

Enhancing Solar PV Array Output and Efficiency through IoT- Based Modern Techniques

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Abstract

Solar PV arrays are an essential part of the shift to renewable energy sources because they use semiconductor materials to directly turn sunlight into electricity. By lowering greenhouse gas emissions and promoting energy independence, solar photovoltaic arrays can make a substantial contribution to the world's energy needs. One revolutionary method for increasing the output and efficiency of solar photovoltaic (PV) arrays is the incorporation of Internet of Things (IoT) technologies. This study explores the implementation of IoT-based modern techniques to enhance the performance of solar PV systems. By leveraging real-time data collection and advanced analytics, IoT platforms facilitate precise monitoring and control of PV arrays, enabling dynamic adjustments to maximize energy production. Key innovations include the use of smart sensors for continuous performance assessment, predictive maintenance to minimize aging effect and adaptive algorithms to optimize the angle and orientation of solar panels in response to environmental conditions. Additionally, IoT-enabled energy management system improves the synchronization between energy generation and consumption, ensuring efficient energy storage and distribution. This paper presents a comprehensive analysis of various IoT-based strategies, highlighting their potential to significantly boost solar PV output and efficiency. The usefulness of these methods is illustrated by case studies, which show increases in energy yield, lower operating costs, and a smaller carbon footprint. The results highlight how important IoT is to the development of solar energy technology and open the door to more robust and effective renewable energy systems.

Keyword: Technology, environmental effects, solar PV materials, and renewable energy systems

INTRODUCTION

Though the amount of solar energy that reaches any given point varies depending on a number of circumstances, including geographic location, time of day, season, local weather, and the surrounding landscape, every site on Earth receives a significant amount of sunlight throughout the year. The maximum amount of solar energy a point on Earth's surface can receive occurs when the sun is closer and its rays strike the surface perpendicularly. Different angles at which the sun's rays strike the surface generate variations in solar radiation. The unit of measurement for solar radiation, which is essential for solar photovoltaic (PV) systems, is usually kWh/m². British thermal units per square foot (Btu/ft²) are used to measure solar heating systems. Edmond Becquerel, a French physicist, discovered the photovoltaic conversion principle for the first time in 1839. The fundamental building blocks of all PV systems, solar PV cells are made of photovoltaic materials that use the photoelectric effect to transform sunlight into electrical current. Light absorption, electron transfer within the semiconductor material of the PV cell, doping, band gap, and the PV cell's general structure are some of the variables that affect how efficient solar PV cells are. The PV cell's built-in electric field controls these variables. An incoming photon is absorbed

when its energy surpasses the semiconductor's band gap, which causes electrons in the valence band to become more energetic and migrate into the conduction band. The PV cells' band gap narrows with increasing temperature, which lowers the power output of the panel.

Basic working of solar photovoltaic cell

Solar photovoltaic (PV) cells are amazing gadgets that use the photovoltaic phenomenon to convert sunlight directly into power. Here's how it works: sunlight energises the electrons in a photovoltaic cell, which is often made of semiconductor materials like silicon. The electrons move as a result of this energy boost, producing an electric current. Two separate layers—one with a positive charge and the other with a negative charge—make up a photovoltaic cell. An electric field is created where these layers converge. When sunlight's photons strike the cell, they provide the semiconductor's electrons energy, which causes them to separate from their atoms. Electric current flows as a result of these electrons moving, and this current is recorded as electricity. A solar panel is made up of several PV cells connected together to increase the power output. These cells produce direct current (DC) power, which is subsequently transformed into alternating current (AC) by an inverter so that it may be used in both homes and businesses. In addition to being clean and renewable, solar photovoltaic systems are essential for lowering greenhouse gas emissions and decreasing our dependency on fossil fuels.

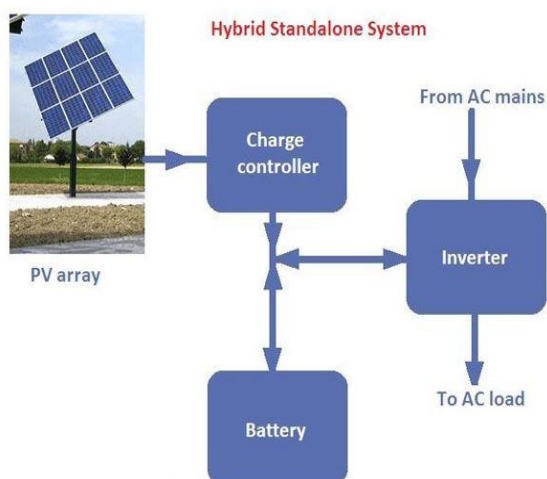


Figure 1: Basic working of Solar PV cell

The efficiency and output of solar panels

One important component that directly affects a solar cell's performance and competitiveness in the market is its efficiency in the renewable energy industry. The ratio of the electrical energy generated by the solar cell to the solar energy it gets from the sun is known as efficiency. Researchers have looked into a variety of technological developments to increase this efficiency, including the creation of novel materials, enhancements to design and manufacturing procedures, and optimisation of the solar cell's energy conversion mechanisms. Solar radiation intensity, also known as irradiance or insolation, is a critical component of solar cell efficiency. The quantity of solar energy per unit area that reaches the solar cell is measured by irradiance, which is influenced by a number of variables, including the sun's position and angle, the atmosphere, and any obstructions or shading that could lessen the amount of sunlight that reaches the cell. In general, the solar cell produces more electricity at increasing irradiance levels. The efficiency of solar panels has significantly increased in recent years, with typical sunlight-to-energy conversion rates increasing from 15% to 20%. Perovskite solar cells, bifacial solar cells, tandem solar cells, and printable solar cells are among the high-efficiency solar panel technologies that can reach efficiencies of about 23%.

Materials used in Photovoltaic Technology

Variations in silicon purity, cost, available space, and efficiency are among the criteria that manufacturers usually prioritise when choosing materials for 90% of the world's photovoltaic (PV) solar cells. The commercial production process must take these factors into account [6].

Monocrystalline Solar Cells Compared to polycrystalline silicon panels' sporadic blue hue, monocrystalline solar cells offer a more uniform look that is more aesthetically pleasing.

Using the Czochralski technique (Figure 2), high-grade cylindrical silicon ingots are sliced on all four sides to make these mono-crystalline cells, which have an efficiency rate of 20–21%. In addition to being more space-efficient than thin-film technology, these panels can produce power outputs that are two to three times higher. Monocrystalline solar panels typically have a 25-year lifespan.

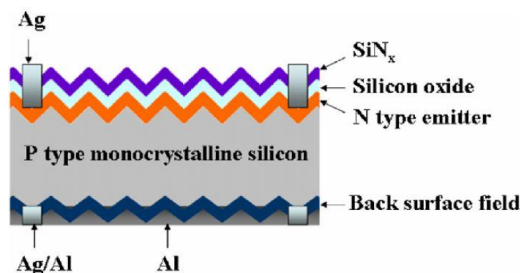


Figure 2: Crystalline silicon solar cell structure

Polycrystalline silicon solar cells Multicrystalline or polycrystalline solar cells are a kind of photovoltaic technology that uses sunlight to create electricity. Polycrystalline cells are made up of several silicon crystals, as opposed to monocrystalline cells, which are formed from a single continuous crystal structure (Figure 3). Polycrystalline cells are less expensive because of this simpler and less expensive production technique. The differently orientated crystals give these cells' surfaces a characteristic speckled look. Despite having a lesser efficiency in converting sunlight into energy than their monocrystalline counterparts, polycrystalline solar cells are still a cost-effective choice for a lot of household and commercial solar installations.

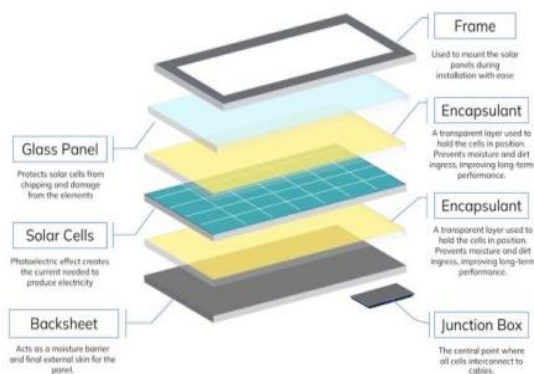


Figure 3: Polycrystalline Silicon Solar Panel Components

Multijunction solar cells Often called tandem solar cells, these advanced photovoltaic devices stack multiple p-n junctions made of various semiconductor materials to increase efficiency. These layers are made especially to absorb specific solar spectrum segments in order to optimise the amount of sunlight that is converted into electrical power. When compared to single-junction solar cells, multijunction solar cells allow for a more efficient utilisation of solar energy because each layer is typically tailored to a certain wavelength range. For instance, the top layer may be made to absorb lower-energy green, yellow

and red light while capturing high-energy blue and ultraviolet light. The thermalisation losses that arise from wasting surplus photon energy as heat are reduced by this layered technique. Because of this, multijunction solar cells have the ability to attain conversion efficiencies that above 40%, a notable improvement over the efficiency of conventional silicon-based solar cells.

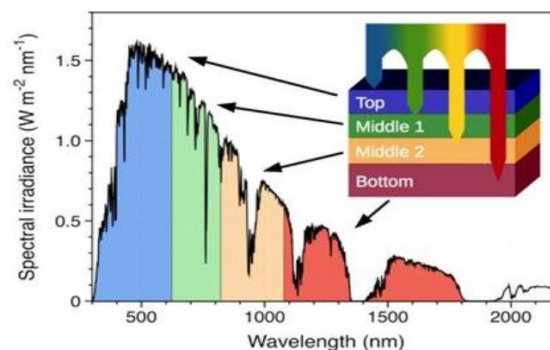


Figure 4: Multijunction Solar Cell

Thin film solar cells Thin film solar cells are a type of photovoltaic technology in which one or more thin layers, or thin films, of photovoltaic material are deposited onto a substrate. These cells are frequently made from materials such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si).

Thin film solar cells are far lighter and more flexible than conventional silicon wafer-based solar cells, opening up a wide range of uses such as incorporation into clothes, portable electronics, and even construction materials like windows and roofing. Because of their easier manufacturing techniques and lower material prices, they are frequently less expensive to make.

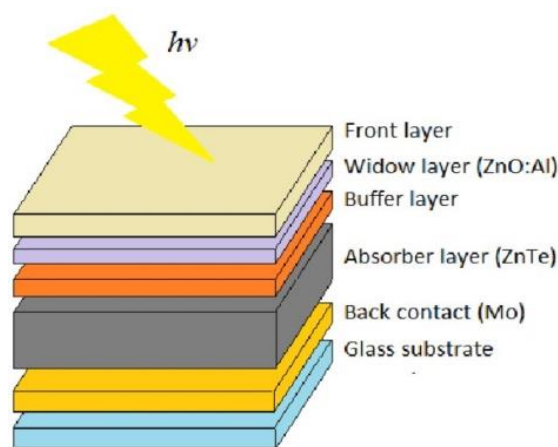


Figure 5: Diagrammatic representation of the layers of a thin-film solar cell

Amorphous silicon solar cells

Amorphous silicon solar cells, a type of thin-film solar technology, use non-crystalline silicon as the photovoltaic material. Since amorphous silicon is coated in a thin layer over a substrate as opposed to typical crystalline silicon solar cells, which are formed from solid silicon wafers, it offers more flexibility and lightweight applications. These cells normally have conversion efficiencies between 6% and 10%, which is less efficient than their crystalline counterparts. They are more environmentally friendly, nevertheless, because they are less costly to make and require less silicon in their manufacturing process. Amorphous silicon solar cells can be incorporated into a range of surfaces, such as consumer goods and building materials, and they also function better in low light. They nevertheless have a big impact on the renewable energy scene even with their decreased efficiency, especially in specialised applications where cost and flexibility are important considerations figure 6.

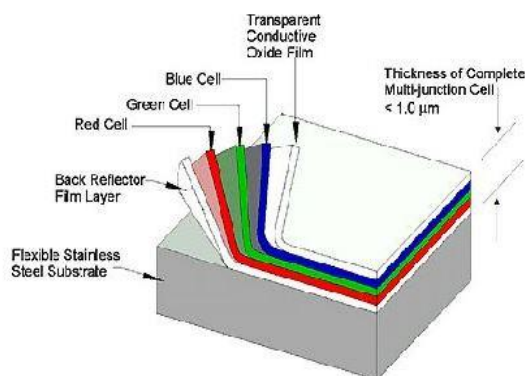


Figure 6: Amorphous silicon solar cells

Cadmium telluride solar cells

Thin-film photovoltaic technology, such as cadmium telluride (CdTe) solar cells, uses sunlight to produce electricity. The compound semiconductor used in the construction of these cells, which is built of tellurium and cadmium, enables effective light absorption and conversion to electrical energy. CdTe solar cells are an appealing alternative for large-scale solar energy applications because of their low production cost when compared to conventional silicon-based solar cells, which is one of their main advantages. Cadmium telluride (CdTe) solar cells have significantly increased in efficiency over time. Currently, efficiency ratings for CdTe solar cells that are sold commercially range from 16% to 18%. Nonetheless, research and development initiatives have increased the efficiency of CdTe cells produced on a lab scale to more

than 22%, demonstrating the cells' potential for greater performance.

Cells using copper, indium gallium, and selenium

Copper indium gallium selenide (CIGS) solar cells, a type of thin-film photovoltaic technology, have garnered interest because of its high efficiency and versatility. These solar cells, which are built of a semiconductor material consisting of copper, indium, gallium, and selenium, can be deposited on a variety of substrates, including flexible materials. This allows for a number of uses in both residential and commercial contexts. With conversion efficiency of over 20%, CIGS solar cells are renowned for their superior solar absorption and efficient energy generation.

Gallium Arsenide

The semiconductor material known as gallium nitride (GaN) has attracted a lot of interest lately because of its special qualities and possible uses. Its broad bandgap, which enables it to function at greater voltages, temperatures, and frequencies than conventional semiconductors like silicon, makes it unique. It is made of gallium and nitrogen. GaN is therefore especially beneficial for applications involving high power and high frequency, such as power converters, LED technologies, and power amplifiers.

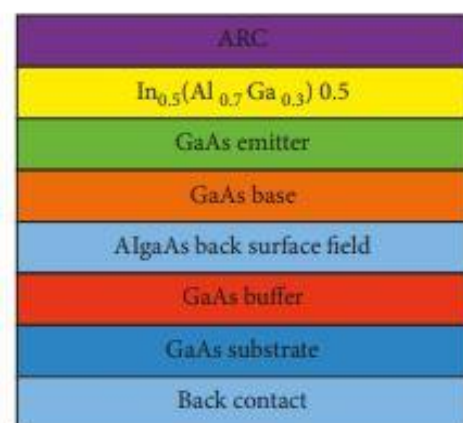


Figure 7: GaA-based PV cells' schematic construction

Gallium Nitride

Emerging technology known as gallium nitride (GaN) solar cells uses the special qualities of this wide-bandgap semiconductor to increase solar energy conversion efficiency. GaN solar cells perform better in high-intensity light settings and can function at higher temperatures than

conventional silicon-based solar cells. A wider range of light may be absorbed by GaN due to its wide bandgap, which makes it possible to convert more sunlight into useful electricity Figure 8.

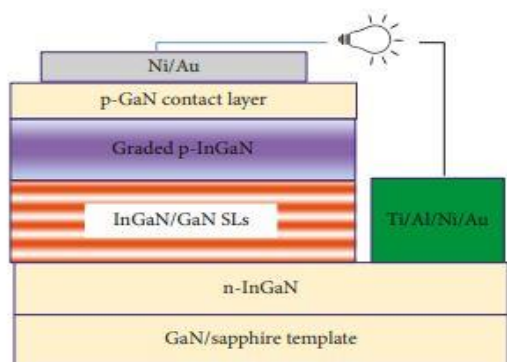


Figure 8: Schematic structure of GaN-based PV cells

Silicon Carbide

Silicon carbide solar cells represent a cutting-edge technology in photovoltaics, harnessing the unique properties of silicon carbide (SiC) to enhance efficiency and durability. SiC's wider bandgap allows for the absorption of a broader spectrum of light, enhancing overall conversion efficiency.

PROBLEMS ASSOCIATED WITH EFFICIENCY OF SOLAR PANEL

A. Solar panel dust particle contamination and its impact on solar radiation

A number of technological and environmental reasons could cause the efficiency of the solar module to decrease. Due to surface shading and reduced solar absorption, the natural pollutants and industrial dust found in almost every region of the world accumulate on the surface of solar modules, lowering their operational efficiency by 25–30%.

The main reason for the loss of solar energy was found to be the buildup of dust on the surface of the solar panels. Compared to regions with relatively clean air, this leads in a 17–25% decrease in the amount of solar radiation that reaches the solar cells. [6] Measurements of the dust settling time and a comparison of the dust layer's thickness and energy efficiency in solar power plants show how important solar panel cleaning is. Cleaning the panels every 20 to 30 days increases energy production by 50% on average. [7] Local and global climates are influenced by aerosols, especially mineral dust. Dust particles, especially those coated with pollutants, serve as efficient ice nuclei

for cold cloud production and condensation nuclei for warm cloud formation. Changes in the microphysical composition of clouds affect their capacity to absorb solar radiation [8], which indirectly affects the quantity of energy that reaches the Earth's surface.

B. The ways in which biological pollutants and precipitation affect solar panel performance

Since it is a completely natural environment, the atmosphere can cleanse itself. Hazardous substances that are emitted into the atmosphere by human activity coat the surface of solar panels. The temperature of the air, solar radiation, precipitation, and other meteorological factors all affect these wind-assisted processes. Pollutant transmission to the upper atmosphere is influenced by the type of temperature distribution in the atmosphere with height.

The degree of temperature difference with height is described by a vertical temperature gradient (0 degrees Celsius) per unit height from the earth's surface, usually 100 meters [9]. It is crucial to differentiate between the primary categories of industrial dust according to their creation methods in order to organise and comprehend the pollution processes impacting solar panels:

Mechanical Dust: This type of dust is generated during the technological process when products are ground or crushed.

- **Sublimates:** These are formed through the volumetric condensation of vapors as they cool after passing through a technological apparatus, installation, or unit.
- **Fly Ash:** The incombustible fuel waste known as fly ash, which is made up of mineral impurities released after combustion, is present in flue gas.
- **Industrial Carbon Black:** This kind of dust, which is made up of widely scattered solid particles, is a byproduct of industrial pollutants.

C. Climate factors that impact solar panel efficiency

Pollutant concentration and mobility in the upper atmosphere are specifically influenced by climatic conditions. Only a small number of the many different climatic elements are currently accessible for quantitative accounting in environmental computations. These consist of the following: humidity, rainfall, surface-atmosphere stratification, wind direction and speed, air temperature, and emissions.[10] Consequently, without precipitating at

the emission locations, small and partially medium-sized dust particles can penetrate the air flows of transboundary regional and possibly global pollution in a dry climate.

On the other hand, these particles are carried away by precipitation in a humid atmosphere and can show up on the surface of the earth close to their points of release.

- **Snow** accumulation on solar panels can hinder their performance by blocking sunlight, reducing their efficiency.
- **Wind**, on the other hand, can be beneficial as it helps cool down the panels, potentially increasing their efficiency as long as sunlight is still reaching them.
- **Rain** itself doesn't directly impact solar panel efficiency, but overcast skies during rainstorms can reduce the amount of sunlight that reaches the panels. However, rain can also be advantageous, as it washes away dirt and dust that might otherwise block sunlight and lower energy production.
- **Hailstorms** pose a different challenge. While solar panels are generally tested to withstand hail, there is still a risk of damage from particularly severe hailstorms.

Dust and Grime Build Up

Over time, dust and grime naturally accumulate on your solar panels, a result of constant exposure to the elements. When a layer of debris forms, it obstructs the sunlight, reducing the panels' efficiency. To maintain optimal performance, it's essential to keep your panels clean and free from such build-up.

METHODS TO IMPROVE THE EFFICIENCY OF SOLAR PANEL

1. Manual Cleaning

With the help of any wipers and suitable support structures, a human operator must manually clean using this method, as shown in Figure 9. Until the dust particles are completely gone or to a sufficient degree, the operator himself evaluates the cleaned surface using a visual method. Because solar power plants need a lot of panels to be positioned at least 12 to 20 feet above the ground, the process is thought to be quite challenging and time-consuming.

The safety of the panel and individuals is at risk, as is the required amount of time. The panels need to be manually cleaned using fluids that operate on the panel

surface, such as cleansers or gels. Cleaning panels by hand necessitates the use of fluids, including cleansers or gels, which interact with the panel and reduce its transparency if not cleaned properly. It is inevitable that the PV panels may sustain physical damage.



Figure 9 Manual cleaning

2. Vacuum Suction Cleaning

A vacuum suction cleaner collects dust and debris, mostly off windows, floors, and other surfaces, by creating a partial vacuum with an air pump. Usually, the electrical power that creates the suction pressure is sent to the Hoover cleaner motor. The power consumption of the Hoover cleaner, expressed in watts, is not consistent with its effectiveness. The input power is converted into airflow and measured in air watts at the end.

As shown in Figure 10, the Hoover can only efficiently clean surfaces other than corners; all other surfaces need to be cleaned by hand. As with the physical movements on the panel, the operator needs to be well trained. Scratches and accumulated dust eventually lead to ineffective solar insolation absorption.



Figure 10 cleaning using vacuum suction

3. Automatic Wiper Based Cleaning

The automatic wiper-based cleaning system uses a water pot and a rubber wiper to clean and spray water with

additives. The process is similar to cleaning a car's windows, and it requires an automated system to function. Figure 11 shows the battery-operated mechanism. Even though this method is similar to earlier ones and is automatically managed by the right mechanism, its outcomes are likewise akin to those of earlier methods.



Figure 11 Automatic cleaner

4. Electrostatic Repulsion

The new method employs electrostatic repulsion to separate and almost jump off dust particles off the panel's surface without the use of water or brushes. A simple electrode is positioned just above the solar panel's surface to start the action. The dust particles are charged as a result, and a charge applied to the panel itself repels them. The mechanism can be operated automatically with a simple electric motor and guide rails along the edge of the display. To move across the screen, the novel gadget they developed only requires an electrode, which might be a simple metal bar.

As the dust moves across the panel, the electrode generates an electric field that charges the particles. An opposing charge is then given to a transparent conductive layer, which is deposited on the glass covering of the solar panel and is only a few nanometres thick, repelling the particles. By calculating the proper voltage range to utilise, the researchers were able to make sure that it was enough to overcome gravity and adhesion forces and cause the dust to rise away [13].

5. Drones with mapping cameras and sensors

Solar panels need to be cleaned, but it can be challenging to do so because they are frequently placed in isolated locations or on top of tall buildings, where they continuously gather dust and other debris. For this reason, a system based on drones is created. It will feature a quadcopter that is kept within a waterproof docking station that is situated close to the problematic solar panels. Two doors on top of the station will swing open at regular intervals, causing the drone to emerge from it onto a

motorised platform. The aircraft will then take off and ascend to the figure 12 on the panel.

The drone will then align itself over each panel using technologies like Lid AR sensors and mapping cameras, spray it with cleaning fluid, and move on to the next one. The aeroplane will return to the docking station and be lowered into it after the cleaning process is finished[14]. Then, if needed, a robotic system will swap out its old battery for a newly charged one and its empty cleaning fluid tank for a full one.



Figure12: Solar Drones

6. Internet of Things (IOT) Based ARDUINO

Internet-based technology to detect any connection or circuit failure problems and continuously monitor the solar panel's parameters. problem will then alert you so that problem can be promptly fixed. The Internet of Things receives the power output from it. Solar power plants need to be continuously monitored in order to generate the maximum amount of power. This helps recover efficient electricity output from power plants, as well as keeping an eye out for issues that affect solar performance, such as weak connections, dust accumulation on panels that reduces output, and malfunctioning solar panels.[15]

In order to facilitate automatic solar power monitoring across the internet from any place, we are deploying an automated Internet of Things (IOT) solar power monitoring system. We monitor the parameters of a 10Watt solar panel using an Arduino-based system [16]. Our method sends the power output to the IOT system via the internet while continuously monitoring the solar panel (fig. 13).

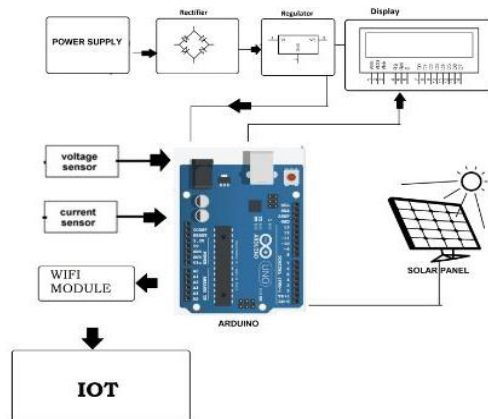


Figure 13: ARDUINO based system

APPLICATIONS OF SOLAR PANEL

1. Generation of Solar Power (Electricity)-

Because solar panels are more affordable and more durable than other energy sources, more people are selecting them for their homes and businesses. Solar energy generates power through photovoltaic cells, which use direct sunlight to generate electricity. The energy generated by the solar power system may cover all or part of the user's monthly expenses.

Extra electricity can be sent to the grid so that users in the area can use it. Off-grid and on-grid solar energy options are available to you. Off-grid solutions only use solar energy and don't need connections or power from the utility company [17]. The system is linked to solar batteries to guarantee backup electricity runs through the night, on cloudy days, and during emergencies.

2. Water Heating

In our homes, workplaces, hotels, and even hospitals, solar energy is commonly used to heat hot water. Homeowners utilise rooftop photovoltaic cells (PV) to capture solar energy and heat water in an insulated water tank [18]. After that, the hot water is kept in the tank for use throughout the house. Solar systems can also be used to heat swimming pools by circulating water through a solar collector and letting it warm up in the sun.

3. Drying of Animal and Agricultural Products

Furthermore, solar energy can be used to dry agricultural and animal products such as fruits, milk, fish, potato chips, and maize grains. Items are kept in a cabinet dryer, which is a box with a transparent sheet at an angle covering it, a black painted inner side, and an insulated bottom foundation. Inside the cabinet, ventilation holes are

punched at the top and bottom to let air flow over the drying material, which is set on perforated trays.

4. Solar Energy Lighting

Because solar energy is easily available, inexpensive, and ecologically benign, it is a good option for road signs, security lights, street lights, and interior lighting. As solar energy doesn't evaporate or lose power as other energy systems do, it's a terrific way to save money on electricity, energy, and lighting for your home or place of business.

5. Solar-Powered Water Pumping for Irrigation

Water can be pumped for summertime irrigation using the solar energy generated by a solar panel system. Crops lose more water through transpiration during the summer, while solar panels generate more solar energy because they receive more sunshine. Solar energy solutions are a great option for irrigation because they are affordable and widely accessible.

6. Solar Energy Water Distillation

Solar energy can significantly help with water distillation, especially in coastal or semi-arid areas with saltwater and abundant sunlight. In these locations, salty water can be converted to pure, drinkable water using sunshine. Through clear glass, heat from the sun is transferred to a shallow, blackened basin that holds salted water. The heat radiation is absorbed and converted to heat in the blackened bay. Heat from the saline evaporates as pure water condenses back into pure form as vapour. After that, the potable water is gathered in basins and transferred to storage tanks. Solar energy has numerous benefits for the environment, your health, finances, and general well-being. Lighting, water distillation, and the drying of crops and livestock can all be accomplished with solar energy. Additionally, it can be utilised to drive air ventilators in your home and water crops during the summer [19]. In addition to being long-lasting and reasonably priced, solar energy systems add more value to your house than any other type of energy system.

CONCLUSION

There is a chance to implement innovative, renewable energy systems in practice as energy is becoming more scarce and energy resources are depleting. With more PV solar-based gadgets becoming available on the market, the utilisation of solar PV systems is looking more and more promising in this regard.

The issue of dust deposition on solar PV panels is taken into consideration, and several cleaning methods are investigated. By increasing the solar panel's efficiency, the Arduino controller facilitates the effective and efficient use of solar energy. Fuel is not needed for solar energy since it instantly transforms UV light into DC electric power. The DC output power is determined by the efficiency of the solar cells that comprise the power extraction mechanism of the solar panel. The main indicator of a solar cell's worth is its efficiency. A few of the main variables that have a significant impact on solar cell efficiency are low solar radiation falling on the cell, a clear sky and visible light threshold frequency, an increase in ambient temperature, the solar panel's shading effect, thicker wires that increase current weight, solar irradiance reflection from the solar cell surface, low inventor efficiency, and batteries used with solar cells. The aforementioned variables are all responsible for the decline in solar cell efficiency. Low efficiency has various heinous effects, such as low power production and extremely high solar cell costs[20]. In the event that the aforementioned factors are resolved, solar energy will become the most reliable and significant power source. The efficiency of the solar system, which depends on all of these factors, can be increased to increase the stability of the power system.

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