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Original Article

A Review on Enhancement of Solar Cell Efficiency and Transmission Capability Using Nanotechnology With IOT

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Abstract: *The fast increasing worldwide use of solar photovoltaic (PV) technology is encountering challenges in maintaining high efficiency, particularly due to issues such as dust accumulation and surface soiling. This review delves into the potential of combining nanotechnology with the Internet of Things (IoT) to enhance the efficiency and transmission capacity of solar cells.*

By minimizing dust deposition and improving the optical characteristics of solar panels, self-cleaning coatings that incorporate nanocomposites like TiO2, SiO2, and ZnO have demonstrated considerable gains in transmission rates and power production. Additionally, real-time PV system monitoring and optimization technologies based on the Internet of Things are featured, allowing for more effective energy management and performance diagnostics. A promising strategy to overcome the operational and environmental issues of solar power generation is the integration of nanotechnology and the Internet of Things, which will ultimately aid in the global shift to sustainable energy.

Keywords: *Solar Photovoltaic, Nanotechnology, IoT, Efficiency, Transmission, Self-Cleaning Coatings, Dust Accumulation, Energy Management.*

I. INTRODUCTION

Solar photovoltaic (PV) power may one day produce more power than all other renewable energy sources combined, according to studies [1]. As a result of dirt and grime, solar PV systems diminish in efficiency. Therefore, it is necessary to implement a mitigation strategy in order to foster the development of green electricity. Separately or in conjunction with the grid, solar PV technology can produce electricity. The worldwide utilization rate of PV technology has jumped from 483 GW to 580 GW, a 21% increase, according to [2]. Firstly, this is because of the high usage rates seen in Asia, and then in Europe. Current technology shows conversion efficiency of less than 25%, even if PV technology utilization rates have been higher. This highlights the importance of identifying both the technology's potential performance boosters and its potential performance stumbling blocks.

Several factors were highlighted in [3] as potential performance killers for solar PV. The PV system's ability to produce energy can be compromised when a number of environmental factors, including as humidity, precipitation, storms, and dust, combine to create distinct forms of soiling. In view of the fact that dust aggregation and accumulation diminish spectral absorption and, by extension, PV system power generation, the importance of studying cleaning strategies was emphasized in [4]. A drop of 3% to 50% in power outputs is possible in this scenario.

Humidity, temperature, and precipitation might cause the declared range to shift. As with weather, dust particle size can affect the efficiency range of the final product. Thus, a self-cleaning technology with a potentially hydrophobic nanocoating surface is one of the new cleaning solutions being investigated. Based on the definition given in [5], nanocomposites are materials that consist of two or more components. They were investigated in the context of nanotechnology. Additionally, the material must have a range of dimensions from around 1 nm to 100 nm tall. Nanocomposites have another use as nanocoatings; these coatings can be put on the material of choice in order to get the desired surface performance. When it comes to creating nanocomposites for UV protection applications, some examples of nano oxides include SiO2, TiO2, and ZnO. Nano oxides have dual purposes: protecting from ultraviolet light and actually cleaning themselves. According to [6], there are many more promising applications of nanotechnology in the solar energy industry than are presently being considered. As dust settles within solar PV systems, they lose some of the power they produce. Nanotechnology could be the key to this problem. By covering solar glass with nanoparticles, transmission rates can be greatly enhanced, leading to an efficiency boost of up to 96%. These coatings considerably boost output power, which is the same as a 10% relative efficiency boost, by reducing reflectance across a wide spectral spectrum.

Additionally, these coatings prevent dust from settling inside the panels and are quickly washed away by rain, which has a direct effect on their efficiency. Nanocoating photovoltaic panels has two main benefits [7]. For areas that get a lot of rain, a hydrophobic nanocoating is a lifesaver. Coatings of this kind remove water instantly and makes surfaces self-cleaning. With this attribute, surfaces are easily cleaned by falling rains or are easily cleaned by spraying water. Self-cleaning surfaces are beneficial because dirt surfaces reduce efficiency and power output. Self-cleaning surfaces reduces power output, and thus will need to be hand cleaned even in hotter, dryer, self-cleaning surfaces will require hand cleaning to get optimal power output. The impact of nanocoating to efficiency of PV panel was studied in [8]. After 40 days of outdoor exposure, primary PV panels with 11 nm silica nanoparticles in the dust was 10 g/m2 and other nanocoating PV panels had 4.30 g/m2. The hydrophobic nanocoating diminishes the electricity production in photovoltaic (PV) panels as described in [9].

The PV panels that were covered with nanofluids showed less dust deposition. Compared to PV panels without nanocoating, their performance was 11% better on average. During dust storms and nighttime, another study looked at what happened when PV panels were covered with motorized curtains. Further investigation into the potential of hydrophobic coatings to lessen dust buildup on PV panel surfaces was also conducted. In both instances, reducing the impact of soiling enhanced the efficiency of PV systems. Our solar PV panels were already very efficient before we added the SurfaShield G nanomaterial, which is primarily titanium dioxide, to the mix. The extreme weather of Jordan's Levant region was the setting for three months of indoor and outdoor trials. Results showed that nanocoating increased efficiency by 2.3% and power by 20%. The nanomaterial SurfaShield G outperformed SiO_2 by a margin of 0.3 percent. After dust has accumulated, the efficiency of SiO_2 nanoparticles decreases by 0.4% and that of SurfaShield G nanomaterials by 0.2%. They discussed how a nanocomposite coating of TiO_2, ZnO, and CNT can improve solar PV efficiency in [10]. An antireflection nanocomposite material that included carbon nano tubes (CNTs) increased efficiency by 31.25 percent. When exposed to more sunlight, the coated PV panels performed better in terms of transmittance performance, leading to greater efficiency. According to estimates, a 12.5 MW solar power plant might save about USD 100,000 per year due to nanocoating, which improves performance.

II. LITERATURE REVIEW

Traditional power plants use fossil fuels, which are a major contributor to global warming and the most polluting energy source in the world. Forests, aquatic life, buildings, and insects are all negatively impacted by acid rain, which is a byproduct of burning fossil fuels [11]. A myriad of intricate issues are associated with fossil fuels, of which this is just one. Carbon dioxide emissions from burning coal are around one metric ton per metric ton of coal. The release of this hazardous and toxic carbon dioxide into the atmosphere is a major contributor to climate change, the greenhouse effect, ozone depletion, and severe weather events.

Many believe that the Sun is the most important and fundamental power plant in the universe. Using photovoltaic cells, one may harness the Sun's enormous radiation output, which it releases at a rate of many megawatts per second [12]. The fundamental component of solar cells is silicon, a semiconductor. The semiconductor band gap specifies the material spectra used in photovoltaic cells, which allow for the effective transfer of solar energy to charge carriers. Solar cells may soak up a lot of light, but only a fraction of it will really produce power. The transition of electrons from the valence band to the conduction band occurs when light interacts with semiconductor materials [13]. The band gap energy provided by falling incident light facilitates this process. The electron would be excited and then vibrate back into its valence band, but if the energy required to close the band gap isn't met, then it wouldn't have any useful effect. Plus, producing more energy than is required to keep the band gap intact would change the material's properties.

An electrical circuit divides the newly formed electron-hole pairs produced when light strikes semiconductor materials, resulting in the generation of electrical current. However, silicon solar cells are extremely expensive and have a very poor efficiency. Solar cells' poor efficiency is mainly caused by a number of factors. Among these issues are insufficient cell performance in reaching the minimum band gap energy, surface reflection (wasteful use of solar energy), auger recombination (electrons and holes recombining), and heat losses (energy excess compared to the band gap). Half of the deterioration in solar cells occurs in the second and third groups [14]. Figure 1 shows that solar cells can experience these two losses, which result in a maximum efficiency of 34% (the "Shockley-Queisser limit"). To improve efficiency beyond the "Shockley-Queisser limit" and to lower prices, nanotechnology and nanomaterials are increasingly being used to improve solar cells.

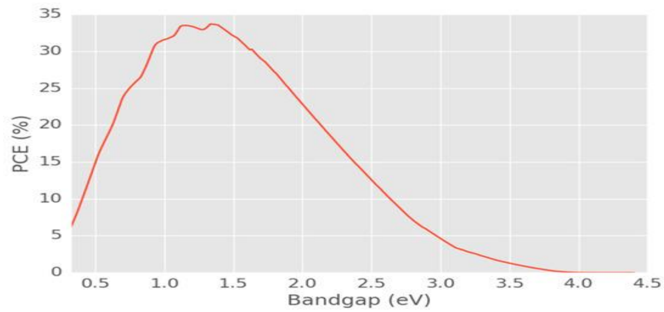

Figure 1 : Shockley-Queisser limit at 1.2 eV which is 33.7%.

Modern technology, known as nanotechnology, operates on a size of the nanoscale. The spatial structure demonstrates that materials can be utilized for several functions even at the level of a billionth of a meter, which expands the application reach of numerous technologies, particularly solar cells. When it comes to nanomaterials, in particular, the surface particles known as nanopowders can change the electrical characteristics, thermal conductivity, melting points, and temperature of the underlying materials in comparison to the bigger components of the same particles. On the nanoscale scale, material surfaces and structures interact with one another and bigger surfaces and spatial structures. It is possible to make surfaces more reflective and translucent by using new phenomena created by certain structures in nanomaterials, such as scattering (diffraction) [15]. Figure 2 shows that many energy losses occur as a result of the material's interactions at the nanoscale.

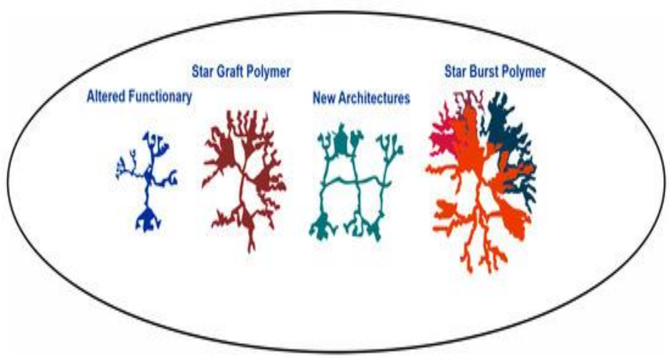

Figure 2 : "Model compound" plus HBP-based synthesis.

Researchers began working on nanometer-scale silicon wafers, reducing their bulk to more discrete shapes, to improve solar cells' efficiency. This would allow nanostructures to respond constructively to various light spectra. This was achieved by coating solar cells with nanoparticles that had been dispersed in isopropyl alcohol. Particles clung to cells after alcohol evaporated. The cells showed an efficiency surge of almost 60% in the UV light region for a 1 nm layer, according to the observations. Efficiency increased from 3% in the visible spectrum to 10% overall and from 60% to 68% in the ultraviolet spectrum when the 2.85-nanometer film was used [16].

However, efficiency in the visible region was still lower. In nanostructuring, a wide variety of methods are employed to create both two- and three-dimensional structures. As an example, a method known as laser ablation is employed to create nanostructures on textile materials by means of laser radiation. In laser ablation, precursor materials are vaporized after being exposed to high-power laser irradiation; this process leads to the formation of nanoparticles [17]. Chemical vapor deposition (CVD), biomimetic techniques, nanoreplication, focused electron beams (FEB/FIB), and other approaches are also available. The utilization of concentrated electron beams to deposit the finest nanostructures on materials was a hallmark of FEB, as the name suggests [18]. Chemical vapor deposition results in the production of carbon nanotubes and tiny particles. A thin layer is built up on substrate materials' surfaces through the reaction of material vapors in chemical vapor deposition (CVD) [19].

The use of nanostructures to naturally occurring materials is the basis of biomimetics. Stamping methods are utilized in nanoreplication procedures to create large-area nanostructures [20]. In order to boost the use of nanomaterials in the energy industry and reduce costs, methods and procedures that allow the nanostructuring of things at higher scales are needed [21].

III. INTEGRATION OF NANOMATERIALS IN THERMAL ENERGY STORAGE (TES) SYSTEMS

By adding nanoparticles to PCMs, their thermal behavior is enhanced, resulting in faster melting and solidification rates and a shorter phase change period. By utilizing PCMs in solar collectors, their operational hours can be extended and their thermal stability improved. One of the major problems with PCMs, especially when solidified, is their low thermal conductivity; this resolves that issue, according to [22].

A. Nanomaterials' Types

Nanocarbons, nanometals, and nanometal oxides are the three main types of nanomaterials being used in TES. A family of materials known as nanometals is characterized by the manipulation of metallic particles on the nanoscale, usually with dimensions smaller than 100 nm. Metals' high heat conductivities are common knowledge. When compared to their bulk equivalents, these materials take on new and improved characteristics as a result of their shrinkage. Due to their remarkable optical, thermal, and electrical characteristics, nanometals find immense utility in numerous technological domains. They are defined by a high ratio of surface area to volume. Thanks to its exceptional thermal conductivity value of around 430 W/mK, silver is the metal of choice for electrical and thermal conductivity applications.

After silver, gold and copper have almost identical thermal conductivity ratings, putting them in second and third place, respectively. Silver and gold, on the other hand, are known for their exorbitant prices. But as you can see in [23], copper is a more cost-effective option and outperforms silver and gold in a number of uses. Intriguing nanomaterials also include nanometal oxides, which are made up of metal cations bound with oxygen. The composition, size, and structure of these materials determine the varied qualities they exhibit. Catalysis, environmental cleanup, energy storage, and electronics are just a few of their many useful uses. Nanometal oxides, particularly alumina and copper oxides, have thermal conductivity values between 30 to 40 W/mK, which is rather high. Their large surface areas and high reactivity are beneficial in many reactions.

The use of aluminum oxide (Al_2O_3) nanoparticles in low-temperature TES phase-change materials (PCMs) has been studied to improve their thermal performance [24]. These nanoparticles improve the efficiency of energy storage and release by enhancing the heat transfer within the PCM. The use of nano-titanium dioxide (TiO_2) in low-temperature TES systems has also been investigated [25].

Working as a nucleating agent in PCM subcooling reduction and more orderly phase transitions makes TES more efficient. Improving nano-iron oxide (Fe_2O_3) PCMs in low-temperature TES has also been investigated. Their presence can improve heat transfer and temperature control within the storage medium (see [26, 27]). For low-temperature TES applications, the adaptive characteristics of nano-zinc oxide (ZnO) have also been investigated. As stated by Manoj Kumar P. et al. it can be incorporated in PCMs for temperature gradient control and an overall thermodynamic improvement of the TES system. Low-temperature TES applications have seen investigations of nano-copper oxide (CuO) particles and their potential to increase PCM thermal conductivity.

Improving heat transfer and reducing temperature fluctuations within a system are also beneficial. Low-temperature TES systems have shown promise with the use of the nano-cobalt oxide (Co_3O_4) metal oxide. Incorporating it into PCMs can improve energy storage and lessen the variation in temperature. Carbon-based nanomaterials, which include carbon nanotubes (CNTs), graphene, fullerene, and other materials, offer remarkable dielectric, mechanical and thermal properties. Such features have earned nanomaterials distinctive consideration. Due to unparalleled thermal conductivity ranging from 1000 to 3000 W/m·K, and beyond, carbon nanotubes stand out and have been highly documented and researched for various advanced applications in this area [28]. Graphene, which consists of a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice, also has exceptional properties. In addition to remarkable thermal conductivity (over 3000 W/m·K), it possesses extraordinary mechanical strength and electrical conductivity. Electronics and energy storage are only two of the many sectors that might undergo a radical transformation as a result. Among the many benefits and drawbacks of nanomaterials used in thermal energy storage (TES), nanometals stand out due to their high thermal conductivity and increased heat capacity, which enhance heat transmission inside the storage medium.

The primary drawbacks include the higher price tag and problems with agglomeration, which compromise heat transmission capabilities. Nanometal oxides provide greater stability and oxidation resistance than pure metals. However, manufacturing costs are higher because to reduced thermal conductivity and more complicated synthesis. Some applications may benefit from the excellent heat conductivity and lightweight nature of nanocarbons like graphene and carbon nanotubes. They are also chemically stable, which means they won't react as easily with the storage solution. Research on the improved functionality of carbon nanotube-modified paraffins was conducted in [29]. An improvement in efficiency in charge/discharge regimes was brought about by the remarkable thermal conductivity that these nanotubes exhibited. Incorporating carbon nanotubes also allowed for the creation of strong thermal devices, which showed a large amount of heat transfer by means of regulated thermal contact. The effectiveness of carbon nanotube-enhanced magnetically-controlled heat storage materials was proven in real-world applications like self-rescue systems.

In a major development in harnessing solar energy, materials with thermo-optic switching properties, like paraffin with carbon fillers, have been created. These materials are perfect for thermal energy storage since their optical characteristics can change as a function of temperature [30]. Adding nanomaterials such as graphene and carbon nanotubes to paraffin improves its heat absorption and release properties. Due to their unique attributes including high thermal conductivity and customizable properties, nanocarbons, nanometals, and oxides can serve as a versatile thermal energy storage system component.

As this overview illustrates, solving traditional PCMs problems used in solar collectors leverage nanomaterials. A shared characteristic among them is the ability to manipulate temperature differences and enhance thermal conductivity, resulting in improved energy storage. The quest to design effective and efficient thermal energy storage systems welcomes the contribution of nanocarbons, nanometals, and nanometal oxides to system TES. There unique attributes including high thermal conductivity, tunable properties, and customizable elements highlight the value of these materials. This is indicative of the improved solar collectors' allowance for increased engagement in renewable energy systems.

B. The Use of Nanomaterials

The numerous techniques for improving the transmission of heat within phase-change materials (PCMs) will be detailed through the lens of renewable energy, and thermal energy storage in buildings. Some of the methods under exploration include macro and micro-encapsulation, the addition of metallic fins, the inclusion of materials with extreme thermal conductivity, and the addition of nanoparticles. Several methods, such as those described in the previous paragraph, contribute to improving the heat transmission of the PCM constituents [31]. For example, micro-encapsulation and macro-encapsulation of PCMs are used in stainless steel cylinders or spheres, expanding heat transfer surfaces with metallic fins, and inserting high thermal conductivity materials or nanoparticles, etc.

For the first time in the last decade, PCMs with nanoparticles in thermal energy storage in buildings, as well as in renewable energy, are becoming instrumental. Nanoparticles are designed to advance the heat transfer medium. Research done by [32] analyzed the heat transmission in a ventilation system using paraffin RT30 for building heating and sinusoidal encapsulations. For the paraffin, a 0.04% addition of nano-sized alumina (Al2O3) substantially increased its latent heat storage. Employing alumina nanopowders is the most time-efficient method, as evidenced by a reduction in solidification time of 5.49 percent.

To get even better results, try combining Al2O3 nanoparticles with metallic fins in PCM storages. You'll see a reduction of solidification time of 12 percent and melting time of 6.4%. Research from [33] shows that adding nano-Fe2O3 to a mixture increases its density and viscosity regardless of the mass fraction. An increase in thermal conductivity of 10.04%, 57.14%, 76.19%, and 78.57% was noted at 0.5%, 1%, 2%, and 3% mass fractions of nano-Fe2O3 added to paraffin wax, respectively. Zinc oxide nanoparticles were shown to have no effect on the paraffin's chemical structure, according to the study's findings [34].

Incorporating 2% nano-ZnO particles into the paraffin also boosted its thermal conductivity by up to 41.67% and greatly improved its thermal stability. In reference [35], three different weight percentages of copper oxide (CuO) particles were used in the phase-change material (PCM): 2%, 5%, and 10%. The particles had an average size of 40 nm. In its liquid condition, the composite's thermal conductivity improved by 6%, 6.7%, and 7.8% due to this dispersion. An increase in 5%, 14%, and 30% in the mass fraction of CuO nanoparticles was observed in the dynamic viscosity. After reaching solidification at the maximum flow rate, the heat transfer coefficient increased by approximately 78%.

There has been some research into several materials, but further study is required. Researchers have looked into the possibility of combining nanocarbon with nanococonut shells [36]. The nanococonut shell proved ineffective compared to the nanocarbon, even though it had a more environmentally friendly profile. Developing PCM and nanoparticles with a lower environmental impact is a difficult issue in this field. An organic PCM did manage to solve one of these two problems, but expanded graphite was still employed to enhance the thermal properties of thermal energy storage in [37].

IV. IOT APPLICATIONS IN RENEWABLE ENERGY INTEGRATION AND MANAGEMENT

A. Overview of Renewable Energy Technologies

Technologies for renewable energy sources, such as solar, wind, and biomass power, have come a long way in the past few years. Solar thermal systems and photovoltaic cells absorb heat from the sun and turn it into electricity; this green energy is becoming more popular because of its efficiency and cheap running costs. As the global population rises and non-renewable resources become more scarce, there is an increasing demand for cleaner energy alternatives. An integrated solar combined cycle (ISCC) plant and parabolic trough collectors' model of a solar-aided power producing plant was built inside this framework to investigate the feasibility of hybrid solar technology in Bangladesh.

To evaluate the two models' practicability and possible effects on energy generation and emission reduction, they were run through THERMOFLEX version 31 software simulations [38]. Solar power technology has come a long way, but photovoltaic systems have gotten much better with the addition of the Internet of Things (IoT). In order to track weather conditions and solar power output in real time, a new study details an inexpensive Internet of Things (IoT) system. The continuous data collecting provided by this technology is essential in smart grid applications, enabling better energy management and solar power plant performance optimization. Solar power systems can become more efficient and dependable with the use of IoT technology, which will lead to a greener energy infrastructure. Figure 3 depicts the four primary layers that make up the HRES IoT architecture: power, data capture, communication network, and application [39].

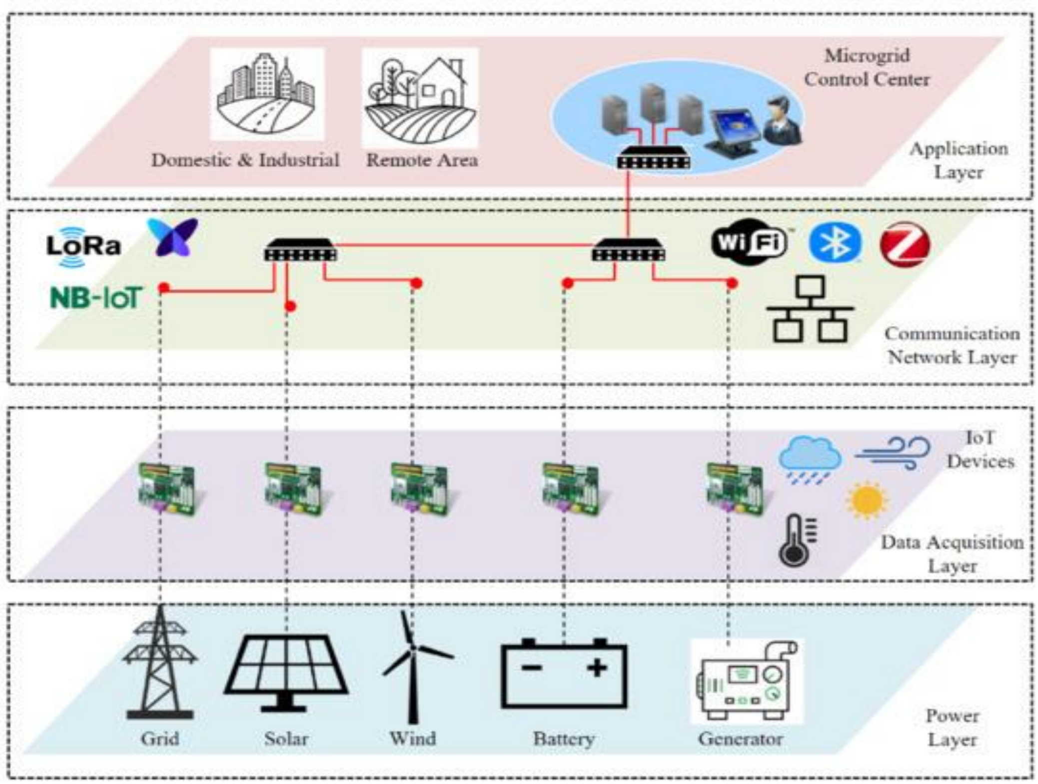

Figure 3 : Intelligent Hybrid Energy System Architecture Based on the Internet of Things.

A possible solution to the issue of inadequate energy supply in smart cities has been suggested by recent research in India: solar photovoltaic (PV) distributed generating systems. An inexpensive energy source, these devices are built to harness solar energy. Some issues with solar PV waste disposal prompted one study's authors to propose the concept of "dumping cost" as a means of dealing with soil contamination caused by old solar panels. The study also detailed a control system that reduces power loss and grid congestion by delivering electricity at a unit power factor. Prototype testing and validation using MATLAB Simulink version 2020 simulations demonstrated the approach's usefulness in optimizing energy supply from solar PV systems [40]. The rotation of wind turbines, a sustainable energy source, can presently efficiently transform even the gentlest breezes into usable electricity, making wind power a viable option.

Recent studies have compared four different manufacturers' 5 kW rated wind turbines using the WERA model to see how well they perform in low-speed wind locations. Research carried out at four locations in Kerala, India, indicated that in low-wind regions, energy production is greatly enhanced by lowering the cut-in and rating wind speeds. To improve system performance and maximize energy absorption in low-wind conditions, turbine velocity power response is critical, as this research shows [41]. Biomass energy has the potential to convert organic materials into biofuels, thermal energy, or electrical power; it is both renewable and versatile. Research in Sailchapra, Bangladesh, investigated the feasibility of an 80 kW biomass power plant on its own, highlighting the significance of biomass energy in solving the rural areas' power outages. An abundant source of biomass fuel, Sailchapra harvests hundreds of tons of rice husk and thousands of tons of straw each season. The area can produce a lot of electricity by gasifying this biomass. By simulating the power plant using HOMER Pro version 3.1.4, the researchers demonstrated that electrifying Sailchapra and improving the local economy was both feasible and desirable [42]. Table 1 shows the growth and utilization of renewable energy in different nations and localities. Solar, wind, and biomass power are just a few of the renewable energy sources highlighted, along with local projects and achievements.

Table 1 : Research, Implementation, and Regional Comparisons of Renewable Energy Sources.

Region/Country	Solar Power	Wind Power	Biomass Energy
Bangladesh [43]	Concentrate on solar thermal power facilities that use hybrid technology	Wind energy has not progressed much since wind speeds are modest.	Establishment of power stations that use biomass fuel in remote regions
India [44]	Solar photovoltaic (PV) generation with a focus on urban distribution	Improving the efficiency of wind turbines in areas with low wind speeds	Reducing agricultural waste while still allowing for some development
Denmark and Germany [45]	The widespread use of solar photovoltaic and solar thermal systems	Pioneer in large-scale energy production using offshore wind technology	Energy plans at the national level incorporate the use of biomass fuels for heating and electricity production.
Sweden [46]	Installing photovoltaic solar panels on homes and businesses	Growth of onshore wind farms is moderate.	Power grids that incorporate biomass energy sources that are well-established
China [47]	Solar thermal plants and large-scale photovoltaic projects	Wind farms, both on land and at sea, are rapidly expanding.	Utilisation of forest and agricultural byproducts, growth of biomass power stations
United States [48]	Among the most prominent solar PV systems, with a wide range of uses in different states	Several offshore projects, large wind farms on land	Several uses, such as biofuels and waste-to-energy plants
Australia [48]	Developing solar thermal plants and substantial investment in solar photovoltaics	Increase in the number of wind farms, promising future for wind power	Waste management, biomass energy from forestry and agricultural byproducts
Singapore [50]	Rooftop solar PV's rapid expansion and the scarcity of land suitable for large-scale solar farms	Due to space and location limitations, wind energy development has been minimal.	Due to space constraints, research into waste-to-energy technologies

B. Role of IoT in Renewable Energy Integration

The grid may find it much easier to incorporate renewable power sources with the assistance of the Internet of Things. Adjustments, monitoring, and real-time data analysis are all made possible with the help of the Internet of Things in renewable energy systems. Devices like the ESP32 controller are essential components of Internet of Things systems that gather data from current and voltage sensors and transmit it to a cloud server. The use of real-time monitoring capabilities makes it possible to control energy loads optimally, reduce greenhouse gases, and make renewable energy systems more efficient. When solar photovoltaic systems are coupled with the Internet of Things (IoT) technologies, the control over the energy produced and the energy distributed improves greatly, resulting in continuous and reliable energy supply. This approach improves the solar powered system automated energy controllers performance and their overall energy management sustainability [51].

The Internet of Things (IoT) is not only being integrated with solar renewable energy systems; it is also being used in the production of renewable hydrogen. Thanks to contemporary industrial IoT advancements, hydrogen generators utilizing Proton Exchange Membrane (PEM) technology can now integrate sophisticated monitoring systems and new data collection techniques. These generators can now use IoT technology to analyze operational systems data, thereby enhancing integrated hydrogen production and renewable energy systems coupled with efficient seamless hydrogen synthesis. IoT systems in hydrogen production also assist fuel production with real-time data analysis that improves energy management, thus described in [52].

The use of the Internet of Things (IoT) in optimizing the use of energy and constructing demand response systems reveals the key role that IoT plays in the integration of renewable energy sources. The system's ability to control energy consuming devices helps reduce peak loads, balances loads, and anticipates needs. Overall, the approach taken increases the power system's efficiency and reduces the energy consumed. The reduction in energy consumed and efficiency of the power system is achieved through the seamless incorporation of renewable energy sources into the grid made possible through the use of IoT technology.

V. AIOT IN PV SYSTEMS: BACKGROUND

Artificial intelligence (AI) is enhancing PV energy tracking, management, and optimization. This part offers a brief overview of AIoT with a discussion on IoT and AI techniques that augment the performance of photovoltaic systems.

A. Artificial Intelligence Techniques

Artificial intelligence (AI) comprises computer systems created to replicate certain cognitive features of humans, such as learning, reasoning, problem-solving, and interpreting language [54]. The concept, however, is broad as it tries to capture computer systems sustaining and surpassing human intelligence in various tasks.

Machine learning (ML) is especially useful in complex situations where traditional approaches do not work or are too complex to apply. It is also highly adaptable to new information and thrives in changing environments. Inproblems with lengthy and complicated rules, ML is the way to go because, unlike conventional approaches, it works well when there is no obvious relationship between the inputs and the outputs.

When trained on massive datasets, deep learning (DL) improves upon machine learning's accuracy in classification and prediction. The necessity for human feature engineers is rendered obsolete by DL algorithms' ability to directly process raw data and automatically extract pertinent features. For complicated issues that conventional ML methods can't handle, DL is the way to go. In situations where data is few, ML algorithms typically prove to be more effective than DL approaches since they require less data. A new subfield of AI, Generative AI (GenAI) has recently generated a great deal of interest. Synthetic data, pictures, music, and text that is nearly indistinguishable from real data is produced by GenAI models, which differ from traditional AI models in that they learn patterns and structures from large datasets [55].

Most importantly, there are no hard and fast guidelines for determining which artificial intelligence method is best suited to a specific task [56]. When making a selection, it is important to think about the problem's characteristics, the data that is at hand, the algorithm's complexity, the implementation challenges, and the required precision and generalizability.

B. Internet of Things

A great benefit to mankind has been the development of the internet, which has allowed for the seamless communication of gadgets and the unlocking of innumerable applications. The "Internet of Things" (IoT) is a new type of network that allows "things" (physical items) to communicate with one another through the web [57]. They are able to gather useful data and provide a plethora of services because of the sensors and communication networks they use. The problem's characteristics, the data at hand, the algorithm's complexity, the logistical challenges of implementation, and the required precision and generalizability are all factors to be considered while making the selection.

After that, you have to pick the right parts, including things like sensors, communication protocols, storage, and computing power. To accomplish its goals, an IoT platform needs to incorporate environmental sensors and appropriate communication technologies [58]. In Figure 4, we can see the parts that make up an Internet of Things platform.

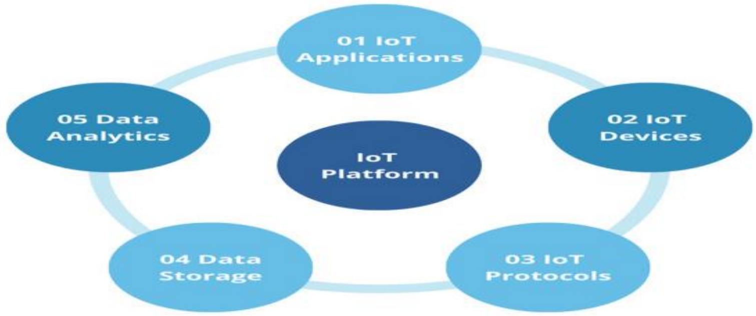

Figure 4 : Flowchart showing the parts of an internet of things platform.

C. Core Technologies Enabling IoT Systems

Internet of Things (IoT) systems are enhancing the efficiency, dependability, and performance of photovoltaic (PV) system administration. Solar irradiance, panel temperature, and energy output can be monitored in real-time through the integration of cutting-edge sensors, actuators, communication technologies, and computational algorithms made possible by the Internet of Things (IoT).

These features enable predictive maintenance, remote monitoring, and quick defect detection, which drastically cut down on operating expenses and downtime. The importance of the Internet of Things in advancing options within renewable energy and ensuring energy generation remains constant is undeniable. Current investigations in this field target the integration of IoT with photovoltaic systems.

Investigations of IoT systems show the use of sensors to collect data in real time and improve the functioning of the system [59]. Photovoltaic (PV) systems utilize sensors to monitor variables like temperature and solar irradiance. This information helps to optimize performance and implements intelligent energy management to reduce energy consumption and cost. While all temperature sensors are crucial, some are assigned to monitor the temperature of the inverters and the PV panels. These sensors are crucial to identify and prevent overheating, enhance cooling processes, and sustain uninterrupted energy output. Excessive heat reduces PV panels efficiency therefore overheating PV panels and inverters need to be avoided.

Other performance detractors are panel environmental conditions. Moisture degradation, electrical leakage, and even panel corrosion is possible under certain humid and/or wet conditions, making the relative humidity and temperature (hygrometric) sensors even more valuable. Light sensors that measure solar irradiance and sunshine intensity are also beneficial in scoring this goal. This information allows solar tracking systems to optimize energy generation by dynamically adjusting panels to varying light conditions [60].

Energized systems to perform power factor correction in PV systems utilize current and voltage sensors to identify energy production and voltage issues. These systems enable monitoring the output power of the panels and inverters. Performance monitoring also includes the detection of dust and debris that accumulates, and even the self-simulation of the control system to respond to decrements in solar irradiance and maximum power point tracking to prevent economic losses.

These sensors gather data that enables regular cleanings, which keeps the panels running at peak efficiency [61]. For the purpose of evaluating the system's efficiency in respect to the expected power output, pyranometer measurements of the world's solar radiation are also essential.

In order to guarantee optimal operation, the system triggers actuators to execute the required mechanical actions once the sensors have collected and analyzed data. Photovoltaic (PV) systems rely on actuators to automate cleaning mechanisms, control switches and inverters remotely, and adjust the solar panels' angles in tracking systems, among other performance optimization activities. When everything is taken into account, this link enhances automation, efficiency, and energy management [62]. When it comes to photovoltaic systems, pneumatic actuators are occasionally employed, particularly in cleaning systems, to provide motion by means of compressed air.

They allow for precise and fast panel maintenance and debris removal. To generate linear or rotary motion, electric actuators, on the other hand, depend on external energy sources like batteries. To enhance energy capture, they are commonly employed in photovoltaic systems to tilt and position solar panels in solar tracking systems. In order to keep panels efficient, automatic cleaning systems rely on electric actuators to remove dust and debris. Low-Power Wide Area Network (LPWAN) technologies are crucial for making long-range, energy-efficient communication possible for Internet of Things (IoT) devices.

When it comes to large-scale or standalone PV installations, these technologies shine for remote monitoring and management. Smart grids and building automation are perfect applications for LoRa, a popular LPWAN technology that provides long-range communication (over 10 km in rural regions) with minimal power consumption. Especially in outlying places, LoRa allows PV systems to regulate and monitor energy consumption across great distances [63]. Particularly in off-grid or faraway places where conventional communication networks do not exist, satellite technologies are vital to PV systems. Due to these innovations, data may be easily transferred between PV systems and control rooms. This paves the way for ongoing monitoring of performance, detection of issues, and preparation for maintenance. Whether it's a massive solar farm or a small, standalone installation, satellite communication allows for accurate monitoring of system efficiency, weather, and energy production. Remote optimization and management of PV systems by operators may reduce operational costs and the need for on-site intervention [64]. Table 2 analyzes multiple wireless communication solutions for PV systems.

Table 2 : Analysis of PV system wireless communication technology.

Technology	Range	Power Consumption	Applications in PV Systems
Wi-Fi	≤100 m	High	Energy production and system performance monitoring and control from a distance. Not optimal for photovoltaic systems.
Bluetooth Low Energy (BLE)	≤30 m	Low	PV systems on a smaller scale for use in smart homes and businesses.
Zigbee	≤100 m	Very Low	The integration of smart grid technology, energy monitoring, and the facilitation of effective communication among PV components.
LoRa (LPWAN)	≤50 km	Very Low	Remote and large-scale photovoltaic system monitoring and energy management.
Satellite Communication	≥1500 km	High	Power conversion devices that operate independently of the grid, allowing for monitoring of system health, diagnosis of problems, and optimization of large-scale solar farms.

VI. CONCLUSION

Solar photovoltaic systems can be made more efficient with the use of nanotechnology, especially nanocoatings, which can reduce the harmful effects of dust and other environmental factors. Improved PV panel performance for long periods of time, particularly in dusty conditions, is possible with the help of hydrophobic and self-cleaning coatings, which keep transmission rates high. Connecting PV systems to the internet of things (IoT) improves their efficiency by allowing predictive maintenance and real-time monitoring, which in turn optimizes energy production and decreases operational downtime. Research into improving the efficiency and cost-effectiveness of nanomaterial characteristics and IoT integration is necessary, notwithstanding the encouraging advances. Future solar energy systems will rely heavily on the interplay between nanotechnology and the Internet of Things (IoT), which will allow for more robust and environmentally friendly renewable power sources.

VII. REFERENCES

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