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(Review Article)

Enhancing solar energy systems: The role of computational and automation techniques in achieving net zero by 2050

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Abstract

This review aims to show how computational and automation can be applied to optimize the solar power system toward net-zero emissions in 2050. It emphasizes the power of data analytics, machine learning and automated systems for optimizing business models and measuring the performance of solar technology. The role of solar power in decarbonizing our energy needs and lowering carbon emissions is discussed along the global climate agenda. It also discusses novel uses such as self-teaching robots for solar panel inspection and automated manufacturing to increase the efficiency and sustainability of solar power generation. Additionally, it addresses the need for sophisticated research tools such as computational fluid dynamics (CFD) and finite element analysis (FEA) to create new technologies in the solar market and ultimately meet the ambitious renewable energy targets of 2050.

Keywords: Solar Energy; Automation; FEA; CFD; Net Zero Emissions

1. Introduction

Net-zero greenhouse gas emissions by 2050 are a prime goal in the global climate change mitigation strategy, and solar energy sources are key to this goal. Solar power, with its high abundance and sustainability, presents a viable means of decreasing fossil fuel dependence and thereby dramatically lowering carbon emissions. As the European Green Deal emphasizes climate neutrality will be possible only with innovative approaches in renewables, especially by optimizing photovoltaic or PV systems to support increasing energy demand while ensuring that it's ecologically efficient [1].

The requirements for improving the solar energy grid are underpinned by rising temperatures on the planet and the need for meaningful action on climate change. Comprehensive systems that blend computational and automated methods are critical for optimizing the efficiency and reliability of solar systems. These approaches both make optimal energy usage as well as facilitate better integration of solar arrays into a pre-existing grid by solving issues related to energy storage, load balancing, and demand response. Such developments are critical to moving to a cleaner energy future and to meeting the very high goals laid out for carbon neutrality [2].

Moreover, the adoption of these new techniques encourages the adoption of green energy systems, which also fit with the general goals of worldwide environmental policies. Stakeholders can exploit data analytics, machine learning, and automation to tailor business models, drive performance, and rigorously test solar technologies – making solar power one of the most promising competitors on the pathway to net-zero emissions by 2050. It is of the utmost importance, as it is a meeting place of innovation and sustainability to meet today's environmental needs [3].

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In this review, we will examine how computational and automation tools can further enhance the efficiency of solar power systems and help reach net-zero objectives, showcasing how technology and environmental conservation play an essential role in ensuring a sustainable future.

2. Applications of Automation Techniques in Enhancing Solar Energy Systems

The adoption of automation technology in solar energy systems is essential to increasing efficiency, reliability, and network connection. These breakthroughs are essential to reaching the target of net-zero emissions by 2050. Automated systems maximize energy generation, control consumption, and better integrate with renewable energy sources, contributing to long-term energy system sustainability.

2.1. Cost Savings

Automation can drastically improve the efficiency of solar power plants through monitoring and controlling tools. Sensors and automated controls enable solar PV systems to work optimally, reacting to weather conditions, and making the best use of energy [4]. This responsiveness provides more power generation and longevity of solar installations necessary for net-zero goals.

2.2. Predictive Maintenance

Through automation, it’s now possible to automate the maintenance of your solar panels predictively, which is crucial for keeping downtime low and extending equipment life. With data analytics and machine learning algorithms, potential errors can be detected in advance and intervention is possible [5]. This preventative mode not only lowers maintenance costs but also ensures stable energy generation, which is essential for a stable energy supply on net-zero platforms.

2.3. Resource Optimization

Automated devices could maximize resource efficiency within solar energy systems. Solutions like artificial intelligence (AI) can even study historical trends and predict energy consumption, which will help with the planning and storage of resources. This optimization is vital to the equilibrium of supply and demand, especially in environments where energy demands are variable.

2.4. Integration with Smart Grids

Automation is an important tool to ensure solar and smart grids integrate seamlessly. Through dynamic control of the flow of energy, automated systems help stabilize the grid and allow the integration of many different sources of energy [6]. Such fusion is necessary to deal with the increasing complexity of energy networks as nations transition to renewables for net-zero emissions.

2.5. Decision Support Based on Data

Solar energy system automation makes data-informed decision-making possible for energy management and policy making. Through sophisticated data collection and analysis, actors can make smart decisions to maximize energy generation and use [7]. These are vital data to inform investments and policy initiatives that will make it possible to achieve net-zero energy systems by 2050.

2.6. Enhanced Energy Storage Solutions

Automated control systems help create and optimize the energy storage modules associated with the solar energy arrays. With this automation of the charging and discharge operations, these devices make use of stored energy in the system, thereby making solar power a more stable energy source [4]. A high-capacity storage solution will be critical to combating solar energy’s erratic nature and reaching net-zero targets.

3. Applications of Computational Methods for Enhancing Solar Energy Systems

Computational methods like FEA and CFD are critical to improving the systems of solar energy with a target of net-zero emissions by 2050. These approaches allow simulations and analyses that can be used to better design, reduce costs and embed solar into larger energy infrastructures.

3.1. Optimizing Design Efficiency

Simulations such as FEA make it possible to reconstruct the structure of solar modules to make systems robust against environmental loads and reduce material consumption. Simulating design combinations can help engineers pinpoint the best structure to position solar panels, which is important for long life and performance in adverse weather [8]. This capability is crucial to developing solar technologies in places that face extreme environmental challenges.

3.2. Flow Optimization of Solar Collectors

CFD is widely applied to fluid dynamics in solar thermal arrays like concentrating solar power (CSP) arrays. Simulated heat transfer rates can be improved and thus, the heat efficiency of these systems can be further improved leading to more energy production [8]. This optimization is important to decrease capital expenditure and enhance solar thermal systems' competitiveness to attain renewable energy goals.

3.3. Interconnectivity with Building Systems

FEA and CFD building energy simulations are important for integrating solar energy systems to build structures [9]. Such calculations enable the creation of bioclimatic buildings that can be more efficient on a number of energy points, and utilize solar panels with high efficiency [10]. Buildings can greatly lower their carbon footprint through a balance between airflow and heat capture and so make up for the overall reduction of emissions.

3.4. Dealing with Thermal and Mechanical Performance

FEA modeling of thermal and mechanical behavior allows us to visualize the behavior of solar energy systems when faced with environmental change and stress [11]. This knowledge is necessary for better performance and life of solar systems which allows for mass use. Good thermal management reduces the cost of operations and makes solar energy systems more economically viable, which are key to net-zero emissions.

3.5. Incorporating Policy Making and Planning

Computational methods can guide policymakers by providing simulation analyses of the potential impacts of strategies and incentives for renewable energy. These insights can inform the development of laws and regulations to promote the deployment of solar power so that net-zero emissions become achievable and feasible [8]. Furthermore, estimating different scenarios permits resource allocation and infrastructure planning.

3.6. Inspiring Research and Development

FEA/CFD research also fosters new solar technologies and upgrades the available ones [12]. Simulating multiple conditions of operation allows researchers to validate new materials and models before prototyping, dramatically reducing the development time [9]. Such advances can unlock technological innovations in solar technology that are essential to achieving lofty renewable-energy ambitions by 2050.

All these applications reveal how computational methods have the potential to improve the performance of solar systems, and they can serve as essential elements in the transition to environmentally sustainable and resilient energy systems.

4. Examples in Action: How Companies Have Used Automation to Improve Solar Power Systems

These are five real-world scenarios where companies have deployed automation to enhance solar power installations, helping us get to net zero in 2050:

4.1. Tesla's Gigafactory and Solar Roofs

Tesla's Gigafactory is responsible for manufacturing Solar Roofs, utilizing cutting-edge automation systems that improve efficiency and lower production costs [13]. Robotics and automation to automate the manufacturing of Solar Roof tiles will improve the efficiency of operations in addition to complying with the global goal to be net-zero emission [14]. Through such technologies, Tesla can create solar solutions that power renewables and eliminate the carbon impact associated with conventional manufacturing processes — a major improvement in sustainability in the energy industry [15].

4.2. First Solar's Automated Manufacturing Plants

First Solar has established highly automated factories that can turn a strip of glass into a functional thin-film PV module within four and a half hours (as opposed to days for competitors) [16, 17]. It has vertically integrated production that puts the entire solar panel manufacturing from raw to finished components in one place for more efficiency and control. The most recent upgrade was a $1.1 billion Alabama plant that will add 3.5 gigawatts (GW) to its capacity to manufacture it; that number is expected to be near 11 GW locally and more than 21 GW internationally by 2026's end. With a cutting-edge automation strategy and cutting-edge technology, First Solar has been able to reduce production costs without neglecting sustainability, including local material imports for its products [18].

4.3. Enel Green Power's Autonomous Solar Power Plants

Enel Green Power is also exploring new technology for the automation of monitoring solar plants and is looking at solutions such as autonomous robots and drones to optimize it. The company has also built a solar-enabled robot called SandStorm. This robot eliminates dust build-up automatically without using water from the solar panels, as dust build-up can deplete power production [19]. Additionally, they use AI and drones to inspect the structures which help in reducing data processing and manual labor requirements for maintenance [20]. This practice does not only reduce costs but also is sustainable as a result of the reduction of water consumption and carbon footprint caused by the cleaning process [19].

4.4. JinkoSolar's Smart Factory

JinkoSolar is maintaining a leading position in the solar PV sector by developing one of the largest smart-factory projects to dramatically improve the production capacity and quality of solar module assembly [21]. Intelligent manufacturing can be used to increase production flows and overall JinkoSolar operational efficiency [22]. Furthermore, the Jacksonville plant controls the lights and cameras in every robot, which keeps strict quality inspection throughout the manufacturing process [23]. This tactical choice also positions JinkoSolar to reach 70GW of solar module production capacity at the end of the year, showing dramatic growth in their production horizon [24].

4.5. LONGi Green Energy's Intelligent Manufacturing

LONGi Green Energy has seen breakthrough improvements in wafer manufacturing through its AI-powered Lighthouse Factory that has subsequently resulted in a 43% quality enhancement and 84% lower cost of production [25]. The company is also striving to further extend its agile smart manufacturing capabilities internationally through projects such as the "Lighthouse Project" [26, 27]. These optimizations confirm the value of AI and automation to increase manufacturing productivity and quality in the solar energy industry, as shown by the recent improvements at its Jiaxing plant [28].

These are just some of the examples where automation becomes a key enabler to make solar energy more scalable, efficient, and affordable—factors that are key to net-zero carbon emissions by 2050.

5. Experiments: How Companies Have Used Computational Methods to Improve Solar Power Systems

Calculation tools such as FEA and CFD are being used by a few companies for optimizing solar-power solutions to reach objectives such as net zero emissions by 2050. Here are five of them:

5.1. Flatworld Solutions

Flatworld Solutions leveraged FEA to perform a comprehensive solar energy assessment for a leading US renewable energy player. This aided in the optimization of design and made solar systems cost-effective and perform in line with sustainability initiatives [29].

5.2. Hynes Solar Solutions

Hynes Solar Solutions used FEA to review and enhance current solar energy systems and designs. In this way, they could optimize system performance and efficiency to support renewables integration and carbon emissions reduction to reach net zero goals [30].

5.3. Tessolar

Tessolar took advantage of Ansys' FEA services to quickly identify design possibilities for its structural composite solar panel mount. Evaluations enabled tuning to enhance the stability and efficiency of the solar system directly assisting in improving the reliability of solar energy systems within the framework of wider renewable-energy portfolios [31].

5.4. Loring Engineers

Loring Engineers has applied CFD to energy-efficient building systems, such as HVAC systems affected by solar power. Their simulations enable engineers to create systems that will be optimally efficient and sustainable—crucial to achieving net zero emissions by optimizing the use of energy in commercial buildings [32].

5.5. Hexagon

Hexagon used CFD to create a tracking device that optimized the placement of solar panels. This technology yielded a massive 20% efficiency gain that allowed for increased solar output and assisted in the overall completion of the process of renewable energy development required to be net zero at mid-century [33].

These are the examples of efficient use of high-performance computation to improve the functionality, efficiency and sustainability of solar energy infrastructure in line with the overall goal of net zero emissions by 2050.

6. Bibliographic Analysis of Automated and Computational Methods for Enhancing Solar Power Systems

The number of articles reviewed from the publications (2015-2024) on automation and computational techniques enhancing solar energy systems, are shown in Figure 1 below:

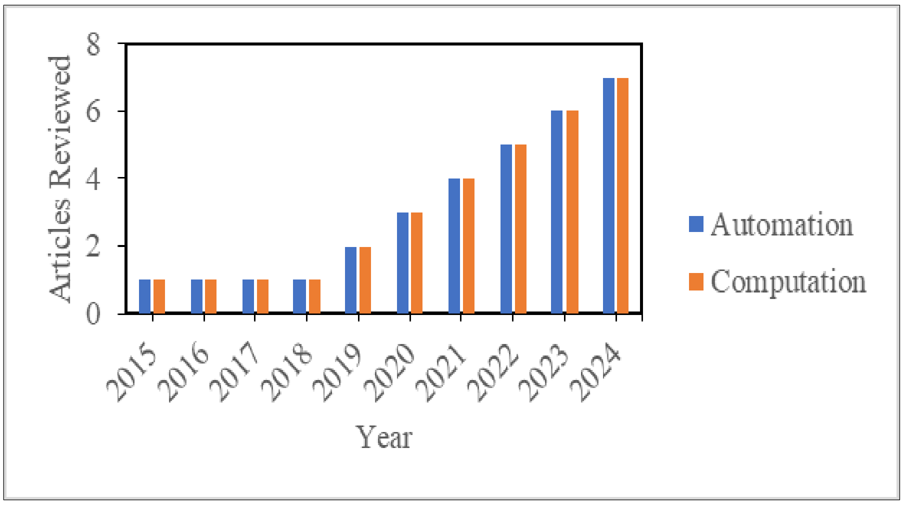

Figure 1 Articles examined for automation and computational techniques enhancing solar energy systems published from 2015-2024

6.1. Innovations and Trends in Automation for Solar Energy Optimization

Table 1 shows the quantitative distribution of the number of reviewed articles published on the automation of solar energy systems and their respective publishers. This information shows the work of multiple publishers and the extent to which automation approaches were used in the literature.

Table 1 Number of articles from different publishers reviewed for automation techniques enhancing solar energy systems

Publisher	Number of articles reviewed
IOP Conference Series	5
IEEE	4
Wiley	4
MDPI	3
AIP Publishing	1
Annual Reviews	1
Bio-Byword Scientific Publishing	1
Cornell University	1
David Publishing	1
E3S Web of Conferences	1
EAI	1
Frontiers	1
IET Power Electronics	1
IGI Global Publishing	1
IIETA	1
IntechOpen	1
JES	1
South Valley University	1
Springer	1
Total	31

Strasser et al. (2015) explored Distributed Energy Resources (DER) enabling trends for smart energy systems using control algorithms, Information and Communication Technology (ICT) and self-healing solutions to improve energy consumption and micro-grid operation [34]. Gopalakrishnan and Biswal (2016) elaborated on communication trends pointing out the Internet of Things (IoT) and Software Defined Networks (SDN) being used to automate microgrids and enhance their efficiency and communication [35]. Potekhin et al. (2017) developed smart control algorithms based on adaptive heuristics and reinforcement learning to deliver an efficient decentralized energy supply with a focus on achieving energy efficiency using data-based decisions [36]. Chen et al. (2018) invented an automatic solar tracking system utilizing brushless DC motors and servo actuators to make PV systems accurate and efficient [37]. In the study, Zhiyong et al. (2019) tested PV thermal storage systems using phase change materials (PCM) and demonstrated increased heat transfer efficiency as well as automatic response to changing solar radiation [38].

Cotfas et al. (2019) analyzed solar PV system improvements by combining sun-tracking with cooling to increase energy yield and efficiency, the growth of PV Systems in the world [39]. Priyadarshi et al. (2020) designed a particle swarm optimization (PSO)-based maximum power point tracking (MPPT) algorithm with IoT for real-time tuning which greatly increased power extraction performance compared to the conventional techniques [40]. Muladi et al. (2020) – A new intelligent tracking system combining a thermoelectric generator and Fresnel lens which yielded 66.46% more energy than traditional PV panels [41]. Sivapriyan et al. (2020) described MPPT algorithms and high-efficiency converters, weather dependence and developments in PV array architecture [42]. Haiqin (2021) designed an automated PLC-driven test solution for domestic solar water heating to reduce manual handling and increase the data accuracy of data while meeting energy-efficiency norms [43].

Kiseleva et al. (2021) researched how PV panels could be used for water heating—especially in Russian climates using MPPT for higher efficiency. They evaluated control systems, pitted PV panels against solar collectors, and found that MPPT was better than constant load discharge systems at harnessing energy [44]. Also, Pravalika et al. (2021) enhanced asynchronous motor drives for PVs using a modified incremental conductance-based MPPT controller. They reported impressive efficiency gains, with space vector modulation methods to minimize output noise [45]. Brahmi et al. (2021) also worked with MPPT and used hysteresis controllers to maximize PV system output in different conditions; simulations and live testing proved the controllers robust [46]. Starzynski et al. (2022) used unmanned aerial vehicles (UAVs), thermal imaging and deep learning to automate PV plant inspections, focusing on cost-efficiency and reliability through frequent real-time testing [47]. Muller et al. (2022) improved the soiling loss detection algorithm to give a better cleaning event identification on PV systems [48].

Nkechi and Yasunori (2022) employed machine learning algorithms to predict solar energy performance, to overcome intermittency and grid instability. They showed that AI could be used for maximizing energy management through prediction accuracy (data quality was a constraint) [49]. So too did Prasad et al. (2022) use machine learning optimization algorithms to enhance PV efficiency. They improved the energy performance and efficiency of their Linear Fresnel Reflector design, highlighting the importance of AI for optimizing the solar power system [50]. Pavithra et al. (2022) were dedicated to automating solar charging stations with safety sensors and RFID for convenient payments. Their work showed us how automation could be put to work in the renewable energy infrastructure to meet the need for electric vehicle (EV) charging [51]. Celsi (2023) posed an even more broad-based approach by examining AI and applied control techniques for energy management, specifically EV charging and predictive maintenance. His work highlighted the critical role of AI-based predictive analytics in the security and reliability of systems [52]. Alaerjan (2023) played a role in improving the communication of renewable power systems, using AI for beam-attachment detection in MIMO networks for achieving greater connectivity and system reliability on solar panels [53].

Abdelsattar et al. (2023) focused on standard and supercharged MPPT algorithms, and showed that intelligent methods such as fuzzy logic and artificial neural networks (ANN) beat traditional approaches in tracking accuracy and speed, although they were more complex [54]. Camacho et al. (2023) reviewed parabolic trough collector (PTC) solar plants' control systems with novel techniques, including portable sensors and predictive control algorithms, to generate more power and improve safety, while fault detection boosted the overall stability of operation [55]. Weici and Abderaouf (2023) also stressed that ANN is preferable to the perturb-and-observe (P&O) method of MPTT for changing climate conditions, further illustrating AI's importance in optimizing energy extraction [56]. Sahoo et al. (2023) presented the progress of renewable energy automation and highlighted how machine learning algorithms and real-time monitoring can help make energy prediction and grid administration more efficient [57]. Venkatesan et al. (2024) combined machine learning and IoT for predictive maintenance, energy forecasting, and fault diagnosis to improve efficiency in energy conversion and predictive maintenance performance [58].

Zhang et al. (2024) discussed solar streetlights, with smart controls that enhanced energy conversion performance and automated control [59]. Tundwal and Dave (2024) studied optimizations using mathematical programming, evolutionary algorithms, and machine learning, which increased the performance and profitability of solar energy plants [60]. Abdelaziz et al. (2024) focused on saving money by developing better materials and power electronics circuits that enhance the overall efficiency of PV systems [61]. Praveen and Menaka (2024) utilized a PID controller and an Oppositional-based Chimp Optimization Algorithm to reduce tracking error and power consumption and improve the efficiency of solar energy generation [62]. Boura et al. (2024) used machine learning algorithms to forecast solar thermal generation that reduced the need for secondary heat, enhancing renewable energy efficiency [63]. Finally, Oyedapo et al. (2024) discussed AI-integrated systems for Africa with predictive maintenance, energy prediction, and smart grid integration to use solar energy efficiently in an environmentally responsible manner [64].

6.2. Innovations in Computational Methods such as FEA and CFD to Improve Solar Energy Systems: Material Efficiency, Thermal Management, Design Optimization

Table 2 presents the number of articles reviewed for computational methods in solar energy systems, and their respective publishers. The distribution of papers shows that research publications come from many places in this area.

Table 2 Number of articles from different publishers reviewed for computational techniques enhancing solar energy systems

Publisher	Number of articles reviewed
IOP Conference Series	9
Elsevier	7
MDPI	5
Wiley	3
AIP Publishing	1
ASME	1
IEEE	1
IJAME	1
iJRASET	1
Sage Journals	1
Springer	1
Total	31

Arena et al. (2015) were geared towards thermal energy storage (TES) optimization via PCM, with CFD simulations to assess various geometrical arrangements of heat exchangers. Their findings showed that triplex designs yielded excellent thermal responses both at melting and solidification, which highlighted the significance of natural convection in optimizing TES performance [65]. Roldán and Fernández-Reche (2016) used supercritical CO_2 as a heat transfer fluid in solar tower receivers and observed it delivered 75% more heat gain than molten salts in a comparable situation. However, they experienced problems with generating consistent thermal profiles that needed design tweaks for application [66]. Montelpare et al. (2017) addressed the Solar Chimney Power Plant (SCPP) design to improve geometric parameters for higher energy conversion. Their work indicated that changes to flow mechanics might even help overcome the low global energy conversion coefficient that can be observed in such systems, thus emphasizing the importance of detailed design to reduce energy loss [67]. When it comes to crop drying, Reddy et al. (2018) teamed a waste heat recovery with a solar crop dryer, and showed that an exhaust heat exchanger provided a significant increase in temperature and thermal efficiency. Their CFD modeling illuminated the mechanics of airflow, demonstrating the advantages of a combination of solar and waste heat harvesting for better crop yields [68]. Raj et al. (2019) conducted a CFD study of macro-encapsulated latent heat storage in solar heating and observed that, by including conduction and convection into their calculation, more than 70% PCM melting was achieved, dramatically improving the efficiency of heat transfer [69].

Ahadi et al. (2019), they used a CFD model of alumina nanofluids for microchannel solar collectors, finding that an ideal nanoparticle size of 2% was significantly better at producing heat than other fluids. The authors mentioned the significance of system geometry where increasing the inclination angle decreases the heat removal capacity [70]. Additionally, Pawar and Sobhansarbandi (2020) investigated the use of PCMs for heat pipe evacuated tube solar collectors (HPETCs), showing that a PCM with 72°C melting point enhanced thermal energy storage performance, with a deviation from experimental measurements of only 2.04% [71]. Hussein et al. (2020) investigated the potential of FEA-based use of truncated cone nanowires in solar cells to optimize light trapping with 15.36% efficiency of power conversion [72]. Da Silva et al.'s (2020) study on plasmonic nanoantennas in organic solar cells found multiple nanoantenna configurations improved light absorption over a wide range of incidence angles, improving the performance parameters [73]. Sacithra et al. (2021) investigated a photovoltaic thermal (PVT) device on a TiO_2-MWCNT hybrid nanofluid with the highest thermal and electrical efficiency of 52.8% and 8.6%, respectively, showing the superior thermal properties of nanofluids over traditional working fluids [74].

Rajamurugu's article (21214) studied a divergent solar chimney pilot plant, performing experiments that showed the higher the collector opening height, the better airflow rates were, and the greater the energy savings. This experimental experiment was followed up with computational analysis on ANSYS Fluent, highlighting the importance of collector geometry to the solar chimney's efficiency [75]. By contrast, Gaur et al. (2021) had developed a new stress-based formula for FEA that successfully solved nonlinear stress responses, omitting elastic moduli, and enabling a better understanding of material behavior under various loadings (most relevant for solar cells). Their case studies of uniaxial bars and beams exposed to pure bending supported the effectiveness of their approach to characterizing structural integrity [76]. In the CFD model for PVT modules developed by Strebkov and Filippchenkova (2021), they have demonstrated that effective coolant flow and optimal distribution of temperature can lead to better solar cell performance and thermal management; their model achieved an accuracy of 1% against experimental data [77]. Hamad et al.'s (2022) study further enhanced the thermal efficiency of PVT systems with CFD calculations and found the 61% thermal efficiency of the system with predefined mass flow rates and hence improved efficiency with a high level of solar radiation in Iraq [78]. Chávez-Bermdez et al. (2022) investigated a U-shape double-pass solar air collector using CFD to compare the effect of novel materials and flow patterns on heat transfer and thermal efficiency, showing instantaneous efficiencies greater than 75% and the efficiency of the double-pass configuration [79].

Budiman et al. (2022) studied the impact behavior of 3D helicoidally designed polymer composites, which were much more impact-resistant than standard encapsulant compounds, and so could safeguard silicon solar cells against degeneration in the harsh environment [80]. Ibrahim et al. (2022) focused on the cooling performance of solar PV modules and conducted CFD simulations to prove that dimpled triangle fins were effective at reducing PV cell temperatures by an efficiency of 6 percent in comparison to traditional designs, prolonging module life [81]. Hobiny and Abbas (2022) used FEA to simulate nonlinear stresses in semiconductors at the same temperature (with different thermal conductivity), and it showed how temperature and displacement act upon silicon solar cells in terms of heating and cooling [82]. Dilipsharma et al. (2023) studied the ducting of solar air heaters with synthetically textured surfaces via CFD and discovered that arc-shaped geometry improved heat transfer, with an enhanced ratio maximum being 1.52, optimizing the design parameters for energy savings [83]. Ramlee et al. (2023) investigated the thermal behavior of 2-phase closed thermosyphons, by using transient CFD simulations and reported that the angle of inclination and initial volume filling ratio played the main role in determining the thermal efficiency of the solar system [84].

Berville et al. (2023) examined the use of PCM spheres in thermal energy storage, establishing that hexagonal structures of these spheres reduced heat transfer by as much as 12.3% over conventional systems, solving thermal storage problems in non-sunny climates [85]. Seo et al. (2023) studied the implantation of metallic nanospheres in lead-free $Cs_2AgBiBr_6$ perovskites solar cells by the finite-difference time-domain (FDTD) method and discovered that the addition of gold and palladium nanospheres enhanced short-circuit current density by 1.6 and 1.8 times, respectively, which boosted light harvesting [86]. Suja et al. (2023) used CFD to model swirling nanofluid jets for High Concentrator Solar Cells (HCSC) thermal control, which demonstrated the jets would lower the cell temperature to 71 °C and yield an electrical efficiency gain of 39.43% through proper cooling techniques [87]. Weinberg (2023) proposed data-driven finite element calculation of microstructured materials, which resulted in highly detailed stress response calculations independent of models and thus enhanced our insights into material behavior in solar energy systems [88]. Sabri et al. (2024) devised a finite element algorithm for calculating the nonlinear viscoelasticity of material, which gave a value of about 1% less error than experimental measurements, useful for calculating the efficiency of solar cells under different stress conditions [89].

In the paper "*Optimized Design of Heliostat Field Efficiency Based on Finite Element Analysis Method*," by Li et al. FEA developed an optical efficiency model, which was successful in heliostat designs and increased energy capture by rigorous analysis of optical properties and shadow shading effects [90]. Cabrera-Escobar et al. also used FEA to develop heat-dissipating fins for monocrystalline PV panels, which decreased operating temperatures by 2.64 K, resulting in 1.32% higher efficiency [91]. Duan et al. developed a finite element model to optimize femtosecond laser scribing on silicon heterojunction solar cells, which was very important in reducing cell-separation losses and maximizing module performance [92]. Biswas and Tripathy parametrically calculated multiple solar collector designs using FEA and found that the cross-flow design produced maximum efficiency (76.16%) while maintaining minimal drops in pressure, indicating that design configurations were crucial for heat transfer efficiency [93]. Kouame et al. analyzed concentrator PV module thermal properties using FEM, discovered parameters that influence heat loss, and confirmed that a correct design could keep cell temperature under 80 °C, optimizing the lifespan and efficiency [94]. Last of all, Chen et al. performed hydroelastic analysis using the Discrete Module Finite Element method for floating offshore solar PV systems, which gave us a structural performance in dynamic wave state and validated the model against existing techniques [95].

7. Conclusion

The paper emphasizes the importance of computational and automation approaches for optimizing solar energy systems to achieve net-zero greenhouse gas emissions by 2050. Combining data analytics with machine learning is critical to optimize operations and performance indicators of solar energy systems to be an effective combatant of climate change. Computational techniques allow solar power systems to be efficient and reliable. This is fundamental to meeting the growing effects of global warming and the need for real climate change mitigation. All of these approaches not only increase energy generation but are more compatible with current energy grids as they overcome issues such as energy storage and load balancing. Simulation analyses can help policymakers understand the impact that renewable energy policies may have. This information is key for drafting legislation and regulations that encourage solar energy deployment and facilitate an achievable and sustainable transition to net-zero emissions. The paper stresses that more research and development in computation and automation will be needed to further advance the solar power technology. This constant development is fundamental for meeting the high objectives set for carbon neutrality and for sustainability in the energy sector. In short, the application of computational and automation algorithms to solar PV technology represents not only a way to improve its efficiency but also a major ingredient in achieving global sustainability targets. It also calls for an integrated stakeholder action to harness these technologies for the sustainable development goal.

Future Scope

This article outlines some promising future research and development projects on solar energy systems, particularly in the areas of computational and automation strategies. The most important research targets include:

- *Higher Level Computational Models*: More complex computer models capable of describing complicated dynamics in solar energy systems will have a lot of potential. These include improving FEA and CFD methods to make more accurate predictions under diverse environments and operational conditions.
- *Integration of New Technologies*: Future research may explore how to incorporate new technologies such as AI and machine learning into solar panels. Such technologies can streamline energy management, maintenance predictions, and real-time alerts, providing improved performance and cost reduction.
- *Environmental Concerns*: It is imperative to research environmentally friendly manufacturing methods and components for the panels. Next research might include lifecycle modeling of solar systems, which looks at the environmental effects of the solar systems from manufacturing to disposal, and how to minimize waste and make them more recyclable.
- *Policy and Economics*: Comprehensive studies are required to assess the economic benefits of switching to cutting-edge solar technologies. In the future, research will shed light on the cost-benefit of scale implementation of these technologies, so policymakers and stakeholders can learn how solar investment makes sense economically.
- *Field Testing and Validation*: One should conduct a lot of field tests to validate the model in terms of computations and theoretical results. This work must continue to be grounded in application studies of the proposed technologies to validate their utility and reliability in diverse environments.
- *Interdisciplinarity*: Supporting interdisciplinary teams of engineers, environmental scientists, and policymakers will lead to creative answers to the solar deployment puzzle. Future programs should likewise look for platforms for exchange and collective research.

To conclude, the future direction of the paper points to an imperative to innovate and cooperate in the field of solar power systems for years to come. Focusing on these areas ensure stakeholders continue toward meeting the elusive net-zero emissions goal by 2050 and further advance the sustainability and efficiency of solar solutions.

Compliance with ethical standards

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