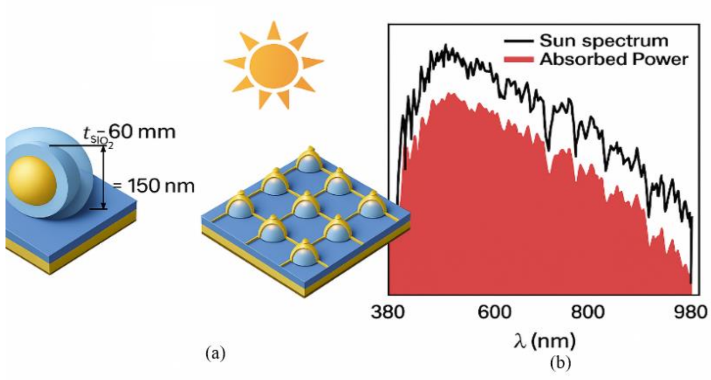


Figure 1. Comparison of experimental and theoretical absorption spectra of absorbing materials [9]

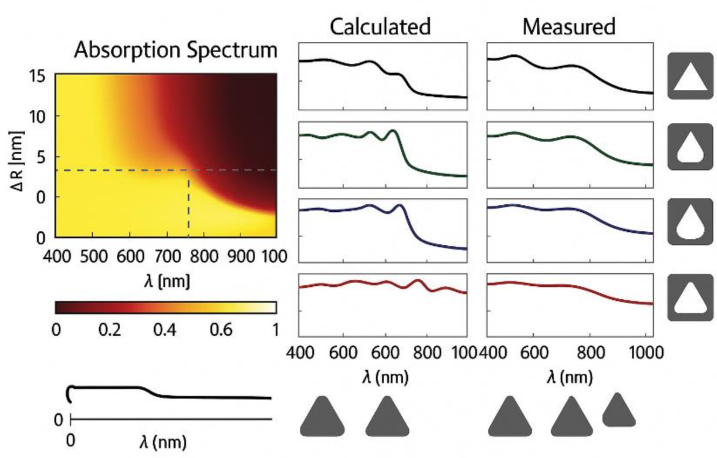


Figure 2. Measured and calculated absorption spectra of the absorbers [10]

3. USING THE PHOENIX PROGRAM TO SIMULATE THE CHANGE IN THE EFFICIENCY OF THE SOLAR PANEL

3.1 Methodology

The research uses a CFD simulation program with PHOENICS software to determine the efficiency of the conventional and nanostructured solar cells. Being acknowledged for their excellent contributions to light harvesting and the flow of electrons, the perovskite crystals and plasmatic particles were chosen in this study as the most appropriate nanomaterials. The simulation looks at variables such as temperature, pressure, velocity, and kinetic energy throughout the solar cell plate. The outcomes of the presented simulations permit a straightforward comparison of conventional crystalline silicon solar cells' efficiency as well as nanostructured alternative options. The flow will be treated as steady, incompressible, and turbulent in three dimensions. The dimension will be expressed in Cartesian coordinates (x, y, and z), and the axis of rotation will be the X-axis. The experiment was carried out using PHOENICS, the domain was chosen, and the number of cells was manipulated until the visibility of the flow pattern around the solar panel was established [1]. PHOENICS constituted the major tool for CFD-simulations within this research, in part because of the substantial use of the program in previous studies for the study of the thermal and aerodynamic characteristics of the solar cells. Have validated the performance of PHOENICS by using it on both conventional and nanoscale solar cells under a wide range of thermal conditions, and obtained simulation results consistent with experiments [18]. The size of the simulation domain was given as follows: To define the simulation area, length was to be 1 meter, width 0.6 meters, and height 0.05 meters.

Boundary Conditions: Inlet was given a velocity of 5 m/s in order to match external flow conditions. Solar panels were set with a surface temperature of 50°C, which is standard in the model conditions of the simulation. The ambient temperature of 25°C was held constant in the model, as the solar panels were immersed in the general environmental surroundings.

Turbulence Models: While applying the k-ε turbulence model, we determined the distances of airflows from the roof. According to research conducted by Gandhi et al. [18], the k-ε model performs well in predicting non-turbulent air flows in solar thermal installations. In several cases, the SST (Shear Stress Transport) model was assessed, especially in the roof vicinity, to improve the simulation results in regions that exhibit extreme flux changes.

Validation Steps: Gandhi et al. [18] validated simulation results with experimental data, in which CFD simulations of temperatures of solar panels in field conditions were done. The results of the simulation approximated those of the experimental data, thus making this study's simulation results valid.

In the first simulation (conventional solar cells-classic, solar panels), the experiment is set up in such a way that the flow pattern and certain flow parameters of interest, like velocity and pressure changes, can be studied, including the most important temperature. Hence, a control experiment will be carried out to ascertain the flow pattern, temperature, velocity, and pressure profile of the original solar panel and later compare them with those of the secondary panel (Nano solar panels) based on the profiles obtained when the solar panels of different simulations are used. The parameters of interest, like temperature, velocity, and pressure, are then taken along the domain of flow in the x, y, and z-axes and then compared to see if there will be any changes to the flow pattern in terms of flow, velocity, and pressure profile. In this simulation study, the same dimensions of the solar panel and the Sun (with the same physical properties like radius and thickness, and the difference will be in the method of manufacturing the material and surface features from the conventional manufacturing of solar cells to manufacturing using nanotechnology material and surface features) will be used; the only variation will be to the simulation (conventional solar cells, classic) 1st simulation or the simulation (Nano solar panels) 2nd simulation.

The location of the solar panel and the Sun in the domain geometry will also be maintained constant throughout the experiment to eliminate errors that might arise from the effect of a change in proximity of the Sun to the source of mass from the inlet, though this will be negligible since only one inlet and outlet are specified for the domain and air in the first simulation (conventional solar cells, classic). However, in the second simulation (nano solar panels). The domain is set up to replicate a scenario of flow across the solar panel and the Sun (see Figure 3). The other parameters that will remain constant throughout this study are:

- Domain size;
- Inlet and outlet size and location;
- Mesh setting and relaxation parameters;
- Number of iterative steps, that is, number of sweeps.

3.2 Numerical CFD model and procedure

3.2.1 Numerical CFD model and procedure

The first step is to select a standard (typical) solar panel that can be represented digitally via the SolidWorks® engineering software package for 3D CAD modeling, as shown in Figure 4.

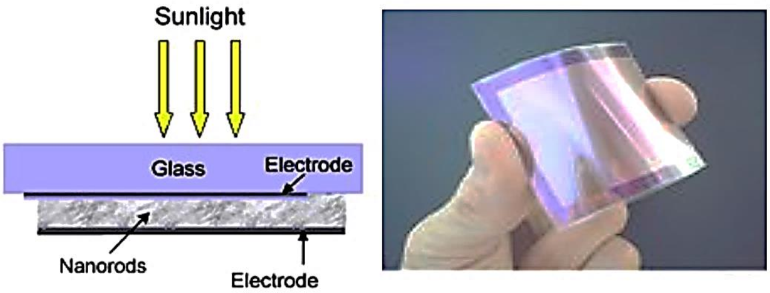


Figure 3. Diagram of a nano solar cell picture of a solar cell, which utilizes nan rods to convert light into electricity [8]

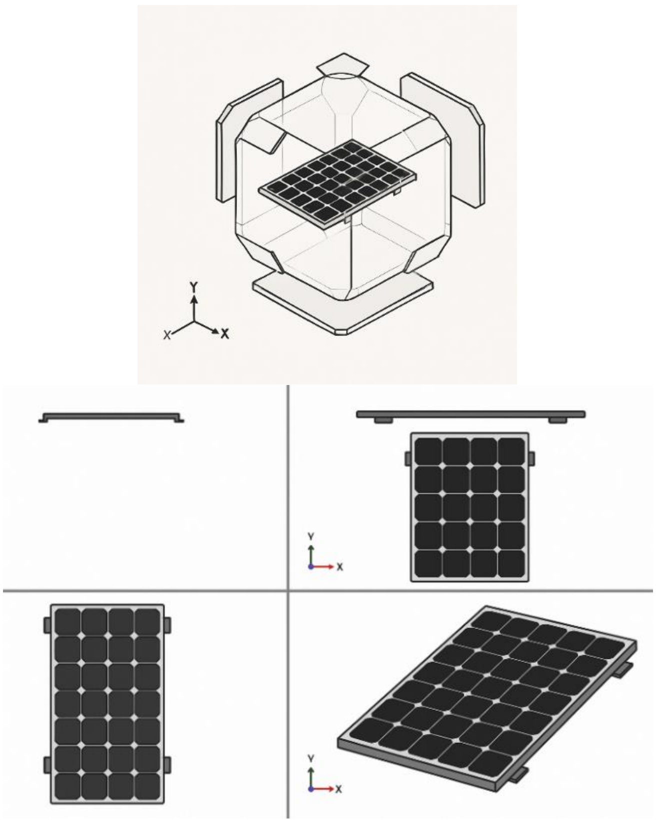


Figure 4. Computational of a solar panel by SolidWorks® software

3.3 The simulation for the solar panel and the sun

Figure 5 shows how to install the solar cells, as well as determine the location of the sun with the angle of the solar azimuth and inclination of the surface angle of the in software.

The first simulation the solar panel and the sun (conventional solar cells). The second simulation the solar panel and the sun (nano solar panel).

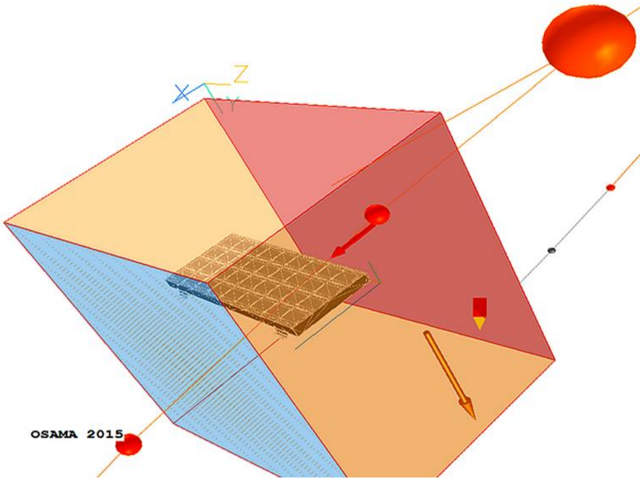


Figure 5. Put the solar model panel and the sun in the software (B)

3.4 Comparing between the different result of the solar panel and the sun, 1st simulation and 2nd simulation

Figures 6 and 7 show the comparison of the start-up results 1st simulation and 2nd simulation.

High temperatures reduce the operational efficiency of photovoltaic panels, thus diminishing their ability to produce electrical energy. A research investigation utilized computational fluid dynamics (CFD) to examine temperature variations on the operational efficiency between conventional (classical) solar panels and nanostructured solar panels.

- First simulation: conventional (classical) solar panels.
- Second simulation: nanostructured solar panels.

Researchers conducted research to examine performance differences between conventional and nanostructured solar panels as they reacted to temperature conditions while evaluating how nanostructure design diminishes heat-related energy loss [7, 8]. By performing this assessment, scientists can determine which technology best maintains operational stability while boosting production levels in authentic operating environments.

For each of temperature, pressure, velocity, and kinetic energy, both conventional and nanostructured solar panels are characterized by their means and standard deviations. The provided results show the typical measurements and their range, aiding in the quantification of uncertainty. All measurements in Table 1, for each solar panel type, are accompanied by their minimum and maximum values, together with the calculated mean and standard deviation.

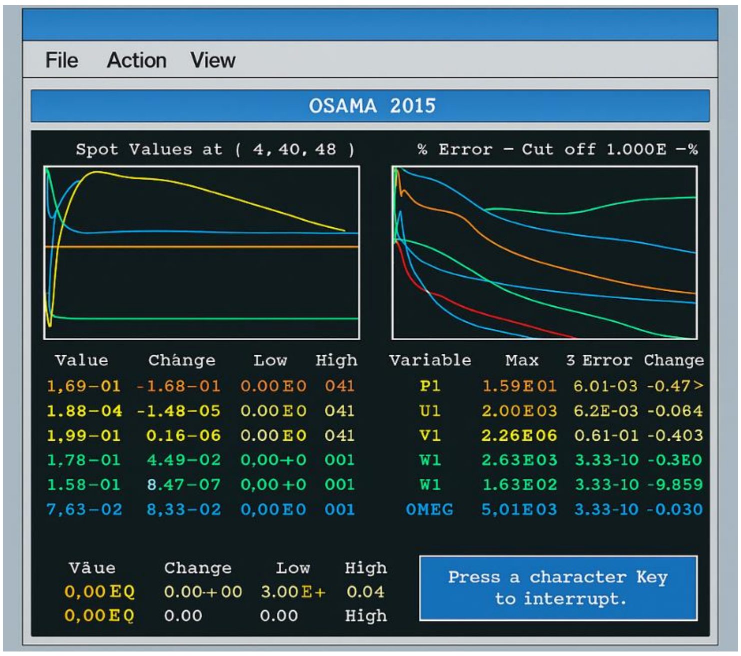


Figure 6. Comparing between the run of solar panel and the different simulations (1st and 2nd, conventional solar cells and nano solar panel)

Table 1. Minimum and maximum measurements for both conventional and nanostructured solar panels

Metric	Conventional Solar Panel (min)	Conventional Solar Panel (max)	Nano Solar Panel (min)	Nano Solar Panel (max)	Conventional Solar Panel Mean	Nano Solar Panel Mean	Conventional Solar Panel SD	Nano Solar Panel SD
Temperature (°C)	54.00	60.00	33.00	48.00	57.00	40.50	3.00	7.50
Pressure (Pa)	301.00	854.00	57.30	421.00	577.50	239.15	276.50	181.85
Velocity (m/s)	5.00	21.00	9.00	36.00	13.00	22.50	8.00	13.50
Kinetic Energy (m^2/s^2)	0.000271	165.455	0.00013	466.62	82.73	233.31	82.73	233.31

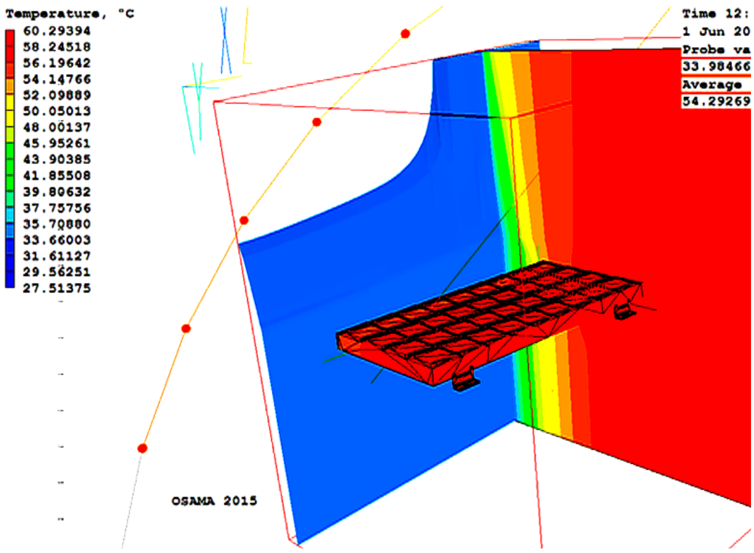


Figure 7. The comparison between the 1st and 2nd simulations (P S)

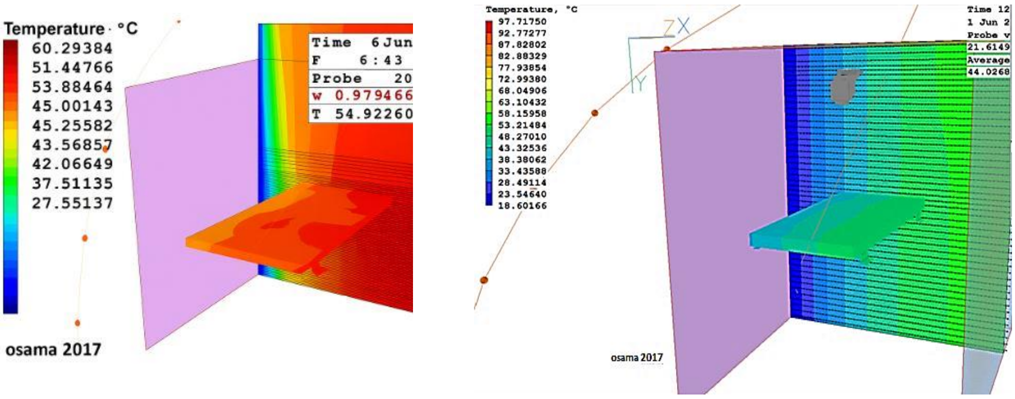
4. RESULTS

The results of this research on nano-cavity Plasmons of solar panels are very important and should be applied to improve the efficiency of existing solar panels. Result presentation and analysis for the 1st and 2nd simulations (PHOENICS) Software: The comparison between all the graphs and charts shows that there is a very significant difference in scores between the first and second solar panel simulations. We note that in the first simulation (conventional solar cells, classic), the degrees of solar panel temperature are between 54 and 60°C as shown in Figures 8 and 9, while in the simulation II (nano solar panels). The degrees of solar panel temperature go down all the way to between 33 and 48°C [19, 20]. This confirms that when made using the nano solar panels is very important and must be used to improve efficiency [21].

Comprehensive data on temperature and pressure as well as speed measurements for the conventional and nano-solar panels are presented here. The results are analyzed to illustrate the effect of temperature on solar cell efficiency and how changes in pressure/speed affects heat management and material strain. At lower temperatures, the efficiency of solar cells increases, mainly due to the fact that, at high temperatures, photovoltaic conversion efficiency is lowered. A research study reports that a 0.4%-0.5% reduction in the overall efficiency for a conventional solar cell can be created by increasing the temperature by 1°C. In turn, the cooling down of nano-solar panels in temperature range of 33-48°C instead of 54-60°C results in increased efficiency of cells for 3-5%, enhancing overall performance of solar cells. Improved efficiency is explained by the decrease in losses from heat and increased effective power generation. The pressure in the nanopanels reduced dramatically according to the simulation from 854 Pa to 421 Pa, while the conventional panels had pressure values ranging from 301 to 854 Pa. Less pressure in the nanopanels means that such nanopanels are abler to reduce material stresses brought by heat and hence reducing the chances of cracking or damage due to temperature changes.

Nanopanels showed greater air velocities, up to 5-36 m/s, compared to panels with a conventional setup, which range from 5 to 21 m/s. Higher velocity air enables better cooling and distributes heat uniformly over the area of the solar cell. Consequently, the performance of the solar cells improves significantly, supported by the enhanced cooling and minimized thermal stress on the material.

An elaborate analysis of the obtained data was made to discuss the synergistic impacts of these three factors upon solar cell efficiency. The observed drop in temperature together with improved velocity and pressure conditions clearly indicates that nanopanels can actually minimize the escaping heat and maximize the overall functioning of solar panels.



(a) (b)

Figure 8. Comparing the values of temperature among four different simulations (1st and 2nd)

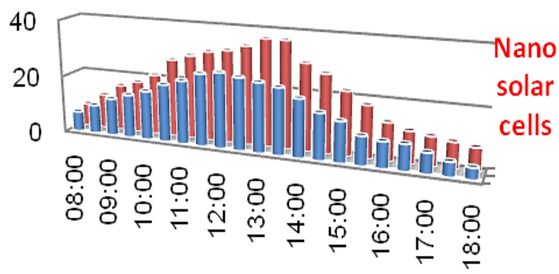
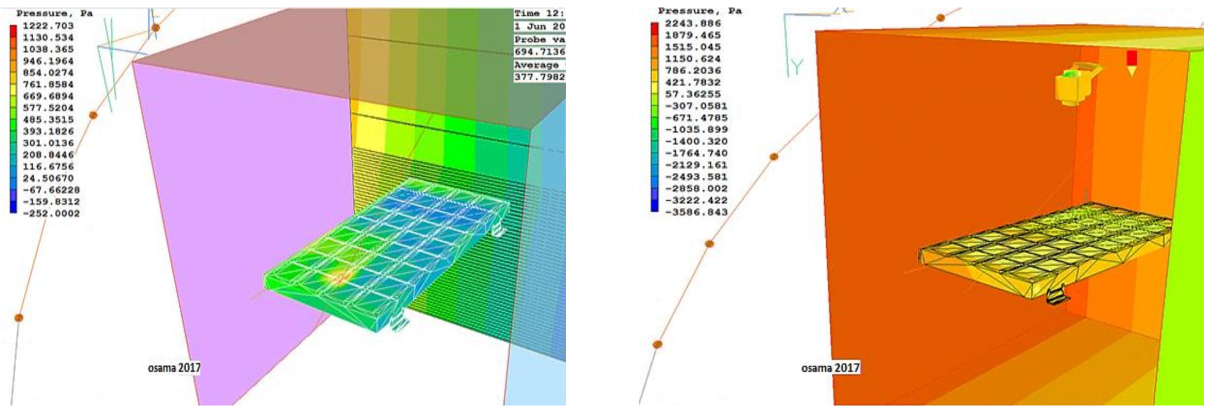
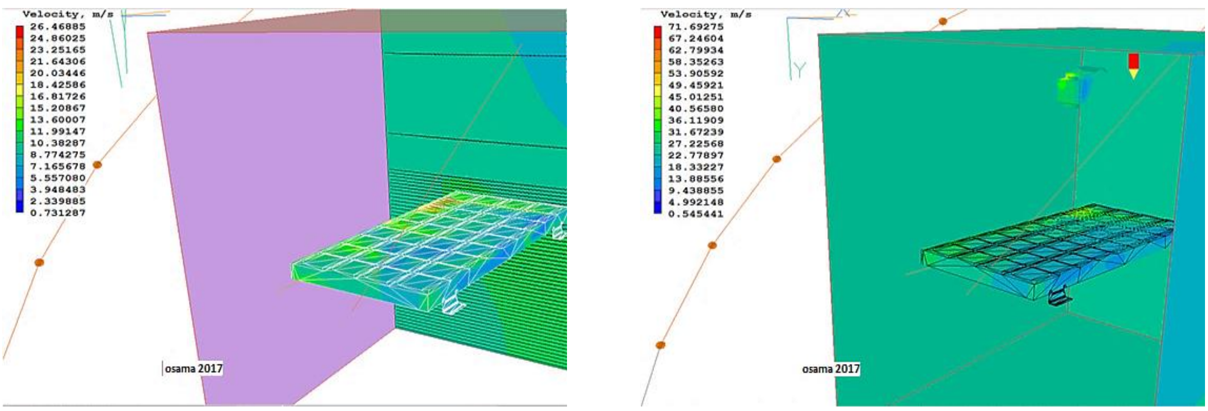


Figure 9. Comparing the values of temperature with the time among four different simulations (1st and 2nd)



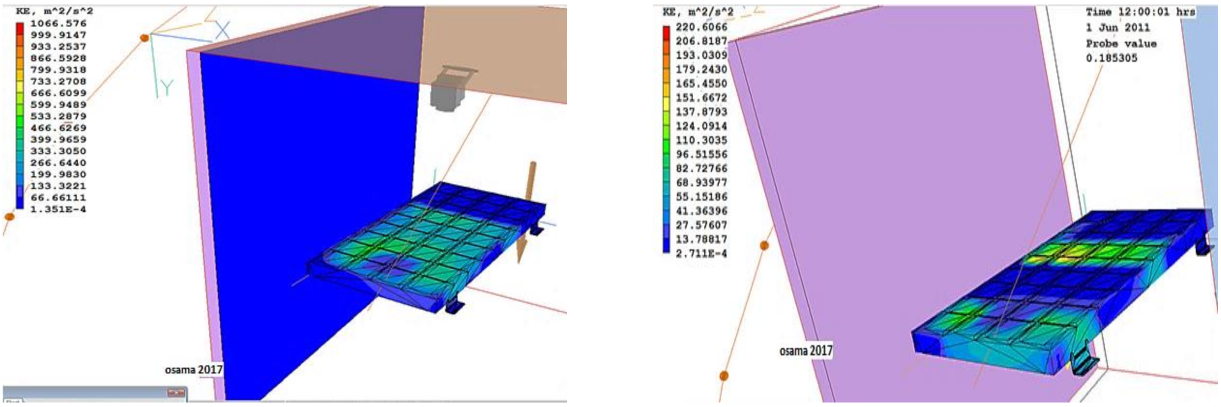
(a) (b)

Figure 10. Comparing the values of pressure among four different simulations (1st and 2nd)



(a) (b)

Figure 11. Comparing the values of velocity among four different simulations (1st and 2nd)



(a) (b)

Figure 12. Comparing the values of kinetic energy (KE) among four different simulations (1st and 2nd)

Table 2. Comparing the values among different simulations (1st and 2nd)

Header	Simulation (1st) Conventional Solar Cells (Classic)	Simulation (2nd) Nano Solar Cells
Temperature	54 to 60°C	33 to 48°C
Pressure	301 to 854 Pa	57.3 to 421 Pa
Velocity	5 to 21 m/s	9 to 36 m/s
KE	2.71×10^{-4} to 165.455 m²/s²	1.3×10^{-4} to 466.62 m²/s²

Moreover, in the first simulation (conventional solar cells, classic), the degrees of solar panel pressure were between 301 and 854 Pa, while in simulation II (nano solar panels). The degrees of solar panel pressure go down in the range between 57.3-42 Pa, as shown in Figure 10 in the comparison of the results 1st simulation and 2nd simulation, because the relationship between temperature and pressure is proportional. In the case of velocity, the reverse process occurs, where the air velocity is working to cool the solar cell technology manufacturer's nanotechnology better than conventional cells as shown in Figure 11 in the comparison of the results 1st simulation and 2nd simulation, as well as the degrees of solar panel kinetic energy was between 133.322 and 466.626 m²/s², while in simulation II (nano solar panels). The degrees of solar panel kinetic energy decrease in the range between 41.363-165.455 m²/s², also kinetic energy as shown in Figure 12 in the comparison of the results 1st simulation and 2nd simulation thus increasing the efficiency of the solar panels. As well as being for all values compared, Table 2 illustrates this comparison, which is specific to this research paper.

5. CONCLUSIONS

Developing and providing sustainable methods for power generation is one of the most pressing challenges facing humanity today. Table 1 and Figures 5-12 demonstrate the significant increase in efficiency that solar panels manufactured using nanotechnology offer. While the current efficiency of these panels may not match that of traditional cells, their low cost compensates for this. In the end, the cost of nanotechnology versions should decrease, and the use of quantum dots should enable them to achieve higher levels of efficiency than traditional cells. In addition to these advantages, solar panels made using nanotechnology offer several other benefits:

• Conventional solar panels experience a decrease in efficiency at high temperatures, whereas solar panels made using nanotechnology do not suffer from this issue.

• Conventional solar panels are susceptible to decreased efficiency under high pressure, whereas solar panels made using nanotechnology are not affected.

• Solar panels made using nanotechnology have the potential for increased efficiency because of the higher air velocity to which they are exposed compared to conventional solar panels.

While this review provides a comprehensive assessment of the potential for nanotechnology to enhance the performance and affordability of solar cells, it is important to acknowledge the limitations of the current study and identify areas for future research. One key limitation of this work is the reliance on CFD simulations to model the behavior of nanostructured solar cells. While the CFD approach offers valuable insights into the underlying mechanisms driving the improved performance of these technologies, the accuracy of the simulations is inherently dependent on the quality and completeness of the input data and the sophistication of the modeling algorithms. Future studies should seek to validate the simulation findings through rigorous experimental testing and real-world performance data. Additionally, the material-level analysis presented in this review is primarily based on the latest published research, which may not fully capture the rapid pace of development in the field of nanotechnology-enabled solar cells. As new materials, fabrication techniques, and device architectures continue to emerge, there is a need for ongoing, in-depth characterization and evaluation to ensure the relevance and timeliness of the findings. Another important limitation is the geographic and temporal scope of the literature review. Future research should expand the geographic coverage and consider a more dynamic, continuously updated approach to the literature review to ensure the insights remain current and applicable to a global audience. To address these limitations and build upon the foundations established in this review, several potential directions for future research could be identified:

1) **Experimental validation:** Conduct extensive experimental testing of nanostructured solar cell prototypes to validate the performance gains predicted by the CFD simulations and provide a more comprehensive, empirical understanding of the technology's real-world capabilities.
2) **Dynamic literature monitoring:** Implement a systematic, automated approach to continuously monitoring and

integrating the latest research on nanotechnology-enabled solar cells, ensuring the review remains up-to-date and responsive to the rapid pace of technological progress.

3) **Expanded geographic scope:** Broaden the geographic coverage of the literature review to capture regional variations in solar cell development, materials availability, and manufacturing capabilities, providing a more globally representative assessment of the potential for nanotech-enabled solar solutions.
4) **Life cycle and environmental impact assessment:** Conduct a comprehensive evaluation of the life cycle environmental impacts and sustainability of nanotech-enabled solar cells, including considerations around material sourcing, manufacturing processes, and end-of-life disposal or recycling.
5) **Techno-economic analysis:** Perform in-depth techno-economic analyses to quantify the cost savings and market competitiveness of nanostructured solar cells compared to conventional technologies, accounting for factors such as manufacturing scale, supply chain dynamics, and policy incentives.

By addressing these limitations and pursuing these potential research directions, future studies can build upon the solid foundation established in this review to provide an even more robust, up-to-date, and actionable understanding of the transformative potential of nanotechnology in the solar energy sector.

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