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Examination of The Impact of Environmental Factors on Photovoltaic Power

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1. Introduction

Today, photovoltaic (PV) technology is considered at the cutting edge of the new approach to energy needs of the planet. Due to the urgency arising from climate change factors together with an over reliance on non-renewable sources of energy such as fossil fuels many countries are focusing on solar energy as a renewable source of power. The photovoltaic systems, which directly convert sunlight to electricity by the photovoltaic effect is beautiful since it is flexible and may be installed at varying sizes. They are employed for petty facilities on rooftops of houses to huge solar farms used in supplying utility electricity. Smart photovoltaic systems are being adopted globally due to continuous technological enhancement that led to cheap production cost and high efficiency value.

Focusing on the positive impacts of PV technology, actual implementations demonstrate the existence of numerous environmental factors that in one way or another, may affect the system's performance. External conditions like dust accumulation, the presence of smoke, the shadow effect of neighboring structures, and fluctuation of weather conditions can greatly influence the amount of direct sunlight intensity on the panels as well as the temperature at which the panels operate. For example, solar module soiling which is particulate matter that may settle on the surface of PVs in areas where dust activity is high or where there is frequent pollution will form a layer that obstructs the penetration of light into the cell. The last two pertaining impacts of climatic elements upon PV systems are high temperature which is usual in many regions of the world with high intensity of sunlight, and it raises the resistances in the junction spaces of the solar cells demising the overall energy yield.

Concerning environmental constraints, PV uptake normally encounters special difficulties in regions with high solar energy potential. In this region, the key problems affecting the efficiency of PV panels include high temperatures, high humidity, dustiness, and smoke from activities such as bush burning. Moreover, these costs are high in upfront, while the correct maintenance and operational needs for PV systems are not commonly known, discouraging consumers from integrating them. Hence, an appropriate understanding of how varying environmental conditions influence the efficiency of PV, including analysis of the best ways to design and install these systems and how they should be managed, is deemed crucial.

PV power generation is an inverse process of photovoltaic effect where certain material produce electric current on exposure to light. PV cells which can be made up of silicon form modules and arrays to create PV panels. Such panels when connected to a circuit provide direct current electricity which must be transformed to AC for various uses. Different from other forms of renewable power generation, PV power directly harnesses sunlight, a inexhaustible and easily accessible resource, to produce electrical power different from the conventional fossil fuel based power supply.

PV systems can be broadly categorized into three main types based on the materials and technology used: on crystalline- monocrystalline, polycrystalline and thin film panels. One type of battery has one level of efficiency or another, and the manufacture of this type of battery is preferable for certain uses. For example, monocrystalline are some of the most effective in converting sunlight into electricity and recommended for areas with limited space while thin-film arrays are somewhat flexible and cheaper when used in large-scale application. As the PV technology develops even further, improvements such as bifacial panels and tracking systems then improves the energy yield and PV systems become even more versatile.

The first aim of this thesis is to analyze the level of impact of factors such as particulate matter, wind, shadowing, and temperature on the performance of photovoltaic systems. In this study, using real-world conditions – emitting smoke to mimic particulate matter, observing the direction of the wind, and conducting experiments on different shading conditions – this work assesses how these conditions can impact PV efficacy. For instance, particulate matter deposited on PV surfaces as dust and a physical barrier to sunlight resulting in reduced power generation. Like shading, shading too can cause uneven distribution of sunlight on the PV panels, leading to different effects on a panel and the areas of cells within the structural framework of the panel.

Knowledge of these interactions is critical to designing mechanisms for reducing adverse impact where possible, including proper panel orientation, novel cleaning techniques, and coatings to further extend the useful life of the systems and increase power generation. Thus, this research seeks to present Specific Research Findings that can enrich understanding of the how PV systems can be designed, positioned and maintained for various climatic conditions. Besides, this thesis offers tips to enhance the sustainability of the sustainability and efficiency of PV systems towards the transformation of other renewable energy solutions.

2. Literature review

2.1 History of Photovoltaics (PV)

Solar panels have been in development since the 1800s and turned into central renewable energy in the 2000s. Three important stages may be distinguished: the emergence of PV as a concept, the development of new technologies related to PV, and the global transformation of the energy system. The following section discusses key developments in the advancement of PV panels to show how a field that started as an experiment in physics has become one of the most popular forms of renewable energy.

Photovoltaic technology came through the photovoltaic effect when French physicist, Edmond Becquerel, detected that some materials could produce electron currents the moment they are exposed to sunlight in the year 1839. Though this was a revolutionary finding of the time, the absence of technology prevented its proper application. While one of the most profound concepts in the history of electrochemistry the discovery set the stage for future development of photovoltaics it took years for the applications of photovoltaic technology to be realized. In 1876 direct photosensitivity was discovered by William Grylls Adams and Richard Evans Day by exposing a selenium plate to light to generate electricity. However, the efficiency observed in selenium cells was grossly inadequate and was not suitable for large-scale electricity generation.

The development came in 1954 when Bell Laboratories scientists in the US came up with the first practicable silicon solar cell. Chapin, Fuller and Pearson together with their team produced a solar cell with an efficiency of about 6 percent, which constitutes the first photovoltaic cell capable of producing enough electricity that can be used to power light bulbs. This development, however, is considered to mark the beginning of modern PV technology. While being more expensive to manufacture than the conventional cell, the silicon solar cell has proved to have adequate reliability and performance standards that can favor it for selective applications such as in spaceships +. Space applications of solar panels began in the latter part of the 1950s, prominently in the Vanguard I satellite thus proving the stability of PV technology in unfriendly environments. This marked the initiation of use of solar energy in space missions for dependable and autonomous systems due to the expensive PV technology.

The energy crises of the 1970, which emerged from shortage of oil and political instabilities fostered attention towards photovoltaic technologies. The unanticipated rise in the price of oil has sparked much concern about other renewable energy sources, particularly solar energy. Such accumulated upgradient in this period was possible through boost in government funding and business venture whereby efficiency was improved and cost of developing solar technology reduced. Due to the high cost of installation of the solar panel to the ordinary household, make their initiation to be observed in areas such as the power supply to rural and developing regions and minor activities like off-grid electricity.

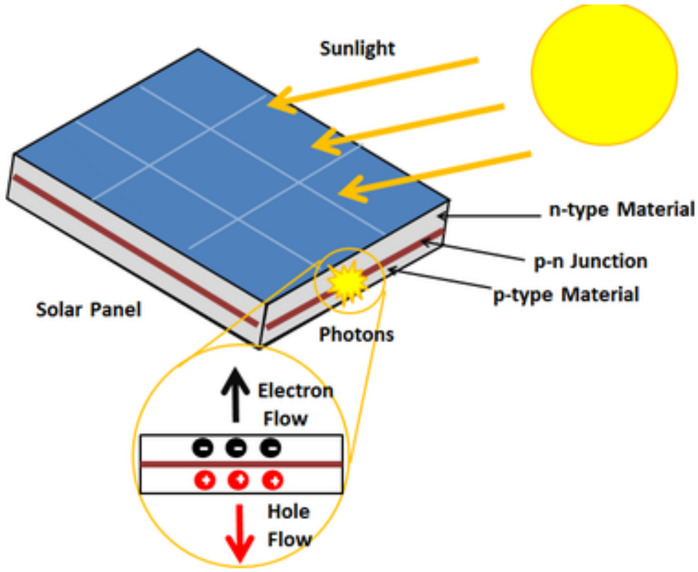
New materials research and production developments in 1980s and 1990s greatly impacted a reduction in the costs improve costs of photovoltaics. However, they are less efficient than the standard silicon cells and, by consuming less material, thin-film solar cells have become cheaper to manufacture. Over the decades governments globally especially the U.S, Japan and Germany introduced legislation and incentives while facilitating the use of solar energy. Factors that influenced the global solar market include feed in tariffs and subsidies for installation of solar power.

In the beginning of 2000s, there was much greater reported installation of solar panels due to advancing technology and reductions in costs. Technological growth in general silicon and particular solar silicon and higher production rates make solar energy a credible contender to traditional energy resources. The growing global consciousness of climate change and energy security has powered the shift towards renewable energy and hence increase the use of solar PV technology. Larger-scale PV solar farms were also then developed alongside growing usage and installation of residential and commercial building rooftop PV systems. Germany and China are at the forefront of the deployment of solar power due to their national policies meant to increase the percentage of share of renewable energy in their energy mix.

In the current world, photovoltaic panels are crucial in the current energy path towards the shift from other sources of energy like fossil fuels to renewable or rather clean energy sources. Solar energy in the recent past has been revealed to be among the cheapest sources of energy one can think of in the current market. Technological improvements are always causing greater effectiveness and dependability of photovoltaic systems, as well as upgraded solutions like bifacial solar panels and improved energy storage systems. The goals of reducing greenhouse gases and achieving global warming targets in essence remain premised on the sandy solar energy.

Therefore, the history of photovoltaic panels marks a complex process of development of science, technologies as well as the energy policies having been in existence in the world. Beginning from the discovery of the photovoltaic effect in the 19th century and scaling up to status of solar power PV technology lineup, solar power has emerged as one of the best solutions to global power needs for sustainable development. Regarding the future, the further evolution of PV technological systems complemented by a variety of policies as well as market trends will greatly define world energy structures.

Figure 1 A diagram shows the photovoltaic effect



2.2 PV as a Renewable Energy Source and Environmental Aspects

The shift in the use of renewable energy sources around the globe is spurred by issues such as global warming, energy vulnerability, and the exhaustion of fossil-based products. Solar power is one of the most important renewable technologies relied on to supply green energy. This review discusses the effectiveness of photovoltaic systems for sustainable energy production, environmentally viable energy, and potential efficiency and adoption enablers and barriers.

The photovoltaic effect was discovered in the 19th century and is relied on by photovoltaic technology to convert sunlight into energy. Since then, technology has had to grow mainly due to better production capabilities, materials, and efficiency. Currently, PV systems can be categorized into three main groups: There are also three types of photovoltaic solar cells, namely, monocrystalline, polycrystalline and thin film. Such panels in monocrystalline panels are famous for their high efficiency and longevity which qualifies them for use in residential and commercial areas that have limited roof space. While not as productive as monocrystalline ones, polycrystalline panels are less costly and therefore well suited for larger systems. Flexible thin-film solar cells are light in weight and can be installed in unique ways in different environments.

The importance of PV technology is in its application of harnessing the renewable energy source, the sun energy source which is discussed in that the solar energy is among the most-renewable sources of energy in the world which can provide the global requirement of energy, multiple folds. PV systems are a versatile energy production that works well at residential level as well as in utility scales solar power plant. This aspect of flexibility makes

PV convenient to be implemented in both the urban and rural areas as a way of enhancing energy security (K. M. L. A. M. Sharaf and A. G. G. J. Salama, 2019).

The application of photovoltaic technology presents several environmental benefits that contribute to the improvement of the sustainability of energy systems. One of the positive attributes of photovoltaic systems is that the impact on environment while running is insignificant. Another argument that solar panels are environment friendly as they do not emit greenhouse gases or air pollutants during electricity generation suggest that utilization of solar energy might reduce carbon emissions in huge impact. The balances of emissions of a photovoltaic system are illustrated through the phases of the life cycle analysis: while there are specific emissions related to production, transport, and installation of the system; the global emissions of solar energy are considerably lower compared to the emissions of conventional energy sources. Another environmental benefit is that the use of solar systems helps minimize water consumption in connection with electricity generation. The problem with conventional methods of electricity generation such as coal and natural gas is that they consume lots of water for cooling and processing. In its operation, photovoltaic systems convert sun light into electricity thereby using minimal water than other systems of electric power generation (A. Jäger-Waldau,2019).

To this, the present researcher emphasized this aspect more, especially for regions that experience water deficits, such as the arid zone. Photovoltaic technology enables effective management of resources and minimizes water competition in the urban and rural domains through the utilization of little water supplies. (M. R. T. Noor et al.,2020).

Photovoltaic systems can also help achieve the best use of the land and the environmentally friendly protection of wildlife. This also shows that usage of roofs and brown field for solar panels can help mitigate on land use conflicts and preserve on natural habitats. The integration of solar technology into building constructions (Building Integrated Photovoltaic or BIPV) holds the ability to produce energy while not having to expand the area used for energy production hence having few effects on ecology. In addition, when large solar farms are designed, they might be designed to coincide with farming practices, a situation that we refer to as agrovoltaics that has two-fold land benefits (P. K. Shukla et al.,2020).

However, the efficiency of photovoltaic systems involves many factors and has various advantages but has some environmental challenges and sustainable management constraints that require to be addressed. One concern is the environmental cost of creating the panels that capture the sun's rays. The process used to manufacture photovoltaic cells involves the use of materials that are averse to human health and the environment such as cadmium and lead. These studies highlight the fact that how addressing these issues is contingent on greater amounts of recycling and end-of-life management for the panels. Efficient recycling methods enable one to contribute to the recovery and reduction of the use of new materials from the natural resources hence promoting circularity in the solar industry. (M. H. M. Z. R. M. O. H. Khalid et al.,2021).

This fact is not the least concern since the nature of this source of energy production is periodically interrupted. PV systems rely on sun power and so their productivity differs with geographical location, time of the day, and climate. To address this issue, I would recommend integrating into energy systems, other utility-scale RE types such as hydro or wind and RE storage systems. Employing multiple energy units contributes to enhancing the reliability and the life of the available solar energy hence ensuring a constant flow of energy even in the situation of low sun irradiation. (T. H. M. Ghani et al.,2020).

Further, the development of large-scale utility solar farms poses some social issues mainly regarding the land use conflict where valuable agricultural land or areas of ecological significance may be developed for the installation of solar farms. A study underlines the need to be a little more careful in planning and selection of the sites where the construction is going to take place. They include siting of solar farms on degraded land or incorporating the use of solar farms in infrastructure systems which may eliminate conflicts of land use. (G. D. H. N. Shah et al. ,2021).

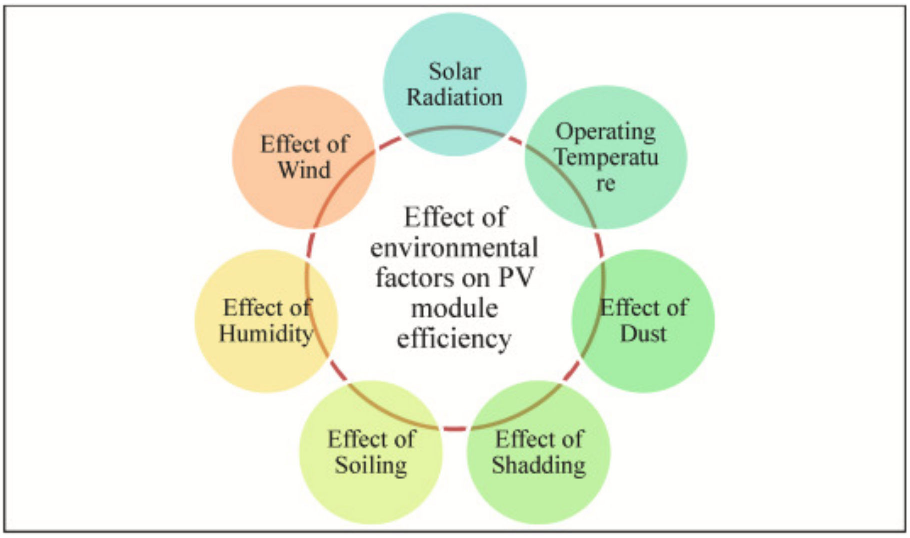
Therefore, policy and regulation play a critical role in the achievement of photovoltaic technology as a sustainable energy system. Governments play a crucial role in creating awareness and encouraging people and companies to embrace and invest in solar energy by coming up with incentives, subsidies and other policies. By studying numerous countries, it is discovered that nations with effective plans to foster the development of renewable power have increased take-up of solar energy extensively. The Feed-in tariffs, tax credits and portfolio standard have shown to be a success when it comes to encouraging investment in the production of solar energy. (W. Xie et al. ,2022).

However, knowledge about and customer acceptance of solar energy technology are prerequisites for the diffusion of this technology. Misconceptions about solar energy can be cleared by community engagement and education could effective way of presenting them to the people. Studying the opinions of people the maintainers of the solar power facility pinpoint that the support of the community is crucial for the further development of renewables: the key issues are determined by policymakers responding to the attitudes of the people. (A. Jäger-Waldau,2019).

In conclusion, photovoltaic technology is a significant trend in the renewable energy sector contributing immensely to the environment. It blows sun-powered energy that is in plenty and does it without emitting greenhouse gas or using scarce water necessitating its consideration as a better substitute for fossil fuels. But for wind power to have its full worth, issues to do with manufacturing, intermittency and its impact on land have to be dealt with using proper policies and practices and better solutions. By promoting the adoption of solar energy, the stakeholders can achieve the full potential of PV technology and increase the companies' share towards providing the energy needed for a developing world while cutting down on the effects of the effects of climate change. Availability and development of new gen PV technology, favorable policies and acceptance by the public makes solar energy the backbone of deployment of renewable energy.

2.3 Effect of Environmental Factors on PV Performance

Figure 2 the diagram shows the different types of effect



The external conditions however differ with the efficiency and output of the photovoltaic (PV) that is used in getting the solar power. Knowledge of wind directionality, dust, smoke, and clouds is important for solar systems efficiency and durability in the process of solar energy collection.

The direction of the wind could influence Solar Cells in two specific behaviors. Wind that blows to the right direction can help to cool the panels; this insulation is important because efficiency of solar panels decreases with heat. Cooler panels make it possible to increase power efficiency and therefore the production of power. On the other hand, since wind can also blow dust and several other materials towards the screens hence increasing on soiling. Places linked with high wind frequencies experience a high rate of dust deposition. Dirt on PV surfaces prevents direct contact between sunlight and the photovoltaic cells because dust forms a barrier to the incidence of solar power. Shortening the daylight hours may seriously reduce power generation, in the worst instances by over 30 percent. This is most likely to happen so when there is a lot of dust in the environment, therefore it accumulates on the pipes.

Dust is a significant factor and causes even greater concern because dust storms occur in arid and semi-arid countries. This shows that the nature and size of the dust particles have a significant influence on the amount of impact towards the reduction in panel efficiency. Fine particles have a larger impact because of their ability to stick more to the surfaces of the panel than the larger ones. Dust collection reduces the amount of sunlight that can penetrate inside the house and besides, squares up an uneven surface to produce more energy noises. To reduce the impacts of dust, cleanliness and maintenance must be maintained properly. As I found in the case of Saudi Arabian solar panel users, they should be diligent in the maintenance of panels especially if they are in the desert. It will be interesting to investigate how various forms of cleaning; robotic cleaners as well as self-cleaning systems will cut down the overall cost of cleaning.

Another hindrance to the efficiency of photovoltaic panels is smog resulting from wildfires, industrial exercises, or the like. The researcher also notes that smoke tends to block sunlight and therefore lessen the amount of energy that falls on the panels. Large-scale fires can be a major cause of reduced energy generation and distribution of electricity. However, the other effect is if the panels are exposed to smoke, this small particulate matter will deposit itself on the face of the panel, thus forming soiling which may require further cleaning. The impact of smoke could clearly vary relative to the thickness of the smoke as well as the duration of smoke encounter. Detach shows that output from the solar panels themselves could be reduced by as much as 50 per cent during times of heavy smoke—a clear indication of how the quality of the air can affect the yield from solar power.

The ability of photovoltaic panels to capture sunlight is regularly compromised by the shadows thrown by nearby structures, trees, or otherwise. When it comes to deterioration of energy output, apart from the series arrangement of the solar cell in a panel, when one of the solar cells is overshadowed, energy output drops drastically. Single cell's shading can hinder current flow, hence decreasing general panel efficiency.; Increased temperature due to minimal current flow in shaded cells leads to 'hot spotting' that might cause irreparable damage. It is therefore important to be very selective with the sites that you choose with a view of being protected from shadowing. Similarly, solar panels should be placed in areas that receiving little shade from neighboring objects. In addition, methods such as microinverters and power optimizers may be used that allow each panel to work independently. The main disadvantage of having shaded panels is that they do not affect the performance of the system quite dramatically.

Environmental conditions also depend on where solar power plants are physically located. Areas with lots of dust will need more regular cleaning and areas with lots of plants may have an additional difficulty from shadow. Additionally, spots that might have to provide extra care after encounters with wildfires or industrial pollution would be those exposed to smoke.

In short, elements like wind direction, dust, smoke, and shadow direction, greatly determine the effectiveness and efficiency of solar panels. Understanding these effects is therefore critical to maximizing the effectiveness of solar power systems based upon their design and placement, and through maintenance. PV systems can have increased life span and efficacy if environmental problems are aggressively dealt with by responding to cleaning, smart site selection, deploying innovative technology, etc. This supports the move toward a sustainable energy future in general and supports making solar energy more constant.

2.3.1 Position, Angle, and Orientation

It has been realized that the efficiency and the total energy output of a photovoltaic (PV) panel greatly depends on the position, angle, and direction of orientation. Altering much of these aspects could assist solar energy systems to get as much sunlight exposure as possible over all the seasons. To achieve maximum efficiency of the solar systems, several forms of interrelations are underlying.

The position of PV panels has to do with the location—installation site—and height. Solar power prospect of a given region is a function of its geographical location because irradiation from the sun differs with latitude, temperature, and even atmospheric density. Those areas closer to the equator can receive direct sunshine throughout the year making them ideal for solar. It refers to the measure in which the height of the installation may affect the access on solar irradiation; certain installations are at higher altitudes that allows clear and little interferences from air hence greater access on solar irradiances.

Installation angle of tilt also has its part which is a critical factor in PV panel. Therefore, there might be variation with respect to geographic location of the solar installation and the goals of the solar installation. In the fixed systems the tilt angle is most often set to maximize the solar energy collection during the period of the day when the sunshine is strongest. It has been established that a standard setting of the tilt angle equals the geographical latitude of the installation location can improve the energy output of the system consistently throughout the year. Some changes can be beneficial seasonally; for example, panel inclination can be more in winter to address lower sun angles, or the opposite, shallower in summer, when the sun rises higher.

It may be stated that the position of PV panels is equally important. Faces of panels are many a time aligned to true south in the Northern Hemisphere and true north in the Southern Hemisphere with a view to capturing as many sun rays as possible. Such orientation makes it possible for panels to receive direct sunlight for a large part of the day especially during mid-morning to midafternoon. Sometimes even the ideal orientation might be changed by other factors, namely shadowing from the neighboring buildings or trees. In some cases, though, the east-to-west directions are beneficial in terms of energy generation during the morning and late afternoon when power useful is high.

These factors have a considerable effect on energy output. The examinational variety shows that shifting the position, the inclination, and the position of photovoltaic panels might notably increase the yield of energy. Optimizing the angle of tilt and the orientation of the solar system increases energy generation by 10% to 30% if compared to poorly installed panels. Other specialized technologies such as tracking mechanisms to alter the orientation of the panels to fit the sun path during the day add on the effectiveness of energy storage. These systems could call for an increased energy output of between 20% to 50% compared with conventional plant utilities although at a greater installation and maintenance expenses Hence, orientation, angle, and placement of photovoltaic panels are critical for efficiency and energy production. The evaluation of these characteristics during system design and installation can greatly improve the efficacy of solar energy applications. The study also reveals that refinement of the position, tilt, and installation direction of photovoltaic panels can increase photovoltaic energy collection and further a greener energy future. It must be emphasized that the application of all these concepts serves to enhance energy returns of installed photovoltaic systems and therefore can be considered to offer more value for money for photovoltaic installation.

2.3.2. Form and Characteristics

Photovoltaic (PV) systems have seen the directional change in the utilization of solar energy and as such it has developed several shapes and features needed to fit the required energy. This paper aims to establish a review of the research on the many varieties in the PV system, their characteristics and their impact on performance and utility in different contexts.

Classification of PV systems based on size, method of installation and the technology used varies. Being fully informed of such types may assist one in optimally using and installing solar power systems in various conditions.

As has been mentioned, photovoltaic systems and their performance depend upon numerous critical factors like design, technology, and ability to work in ambient conditions. Understanding these attributes is important so that only the benefits of the system can be achieved during the use of solar energy.

Performance is an essential characteristic of photovoltaic systems referring to the level of solar light conversion into useful electricity. Different technologies have different degrees of efficiency: Solar cells are of different categories, including monocrystalline, polycrystalline, thin film cells. In down coming due to their single crystal structure there are considerable findings revealing that monocrystalline panels are more frequently found to have the highest efficiency. However, because thin-film panels are not as efficient as thick-film panels, they could have unique application because they are extremely thin and lightweight. Optimizing energy supply and assessing the overall decidability of solar systems require the performance of a photovoltaic system (M. A. H. A. J. H. O. M. O. K. I. J. Shah et al. ,2020).

One of the most crucial requirements for the PV system is standby time along with endurance because the systems are installed usually outside the building and thus are exposed to sundry weather conditions. Researchers have found out that tough and high-standard materials will make the solar panel long-lasting, beyond the twenty-five-year period. The literature review points out that reliability is key to sustaining project performance and overall financial rates of return on investment for solar energy. The durability of PV systems to environmental factors including heat and humidity which include high temperatures and moisture are crucial for its operation (A. Jäger-Waldau,2019).

Another characteristic is the temperature coefficient which determines the change of the PV panel efficiency caused by the temperature differences. That is, panels with lower values of the temperature coefficient work better at high temperatures, that is, there will be fewer losses in efficiency. This characteristic is significant and especially emphasized in this research because it determines the choice of effective PV technologies depending on the climate in specific regions, namely, high ambient temperatures. Mainly, knowing how temperature impacts on PV performance will help in planning and installation of the systems to maximize energy output (G. D. H. N. Shah et al. ,2021).

This is further supported by the current findings of the research, showing that the angle and orientation are important determinants of the energy production of PV systems. Angle and orientation make an allowance for much exposure to light during the day and have a direct relationship with energy production. As found in various studies, these fixed installations should be mounted in a position that depends on geography to acquire as much solar radiation as is possible. Similarly, tracking systems for panel orientation can improve energy collection by as much as a quarter. The incorporation of new tracking system technological features can greatly enhance the layouts of solar systems, especially in areas of fluctuating irradiance. (W. Xie et al,2022).

Thus, certain critical parameters such as soiling and maintenance requirements are significant in affecting the working of PV systems. The photographic shows that dirt, dust, and debris collected on the panels hinder the flow of sunlight hence the generation of energy on the solar panels. Studies reveal that to sustain efficiency cleaning the interiors must be conducted continually to counter dirt, especially in areas where the climate is dry. This paper underscores the importance of maintenance strategies in extending the reliability and efficiency of solar energy systems. (M. M. N. Khan et al. ,2020).

The affordability of PV systems favors the application of the technology based on installation costs, maintenance expenses and incentives to foster the business. Comparison with conventional energy sources show that PV systems competitiveness rises due to higher economies of scale and declining costs of production of solar technology. By evaluating the cost of PV systems based on a levelized cost of energy over the useful lifetime of the technology, the lower cost of silicon solar panels enables the economic feasibility of residential installations and supplemental usage in commercial settings soon. The changing unit cost is an indication of the constant improvement of manufacturing technology, thus increasing the availability of solar energy. (T. H. M. Ghani et al.,2020).

Therefore, the variation of shapes and features of PV systems is a key function in determining the performance and effectiveness of these systems in various surroundings. A grasp of these factors is central to the best use of solar energy technologies as well as a way of improving the impact of these technologies for sustainable energy systems. It is expected that in the future, as the research and development acquisitions progress, the effectiveness of PV technology will grow progressively better in terms of efficiency, durability, and cost. These advancements will over time lead to an increased use of solar energy across the world hence increasing the chances of utilizing renewable energy instead of conventional source of energy hence reducing on greenhouse emissions. Continued commitment of researchers, policymakers, and industry stakeholders to the development of photovoltaic systems means that the future of these systems seems bright and that they could help revolutionize the generation and use of electricity.

2.3.3 Weather and Cleaning Interventions

PV panels are greatly affected by external influences as well as the cleanliness of the panel surface. Each one is important in defining the amount of sunlight that falls on the solar cells – which in turn defines how much energy the system produces.

Weather Impacts:

Precipitation, solar heat, moisture, and cloud altitude have a straight relation to the efficiency of the PV panels.

- **Rainfall:** Rain itself is not a problem but can cause several issues with PV systems. Heavy clouds and rain which are often linked can obscure the sun and lower the energy output for a short time, but rain has the natural ability of washing PV panels to remove dust, dirt, and other forma-economic sources of deposits. Thereby, this spontaneous cleaning makes rain save feasible without manual cleaning in certain areas to preserve panel efficiency.
- **Temperature:** Most panels work better at low temperatures and therefore are much more effective in cold climates. They also mentioned that high temperatures have the

effect of lowering efficiency because the electrical conductivity within the panels rises. As a result, the panels installed in regions with high temperatures will produce less in the afternoon when the temperatures are high, yet the sun intensity is high.

- **Humidity and Dew:** One major common flaw is that high humidity and morning dew result in visibility of moisture on the surface of PV Panels, rendering the solar panels slightly less efficient until the moisture eventually evaporates. Although this affectation appears marginal, in areas with continually high humidity levels, enhancements in cleaning frequency may be desirable for optimal performance.
- **Cloud Cover:** Shiny and clear is the weather when the sun rays directly shine on the PV panels, producing electricity but when the days are cloudy the intensity of sunlight is lower thus less energy. Still, there are a few things you should know about solar energy – that solar panels continue to generate electricity but at a lower capacity during the cloudy days. The amount of reduction depends on the thickness of the cloud and the time covered by the clouds.

Cleaning of PV Panels:

The cleanliness of PV panels is a significant factor that determines their efficiency all the time. Smears of dust, dirt, droppings, pollen and pollution filled the outer surface of the panels decreasing the intensity of light that can reach the outer surface of the solar cells which leads to a decrease in the efficiency of the production of electricity.

- **Dust and Dirt Accumulation:** Location is another factor where accumulation of dust which is normal in deserts sees the efficiency of panels reduced by up to one half if not cleaned after every two weeks. This is a usual phenomenon in regions where rainfall is low and cannot wash away the filth from the faces of the panels on its own.
- **Bird Droppings and Pollen:** Such forms of soiling are predominant in places and when they occur depending on the areas they cover, they reduce the efficiency of the panels significantly if the solar cells sections are covered. Like any other surface exposed to outside conditions, panel surfaces can accumulate organic materials such as bird droppings that create 'hot spots' of higher temperatures in a shaded region to cause lesser efficiency in the overall system.
- **Pollution and Smog:** It is believed that air pollution in urban and industrialized regions will cause lower solar panel performance. Airborne pollutants are like dust that may deposit on the surfaces of the panels and may reflect the incident light hence need frequent cleaning.

Cleaning Frequency:

The frequency of cleaning will also vary depending on the local weather initiator, dust fall, or pollution level and location either in rural areas, urban areas, or industrial areas. In the areas that receive rainfall frequently, natural washing may be all that is required to keep the panels effective. Nevertheless, in the dusty or polluted environment, cleaning through manual or automated operations is required at constant intervals to maintain high efficiency.ways of washing include hand washing using water and soap, use of robotic washing machines, or special anti-sticking layers that prevent, or help in cleaning the surface of dust and other dirt. The choice of the method essentially depends on the scale of the installation together with the existing environmental conditions of the area. However, cleaning of the buildings particularly in regions with scarce water supply raises some questions on sustainability regarding the use of water during cleaning hence the water-efficient cleaning methods.

Weather conditions and the cleanliness of PV panels are among the elements that affect the efficiency and energy emission of solar systems. Although rain and cooler temperatures are considered weather factors with positive effects on the panels by mediating their temperature and cleaning their surface, extreme heat, dust, or pollution negatively impacts efficiency. Accordingly, it was determined that routine cleaning of the panels – especially where the environment is dry or polluted – is crucial to sustaining the long-term performance benefits of PVs. The fact is cleaning necessities and sustainable requirements like using as little water as possible in arid regions to accord with the environmental gains of using solar energy are also important issues in cleaning requirements.

2.4. Legislation, Standards, and Usage

The use of photovoltaic (PV) systems has received a boost due to effective legislation, industrial practices and usage practices. This literature review focuses on the current regulations governing PV systems, the practices that guarantee the quality and safety of the systems, and various uses that show the flexibility of the technology.

Legislation and Regulatory Frameworks

Stakeholder decisions to embrace PV systems are well associated with the governmental policies supporting the use of renewable energy sources. In the literature, analysts found out that legislative frameworks play an important part in the development of solar energy. Many past studies have pointed out the realism of feed-in tariffs (FIT) and net metering policies in fostering PV systems installations among residences and businesses. These policies also improve the economic feasibility of solar investments due to the establishment of favorable financial incentives and predictable prices of solar energy (M. B. Aslani et al.,2020). Furthermore, case studies show that countries, that have developed sound renewable energy policies accompanied by ambitious solar goals, register increased PV systems installation rates, and therefore, make substantial additions to their national energy mix. (M. J. W. Schmid et al.,2021).

In addition, the condition regarding the political regulation is that it is changing and introducing new safety and building codes. Studies also illustrate the significance of installation and operation of solar systems with national and local code compliance. These regulations defend various installations and guarantee the stability of the electrical system, which raises confidence in solar innovation. Proper implementation of the building codes and safety standards offers the best line of defense against the various safety issues bound to occur with the solar systems including electrical ones and issues of structure. (A. S. Rahman et al.,2019).

In many locations, regulations concerning solar energy also have an environmental aspect as well. Large-scale projects require EIAs to determine the social, economic, and physic-chemical impacts of the proposed solar projects taking into consideration impacts on the bio-physical environment. Studies suggest that where professional and time-intensive EIAs provide, they are useful in reducing the negative impacts of large photovoltaic solar farm site selection and planning (A. J. M. A. Z. S. F. N. Malik et al.,2021).

Standards Governing PV Systems

The stringency of the quality and safety of PV systems is anchored on international and national standards. They have adopted the main standards of the International Electrotechnical Commission (IEC) that explain the performance and safety of solar panels. For example, IEC 61215 deals with the procedures for determining the efficiency and reliability of crystalline silicon-based T.P.V. modules for terrestrial use. Studies have confirmed the need for such standards now that PV products must satisfy very high-performance standards and safety requirements before being released into the market. This kind of regulation is critical in ensuring that the quality of the solar energy produced is high as well as avoiding certain risks chief of which is the risks posed by defective solar installations (A. Jäger-Waldau,2019).

Besides IEC standards, one should also speak about the activity of the International Organization for Standardization (ISO) and the Institute of Electrical and Electronics Engineers (IEEE) in terms of the promotion of best practices. ESMS ISO 14001 plays a critical role in steering manufacturing firms towards improved sustainability in production by minimizing on the impact on the environment in the manufacture of solar panels. Some studies establish knowledge concerning the fact that compliance with ISO standards increases the performance of operations in PV manufacturing as well as installation thus strengthening the sustainability of the solar energy business (G. D. H. N. Shah et al.,2021).

Another important application of IEEE standards worth mentioning is in providing requirements for the safe connection of PV systems to the electric grid. IEEE 1547 addresses the technical specifications for DER integration with the grid, of which solar PV systems are a part. This standard is important for future grids whose continuing connection reliability and stability can only be enhanced as more and more levels of embedded solar energy systems are developed to feed existing power systems. Given the trend towards co-integration of increasing levels of intermittent renewable generation, adherence to these standards becomes essential to provide a framework for dealing with some of the issues of voltage control, frequency regulation, and system resilience.

Usage of PV Systems

Various aspects demonstrate the practical uses of PV technology due to its versatility in responding to energy demands. It is usual to see houses with rooftop solar devices, this gives the house owner an option of minimizing electricity bills and dependency on the grid. A study shows that when households install residential PV systems with energy storage solutions, they get more energy security, especially in areas with costly electricity or occasional blackouts. Battery storage systems not only increase self-consumption but also make homeowners participate in demand-side management to stabilize the load during peak demand (W. Xie et al.,2022).

In general, existing studies exploring utility-scale solar farms provide evidence that these installations contribute to the delivery of the national energy needs. The solar project investigates large-scale plants in terms of output productivity and cost estimating that they support a significant share of the renewable energy goals while ensuring the grid stability of electricity delivery. Large-scale solar systems still need proper planning, regarding location as well as impact on power generation and scenery (H. M. Ghani et al.,2020). Lastly, the role of low impact on the ecosystem and high land use intensity in managing and designing these solar farms are highlighted in the research (P. K. Shukla et al.,2020).

In addition, the use of PV technology in off-grid systems is increasing in areas where electric supply is not available. Research has shown that solar electricity systems can adequately provide power to necessary services in rural areas such as health and schools (M. M. N. Khan et al.,2020). Off-grid solar systems are unique, customer-specific energy solutions with integrated backup power supply in the form of batteries. This versatility is highly useful with PV because, without stable electricity, a high quality of life is nearly impossible, at least in developing countries.

Integration of PV with other forms of RE such as wind or biomass increases energy security and reliability in areas that are characterized by fluctuating weather conditions. Examples include research carried out to explain the effectiveness of such systems of getting the best from different breeds of systems. Some of these systems can deliver a stable energy supply and minimize dependence on traditional fossil-based energy, which makes for a sustainable energy solution (F. Y. Wu et al.,2021).

3. Material and methods

3.1 Location

An experiment was conducted at MATE, Institute of Environmental Science, Department of Environmental Analysis and Environmental Technologies Institute, Gödöllő (MATE Environmental Engineering Laboratorium). The coordination is 47.594305158700486, 19.36721638514078.

Figure 3 location of MATE environmental engineering laboratorium

3.2 Structure of the measuring circuit

This study utilizes specialized equipment to investigate the effects of environmental factors on photovoltaic panel performance including:

- Photovoltaic (PV) Panels
- Global radiation sensor
- Almemo
- Wind speed
- Wind direction
- Smoke bomb
- Temperature and particulate matter sensor

Figure 4 Schematic of the measuring circuit

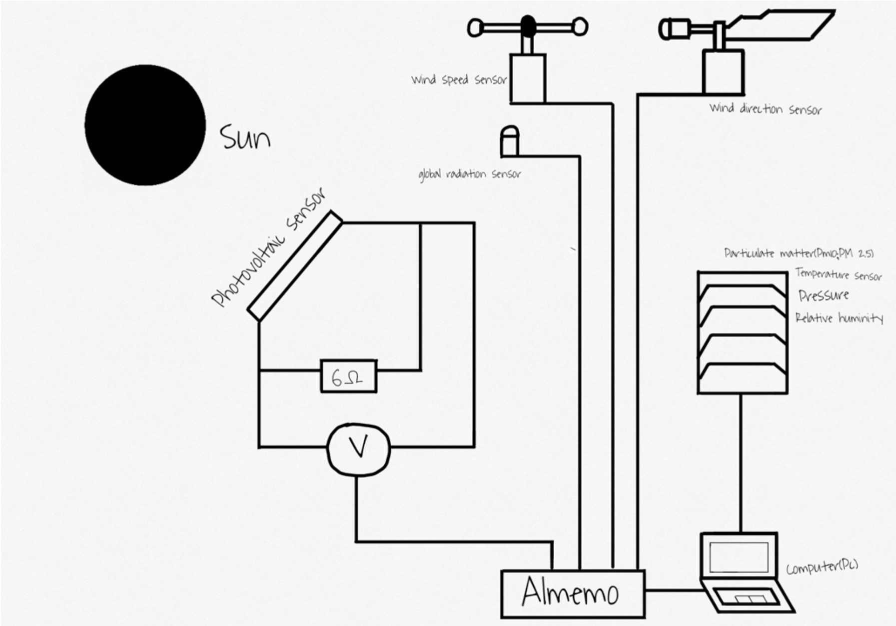
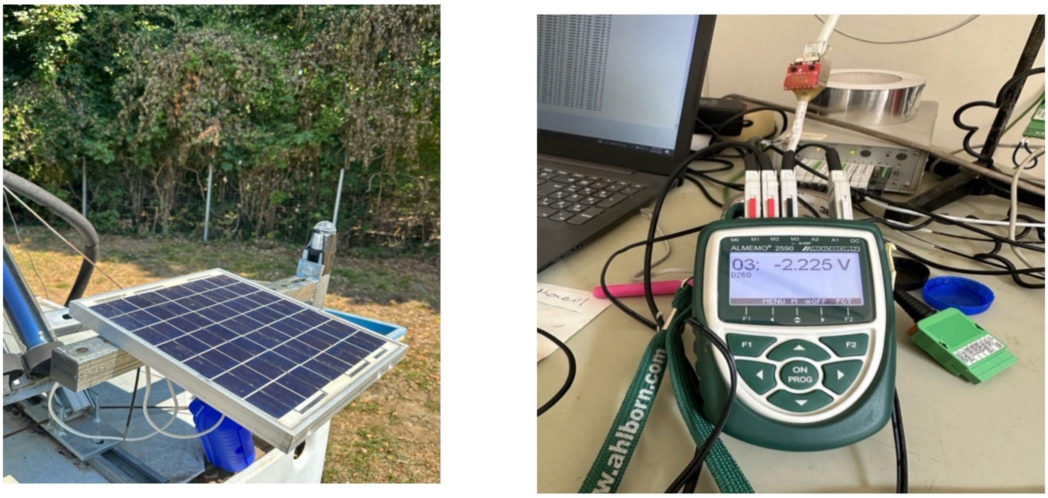


Figure 5 (A) Photovoltaic (PV) panel and (B) Almemo data logger



A B

1. **Sun**: Represents the source of solar radiation affecting the photovoltaic panel.
2. **Photovoltaic Sensor**: Measures the output from the PV panel. It connects to:

- A **6-ohm resistor** and a **voltmeter (V)** to measure voltage output.

3. **Global Radiation Sensor**: Measures the total solar radiation impacting the PV panel.
4. **Wind Speed and Wind Direction Sensors**: Measure wind speed and direction, important for understanding environmental cooling effects on the panel.
5. **Almemo Device**: Likely serves as a data logger or central processing unit, receiving data from various sensors, including:

- PV sensor output (voltage and resistance).
- Wind speed and direction.
- Global radiation.

6. **Environmental Sensor Array**:

- **Particulate Matter (PM10 and PM2.5)**: Measures dust and particulate concentration in the air.
- **Temperature Sensor**: Measures ambient temperature.
- **Pressure and Relative Humidity**: Measures atmospheric pressure and humidity.

7. **Computer (PC)**: Collects and displays the data processed by the Almemo device, allowing analysis of environmental impacts on the PV system's performance.

This setup is useful for analyzing how environmental factors such as wind, temperature, humidity, dust, and radiation affect the efficiency of the photovoltaic panel.

3.3 Methods

To investigate environmental influences on photovoltaic (PV) power generation in detail, a structured approach for data collection was developed. This section describes various methods of data gathering as well as the main steps related to the analysis of the performance of PV systems in different climate conditions. It was about gathering timely and accurate data from different sources to determine the impacts of particulate matter and sedimented dust.

3.3.1Particulate matter (PM10) and sedimented dust

The objective of this experiment was to figure out how smoke and particulate matter PM10 especially affect the output of photovoltaic PV panels. The experiment consisted of the ordered detonation of 10 color bombs in which the effects of smoke and airborne particulate matter were emulated by detonating one color bomb at a time. After the smoke cleared, the resultant particulate matter landed on the PV panels as dust, and the efficiency of the panels was tested before, during, and after the particulate exposure.

Figure 6 Smoke experiment

The smoke was launched in phases by exploding one color bomb after the other with some time in between to manage the release of smoke. This slow emission of smoke ensured that the amount of particulate matter in the air kept on increasing (step by step).

Figure 7 Ten Bombs that use for the experiment

Measurement of Particulate Matter (PM10): The PM10 sensor continuously measured the concentration of particulate matter in the air during the ignition of each color bomb. The recorded data helped track how the number of airborne particulates correlated with changes in the PV panel's performance.

Efficiency During Smoke Exposure: Immediately following the process, the power voltage of the PV panels was measured at regular intervals the capture the immediate impact of the smoke on the panels' efficiency.

After burning off the last color bomb and letting the smoke settle, particulate matter in the air started to reverberate as dust on the surface of the PV panels. Therefore, I allowed this process to occur naturally and over time (e.g. 30 minutes to 1 hour period).

After the dust had settled completely, the power output of the PV panels was remeasured to assess the effects of sedimentation dust on the efficiency of the panels.

Data were collected during two key phases of the experiment:

- **During Smoke Exposure**: Power voltage and PM10 concentrations were recorded as each color bomb was ignited to analyze the real-time impact of airborne smoke particles on the efficiency of the PV panels.
- **After Sedimentation**: Once the dust settled on the PV panels, additional measurements were taken to determine the efficiency loss due to the dust layer on the surface.

Figure 8 Dust on PV panel

3.3.2 Shadow

This study aimed to establish the impact of partial shading on the efficiency of the photovoltaic panel by covering some parts of the panel with liners. Two setups were employed: one of the embodiments where half of the panel is covered with a liner and a smaller part of the panel is covered. The purpose was to mimic the actual shading scenarios and evaluate their effects on the PV panel's voltage. In the first setup, a liner was fit on to the panel half horizontally in terms of its surface area efficiency by covering sections of the panels with liners. Two setups were employed: covering a smaller portion of the panel. The goal was to simulate real-world shading conditions and analyze their impact on the PV panels' performance.

Half-Panel Coverage: In the first setup, a liner was placed to cover half of the panel's surface horizontally. This simulated the impact of larger obstructions, such as buildings or trees.

- **Effect Observed:** Initially, it was hypothesized that covering half the panel would cause a significant reduction in power voltage. the power voltage dropped similarly to the small coverage case, indicating a substantial impact on the overall efficiency of the panel.

Small Liner Coverage: The small liner covered approximately 10% of the panel surface, simulating minor obstructions such as dust or bird droppings.

- **Effect Observed:** As with the half-panel coverage, the efficiency of the PV panels fell sharply. Surprisingly, the power voltage drop was the same as the half-panel coverage, and this was with a much smaller area being blocked. This implies that minor shading of important areas on the panel can significantly affect the efficiency of the panel in the same way as the large shading.

Effect of Half-Panel and Small Liner Coverage

The experiments showed that in both cases the power voltage fell similarly even though the coverage area was different. This unique observation underscores the vulnerability of the PV panels to partial shading, where minor incongruities in sunlight exposure can dramatically affect output. This could be attributed to the fact that the PV cells are constructed in a manner that shading of a particular cell can affect the entire cell.

Figure 9 (A) Half of liner coverage and (B) small liner coverage

A

B

3.2.3 Weather monitoring

Using HungarianMet, a comprehensive set of meteorological data can be gathered, including:

Categorize Rainfall: Classify rain events based on intensity (light, moderate, heavy) to evaluate how different types of rain affect the environmental factors. For example:

- Light rain: < 2.5 mm/hr.
- Moderate rain: 2.5–7.6 mm/hr.
- Heavy rain: > 7.6 mm/hr.

Hungramet represent different periods, and columns represent different weather factors (such as rain intensity, humidity, wind speed, etc.).

Apply the Hungarian Method:

- Use the method to optimally assign each time (worker) to either the "rain" or "no-rain" category (task) based on the cost function.
- The result will be an assignment for each time interval, helping you identify when it was raining.

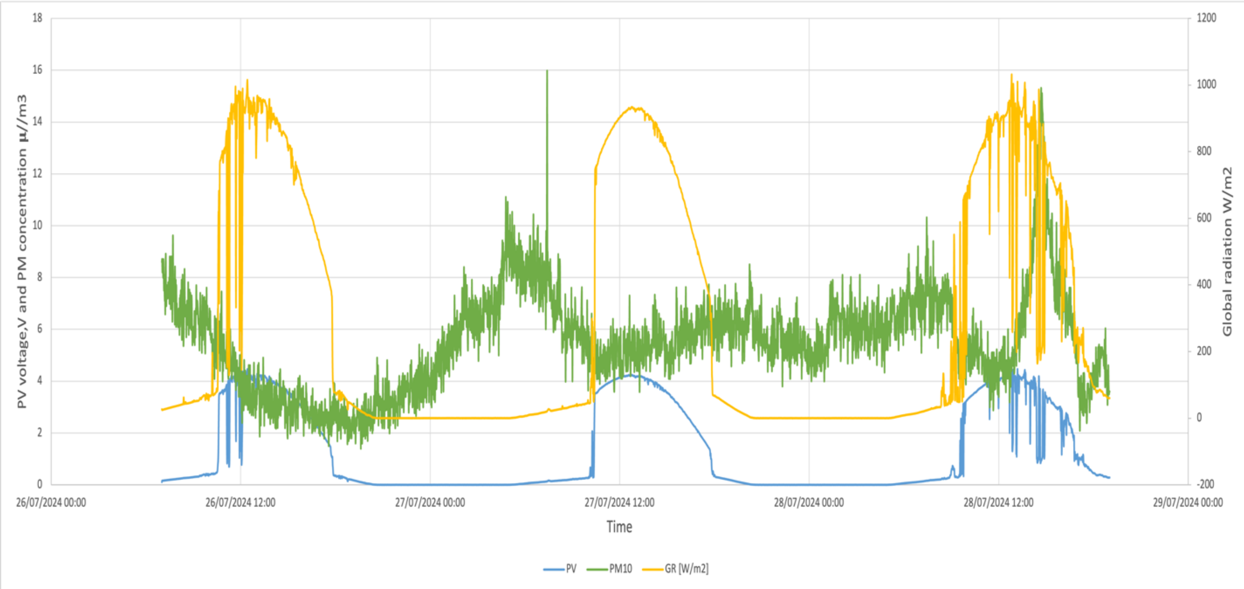
Analysis in the results

- Present the graphs, showing when it rained based on the Hungarian Method analysis.
- Discuss the accuracy of this method in detecting rainfall periods and how the results influence your understanding of the environmental impacts on photovoltaic power.

4. **Results and discussion**

4.1 Particulate matter (PM10)

Figure 10 PV efficiency and global radiation



The chart represents the results of an experiment where color bombs were used to generate smoke, producing particulate matter (PM10). The focus of this experiment is to study the impact of the smoke (which creates PM10) on the efficiency of photovoltaic (PV) panels and its correlation with solar irradiance (GR).

1. **PV Efficiency (Blue Line):**

- The blue line shows the power voltage of the PV panels over time. The output increases during periods of higher solar irradiance and drops at night when there’s no sunlight.
- There are noticeable reductions in efficiency during periods of high particulate matter concentration, which may indicate that the smoke (PM10) from the color bombs has settled on the PV panels, blocking sunlight and reducing their efficiency.

2. **PM10 Concentration (Green Line):**

- The green line represents the concentration of PM10 particles in the air, which were created by the smoke from the smoke bomb experiment.
- As the smoke bombs are ignited, the PM10 concentration spikes, indicating an increase in airborne particulate matter. These particles eventually settle on the PV panels' surface, forming a dust layer that obstructs sunlight and reduces panel efficiency.
- The spikes in PM10 concentration align with the times when the color bombs were set off, creating dense smoke.

3. **Global Solar Irradiance (GR, Yellow Line):**

This line shows the amount of solar energy (in W/m²) received by the PV panels. As expected, it peaks during the day when sunlight is strongest and drops at night. The relationship between solar irradiance and PV panel efficiency is clear: as irradiance increases, the panels produce more power. However, the efficiency may not reach its full potential if there is particulate matter (PM10) on the panel surface.

Impact of Smoke on PV Efficiency:

The PM10 concentration spikes when the smoke bombs are ignited, creating smoke. This smoke initially reduces the amount of light reaching the panels due to the high concentration of airborne particles reflected in the PV voltage drops. After the smoke settles, the PM10 particles land on the surface of the PV panels, forming a layer of sedimented dust. This dust further reduces the panel's efficiency as it continues to block sunlight over time.

Correlation with Solar Irradiance:

Solar irradiance drives the PV panel's power voltage, but its efficiency is diminished when particulate matter (from the smoke bombs) covers the panel. Even during periods of high irradiance, the panel's voltage does not peak as expected, likely due to the dust settling on the panel.

This chart demonstrates the negative impact of smoke (PM10) generated by the color bombs on PV panel efficiency. The smoke bomb increases particulate matter levels, which obstructs sunlight and reduces the energy production of the PV panels, both during the smoke emission and after the smoke settles as dust.

4.2 Wind effect

Figure 11 Effect of wind direction on PV and particulate matter levels

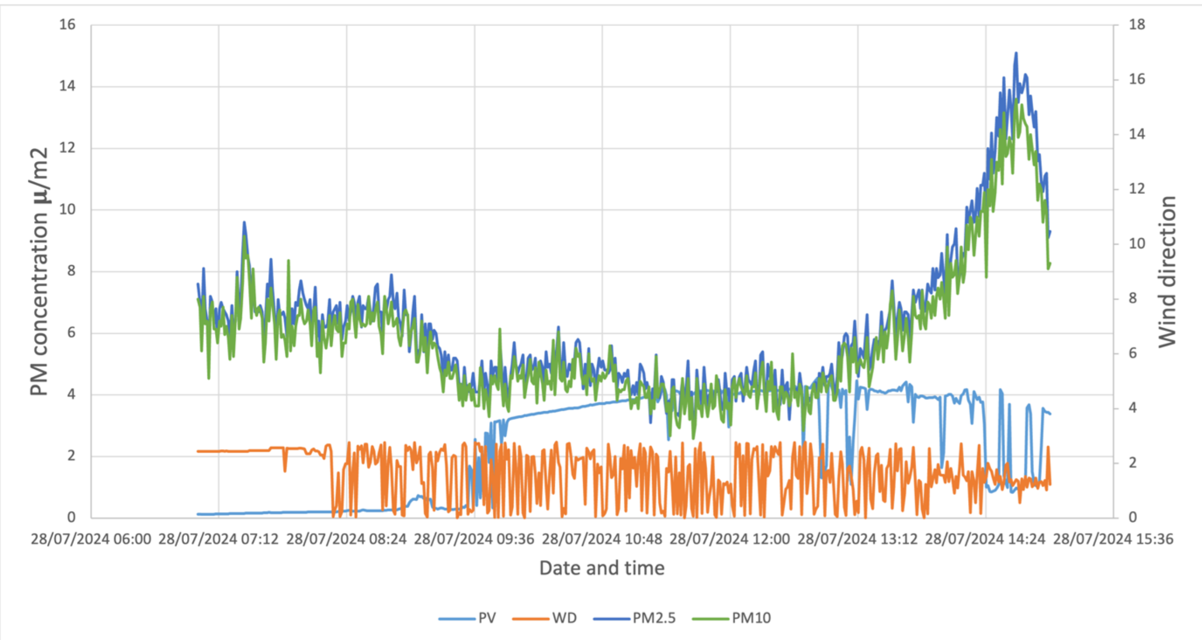
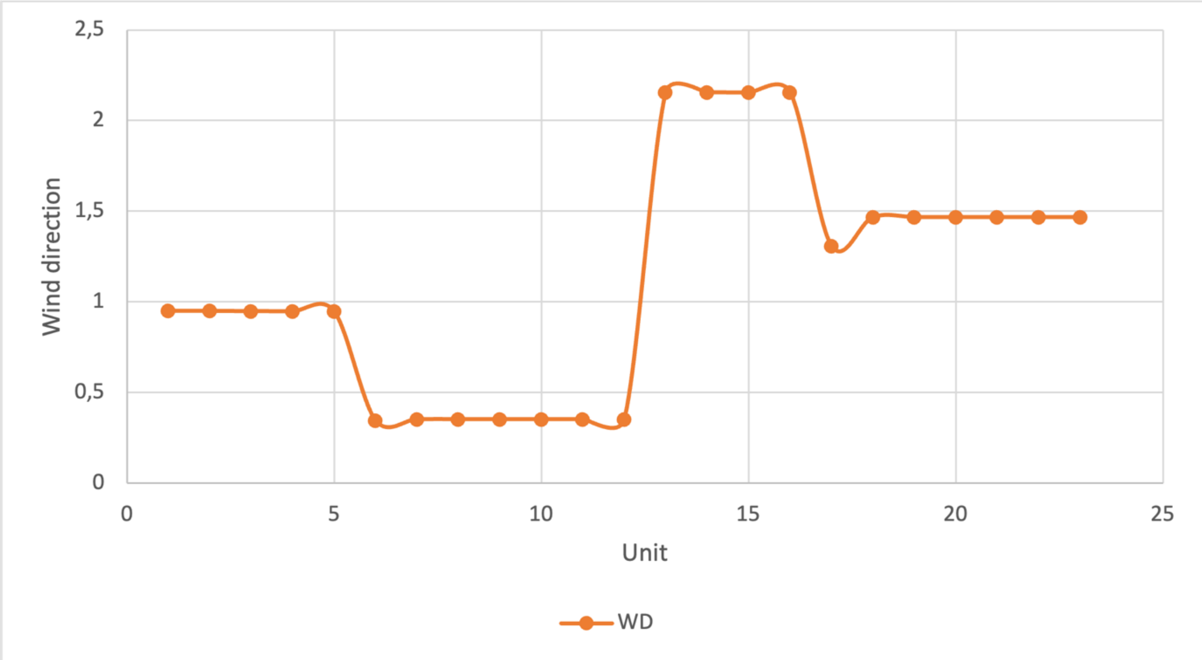


Figure 12 Wind direction chart



The two charts capture the results of an experiment designed to assess how smoke released into the environment affects the concentration of particulate matter (PM2.5 and PM10) in the air and how wind direction influences the distribution of this smoke and its subsequent impact on PV panel efficiency.

First Chart Analysis:

The first chart measures the following variables over time:

1. PV Efficiency (Blue Line): This represents the voltage of the PV panels. Efficiency tends to drop as particulate matter increases, blocking sunlight from reaching the panel.
2. PM2.5 and PM10 (Light Blue and Green Lines): These lines represent the concentrations of PM2.5 (fine particles) and PM10 (larger particles). The experiment suggests that the smoke introduced particulate matter into the atmosphere, and these particles are being tracked to see how they accumulate or disperse over time.
3. Wind Direction (WD - Orange Line): Wind direction shows slight shifts throughout the experiment. These shifts could influence how smoke and its particulate matter spread.

In this case, wind direction plays a significant role in determining where the particulate matter from the smoke (PM10 and PM2.5) ends up. A change in wind direction would either blow the particulates toward the PV panels, increasing the concentration, or away from them, potentially clearing the panels and reducing the particulate levels.

Second Chart Analysis:

The second chart focuses more directly on wind direction (WD)

Wind Direction (WD - Orange Line): This line shows more detailed wind direction changes, which correlate with the movement and concentration of particulate matter in the air.

The changes in wind direction seen in the second chart show how particulate matter (from smoke) can be distributed differently based on the direction of the wind. When the wind changes direction, the concentrations of particulate matter shift, accordingly, leading to either more or less accumulation on the PV panels.

Smoke and Wind Interaction:

- Smoke Release: During the experiment, smoke was introduced, generating a significant amount of particulate matter (PM2.5 and PM10). These particles can settle on PV panels and affect their efficiency.
- Wind Direction Influence: As the smoke disperses, wind direction plays a crucial role in determining where the smoke (and particulate matter) will travel. When the wind blows the smoke toward the PV panels, the concentration of PM increases, leading to more particulate matter settling on the panel surface.
- Effect on PV Efficiency: As the wind changes and directs smoke toward or away from the PV panels, there is a corresponding change in the particulate matter concentration, which impacts the PV panel's performance. Higher particulate matter concentrations will block sunlight, reducing the efficiency of the panels, while lower concentrations (due to wind moving smoke away) will allow more sunlight to reach the panels.

Conclusion:

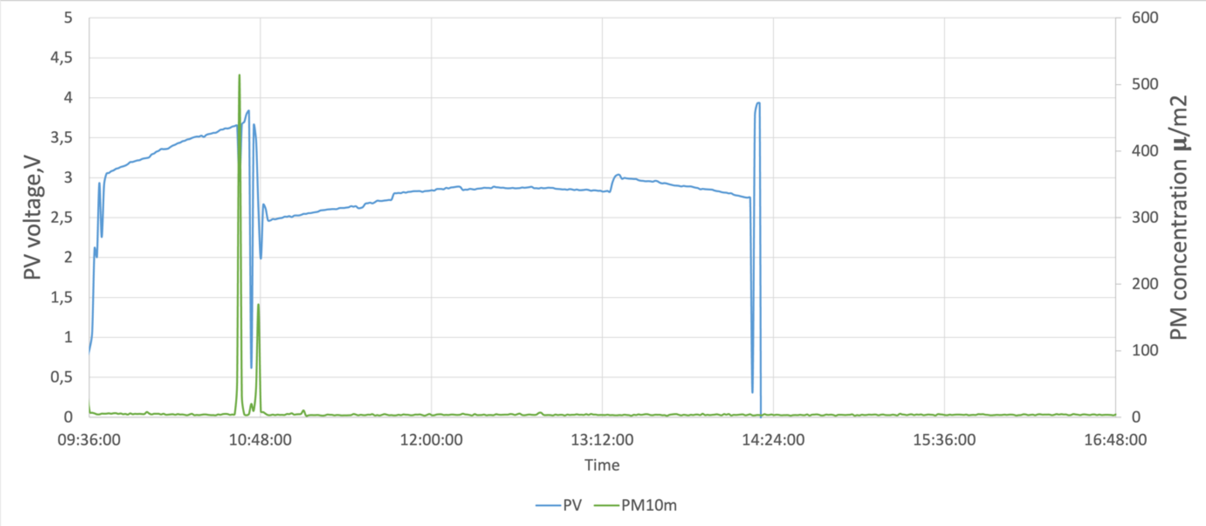
The two charts compare insight into how wind direction affects the dispersal of smoke and particulate matter. In this experiment:

- Wind direction shifts affect where the smoke (and its particulates) settle, influencing the concentration of PM10 and PM2.5.
- As wind direction changes, the particulate matter concentration on the PV panels increases or decreases, which in turn affects the panel's efficiency.
- PV efficiency drops when smoke, driven by the wind, increases particulate matter levels on the panels, obstructing sunlight.

This experiment clearly shows that wind direction is a significant factor in the dispersion of smoke and its particulate matter, and it has a direct impact on the efficiency of PV panels by affecting how much dust and particles settle on the panel surface.

4.3Particulate matter (smoke and dust)

Figure 13 PV output and PM10 levels during smoke experiment



1. **Initial PV voltage (Before Smoke Release):**

- From 09:36:00 to about 10:36:00, the PV voltage (blue line) increases steadily and stabilizes at approximately 3.8–4 kW. This indicates that the PV system is operating at full efficiency in clear conditions, with minimal or no particulate matter in the air.
- The PM10 levels (green line) remain close to zero, showing that there are no significant particles in the air during this period.

2. **Smoke Release at 10:36 (PM10 Spike):**

- At 10:36:00, smoke is introduced into the environment. This is represented by the sharp increase in PM10 concentration (green line), showing a spike as the smoke and particulate matter fills the air.
- Effect on PV voltage: As the PM10 levels spike, the PV voltage drops from its peak of about 4 kW to around 3 kW, indicating that the smoke and its particulate matter are beginning to obstruct sunlight from reaching the panels, reducing their efficiency.
- After the peak, the PM10 levels quickly fall back to near zero as the smoke likely dissipates or settles, but the PV voltage remains lower than before, likely due to particulate matter settling on the surface of the PV panels.

3. **Sustained Drop in PV voltage (After Smoke):**

- Between 10:48:00 and 14:15:00, the PV voltage stabilizes but remains lower than the pre-smoke level. This sustained reduction suggests that the sedimented dust and particulate matter from the smoke have settled on the panels, blocking sunlight and continuing to reduce the panels' efficiency.
- PM10 levels stay low during this time, indicating that there is no more smoke in the air, but the residual particulates on the panel surface are affecting performance.

4. **Cleaning at 14:15:**

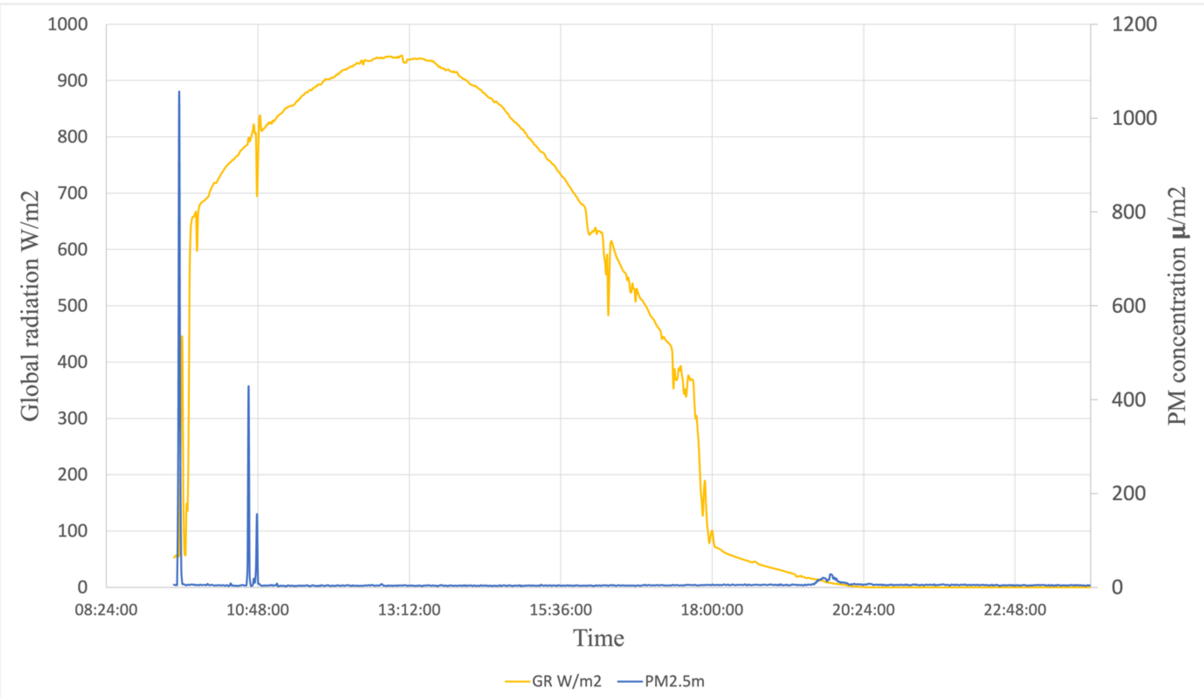
- At 14:15:00, the panels were cleaned. Following this, the PV voltage sharply rises back to its original level of around 4 kW. This indicates that the cleaning removed the dust and particulates that had settled on the panels, restoring their ability to capture sunlight efficiently.
- PM10 levels remain low, confirming that no new particulate matter was introduced during this period, and the improvement in PV voltage was directly due to the cleaning of the panel surface.

Conclusions:

- **Immediate Impact of Smoke:** At 10:36, the smoke release resulted in a spike in PM10 levels and a PV voltage reduction. Sunlight was blocked by the smoke particles reducing the PV panel's efficiency.
- **Residual Effect of Particulates:** Even once the smoke dissipated, PM10 returned to normal, and the PV voltage never recovered to its pre-smoke level. This means particulate matter settled on the panel surface continuing to shade the sun and effect efficiency.
- **Restoration After Cleaning:** By 14:15 the PV panels received their cleaning and returned to their original level of efficiency, as indicated by the rapid rise in PV voltage to the original level. This demonstrated that sustained reduction in PV performance was caused predominantly by the residual particulate matter remaining following the smoke.

This graph does an excellent job of showing the immediate effects and the lasting effects of smoke on a PV system, and how important cleaning is to get your system's efficiency back once it has been exposed to airborne particulates.

Figure 14 Impact of sedimented dust on PV performance during and after smoke experiment



This graph illustrates the effect of sedimented dust on photovoltaic (PV) panel performance during and after the smoke experiment, with a cleaning. Here's a detailed analysis of what the graph shows:

1. **Smoke Release at 10:36:**

- Global radiation (GR W/m²) (yellow line) increases, indicating optimal sunlight conditions.
- The graph shows a significant spike in the PM2.5 concentration (light blue line) shortly after 10:36, indicating the start of the smoke release. This spike suggests that the smoke contains particulate matter that quickly affects the panel, leading to increased PM2.5 levels around the sensor.

2. **Smoke Stops at 10:52:**

- Around 10:52, The PM2.5 concentration begins to decline, which aligns with the cessation of smoke. However, the remaining dust from the smoke particles is still visible in the form of residual PM2.5, indicating that some particulate matter has settled on or near the panel and remains even after the smoke release stops.

Remaining Dust and Efficiency Loss (10:52 – 14:15):

- During this period, although the PM2.5 concentration is lower than the initial spike, there are still some minor fluctuations, suggesting residual dust. The global radiation (GR) line (yellow) maintains a steady curve, indicating that sunlight remains consistent, but the efficiency of the panel might be affected by the dust layer.

Panel Cleaning at 14:15:

- At 14:15, there should be a noticeable drop in PM2.5 levels, which may indicate the removal of dust after the panel cleaning. This would presumably improve the panel's efficiency by removing the accumulated particulate layer.

Conclusion:

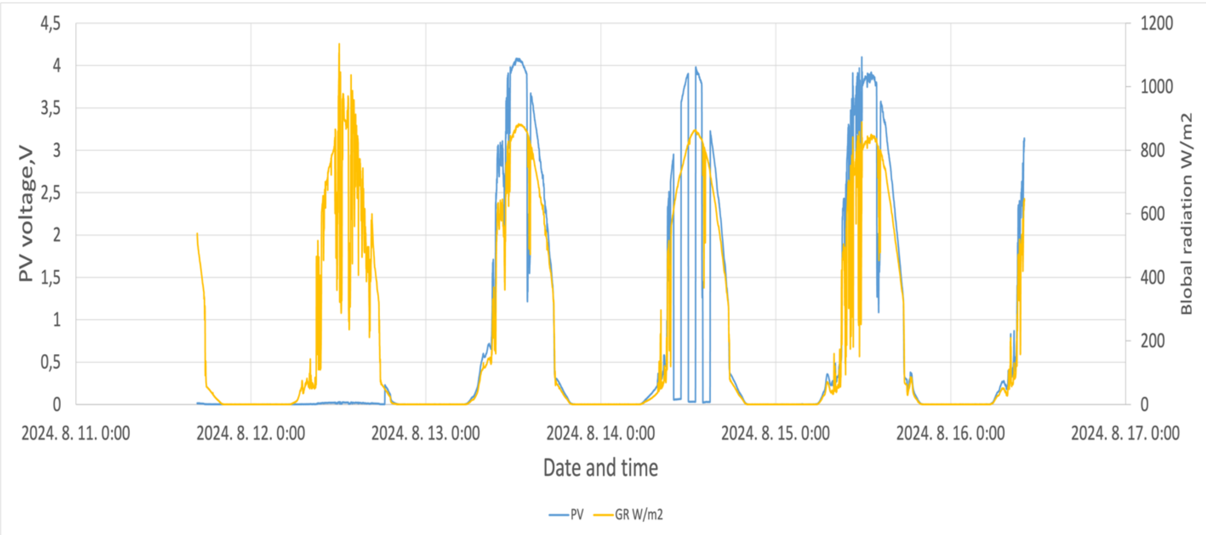
The graph highlights the impact of smoke on particulate matter levels, which in turn suggests potential efficiency loss for photovoltaic panels due to dust accumulation. The drop in PM2.5 levels after cleaning indicates that cleaning is essential for maintaining optimal panel performance, especially in environments with high particulate matter or frequent smoke exposure. This aligns with the findings in the work that smoke and particulate matter can lead to decreased PV efficiency until the surface is cleaned.

4.4 Shadow effect

The shadow effect on photovoltaic (PV) systems refers to the significant reduction in power output that occurs when any part of a solar panel is shaded, even partially. This reduction in performance is often disproportionate to the area of the panel that is covered. Shadows can come from various sources, such as trees, buildings, dust, smoke, or objects placed directly on the panel, such as the liner or net in my experiments.

4.4.1Shadow diagram

Figure 15 Effect of shadow on PV output and global radiation



The graph illustrates the relationship between photovoltaic (PV) and global radiation (GR) over several days, with varying experimental conditions regarding liner coverage. The liner was applied in different configurations to observe its effect on PV efficiency. Below is a detailed analysis of the results, broken down by the periods of the experiment.

August 12–13 (Full-Day Liner Coverage)

From August 12 to early August 13, the photovoltaic panel was partially covered by a liner for a full day. This obstruction caused a significant reduction in PV output, as shown by the blue line remaining substantially lower than the global radiation (GR) curve (orange line). Even though the GR indicates sufficient sunlight was available, the liner blocked a portion of the solar radiation, preventing the PV system from generating electricity at its maximum potential.

The liner's partial coverage significantly reduced the system's overall efficiency by blocking sunlight. The PV output during this period was only a fraction of what could have been generated under unobstructed conditions. Shading from the liner limits the surface area exposed to sunlight, reducing the electrical current generated by the photovoltaic cells. As PV panels are highly sensitive to shading, even partial coverage can drastically reduce their performance.

13–14 August (No Liner – Full Exposure)

This liner was stripped off and the PV panel averted to sunlight. The PV output also rose steeply, and the growth rate function was closely tracked. This is a clear indication of the efficiency of the PV system when there is no interference which would hamper power generation.

This was made possible by the removal of the liner to allow the PV output to increase and reach the available solar radiation levels. The actual power curve has the same trend as the ideal power curve known as the GR curve, suggesting that when a panel comes out in the open it gives off optimal conversion. The discussed photovoltaic system can generate power at the highest achievable efficiency when no shadows are present to obstruct sunlight access to the photovoltaic surface. This phase of the experiment acts as a control of the performance of the PV panel at its peak.

August 14 – 15 (Semi-Continuous Liner – In 1 Hour intervals)

It noted that during this period, the liner was applied and removed probably every hour to study the effects of transient shading. The PV output showed quite a diurnal variation; the blue line declined each time the liner was applied and then rose when the liner was peeled off. However, the GR value was less variable, implying that there was a balance since the coverage of sunlight was almost fixed.

The PV output varied greatly during this period, with significant drops occurring every time the liner was placed on the panel. The intermittent application of the liner caused the PV system to experience repeated reductions in efficiency, like the effect of transient shadows from clouds or other environmental factors. The liner's intermittent coverage is similar to the real world, for example, when trees or buildings cast shadows on the surface. Every time the panel is partially shaded, including for a few moments, the output of the system is reduced greatly, which underlines the fact that PV panels must be always uncovered.

August 15–16 (Liner Removed – Restored Efficiency)

The last step of the experiment was to remove the liner one more time and let the PV panel work at its full capacity. The PV output increased and followed closely along the GR curve as the system was generating electricity efficiently when fully exposed to sunlight.

The PV output was brought back to near maximum level and followed the GR throughout the day. This evidence strengthens the effect of partial shading on the PV performance since the liner removal restored the system's efficiency. When all the surface area of the panel is open to the sun, the PV system can utilize solar radiation to the maximum to produce electricity. The data of this period support the conclusion that shading should not be used for the best performance.

Thus, the data obtained from August 12th to August 16th show that shadowing, in all its forms, has a considerable effect on the performance of photovoltaic systems. During the test when the liner covered the PV panel for a full day, the output was very low even with bright sunlight. The liner was entirely removed to enable full efficiency of the system while when the liner was partially used, the output was stamped by shading effects.

In real-world conditions, shading due to an object like trees, buildings or clouds may result in similar falls in efficiency. The experiment underscores the importance of minimizing shading and keeping the photovoltaic panel exposed to maximize energy generation. The difference in output between the covered and uncovered periods highlights the need for careful site selection and management of potential obstructions when designing solar power systems.

Figure 16 Daily variations in PV output and global radiation (August 26-August 28, 2024)

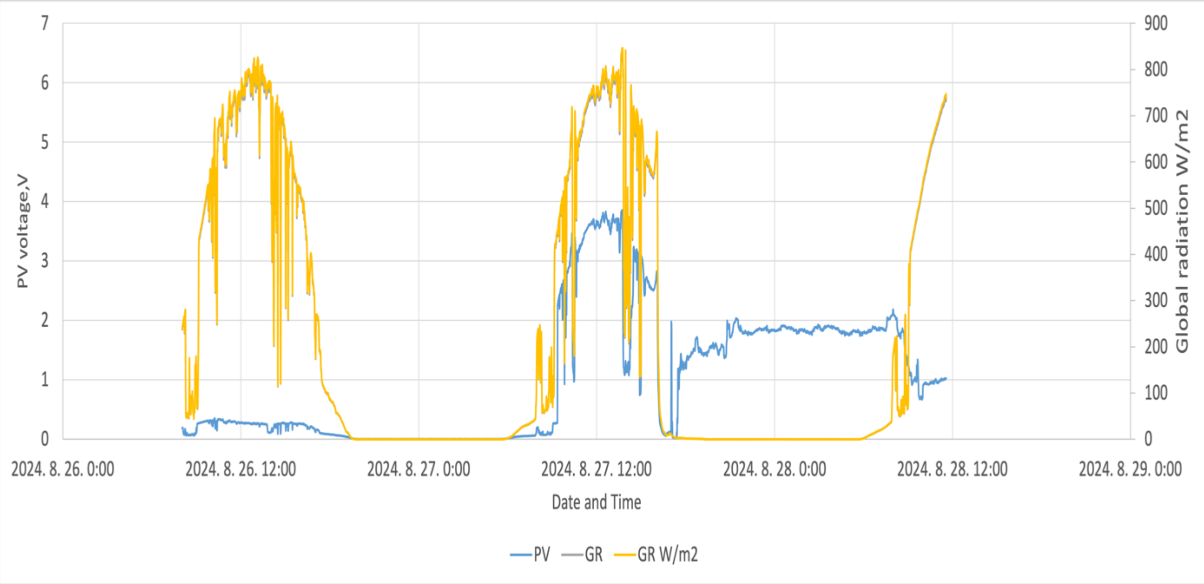
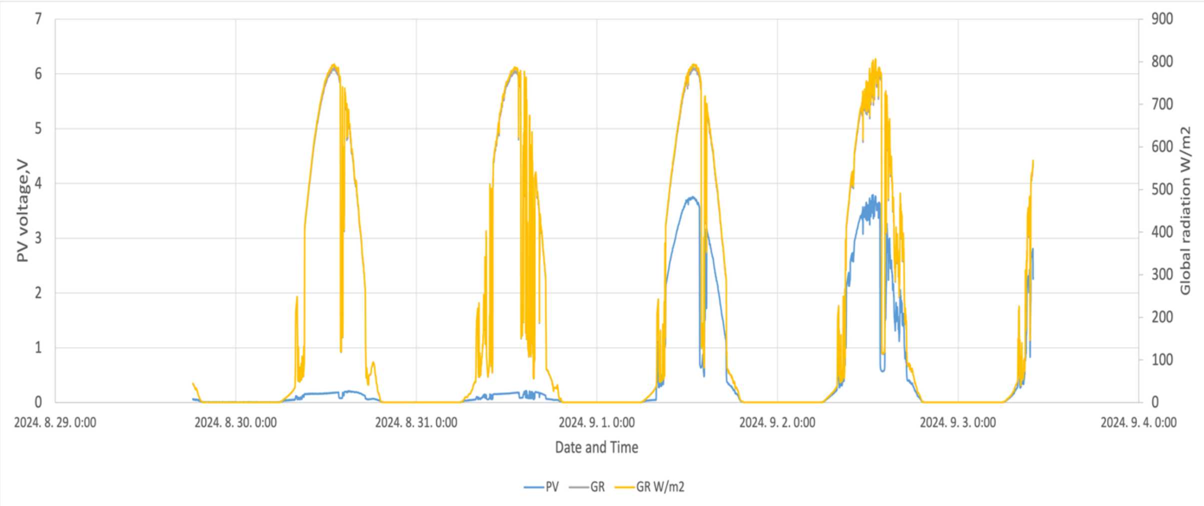


Figure 17 Daily variations in PV output and global radiation (August 29- September 4, 2024)



First Graph (26.08 - 28.08)

This graph focuses on the period between August 26th and August 28th, when you were applying and removing a small liner to the PV panel.

Detailed Observations:

1. **August 26, 2024 (Small liner applied):**

- PV voltage (Blue Line): The PV output remains consistently low, even during peak sunlight hours. The blue line remains well below 1 kW despite high levels of solar radiation.
- GR W/m² (Yellow Line): The yellow line shows significant spikes in solar radiation, reaching around 800 W/m² during the middle of the day. This indicates that, despite optimal sunlight conditions, the small liner dramatically reduced the PV panel's voltage. This shows that even a partial shadow can severely restrict the system's ability to generate electricity.

2. **August 27, 2024 (Liner removed):**

- PV voltage (Blue Line): The blue line shows a clear improvement in the PV output. It rises and closely follows the yellow line (GR W/m²) during the day. This suggests that when the liner is removed, the panel captures more sunlight, and the efficiency improves dramatically.
- GR W/m² (Yellow Line): Similar to the previous day, the global radiation peaks around 800 W/m². However, unlike on August 26, the PV output this time is more consistent with the available sunlight.

3. **August 28, 2024 (Small liner reapplied):**

- PV voltage (Blue Line): Again, we observe a significant reduction in PV output, like what was seen on August 26. The liner reduces the ability of the panel to capture sunlight, even though the solar radiation remains high.
- GR W/m² (Yellow Line): The yellow line again shows strong sunlight exposure, but the PV voltage is not able to capitalize on this due to the shading from the liner.

The conclusion from the First Graph:

- The first graph clearly illustrates the strong negative effect of even a small liner covering a portion of the PV panel. Both the 26th and 28th show low PV voltage, while the 27th, without the liner, shows improved performance, confirming that even partial shading has a significant impact on energy production.

Second Graph (29.08 - 03.09)

This graph extends the timeline, including the period from August 29th to September 3rd, when the liner was removed, and a net was introduced later in the period.

1. **August 29 - August 31, 2024 (No liner applied):**

- PV voltage (Blue Line): The PV output over these days is much higher than on August 26 or 28 without the small liner applied. The blue line closely follows the GR W/m² (yellow line), suggesting that the PV panel is efficiently converting the available sunlight into electricity.
- GR W/m² (Yellow Line): The solar radiation peaks around the same range (700-800 W/m²) during the middle of the day, and the PV system responds well, reaching its peak output.

2. **September 1, 2024 (No liner, no shading):**

- PV voltage (Blue Line): As expected, the PV output closely mirrors the available global radiation. The PV voltage curve is smooth and peaks consistently with solar radiation, indicating that the PV panel is working efficiently without shading.
- GR W/m² (Yellow Line): The global radiation curve is smooth and high during midday, and the PV panel fully utilizes the available energy.

3. **September 3, 2024 (Net applied):**

- PV voltage (Blue Line): On September 3, we saw a noticeable reduction in the PV output, though it was not as drastic as on August 26 and 28. The net introduces a moderate shading effect, leading to a reduction in efficiency, but less severe compared to the small liner.
- GR W/m² (Yellow Line): The solar radiation remains relatively high, but the PV output is impacted by the net. The blue line is lower than it was on the days without any shading (e.g., August 29–31 and September 1).

The conclusion from the Second Graph:

The second graph further reinforces the detrimental effect of shading on PV efficiency. When no liner or net is applied (August 29 - September 1), the PV voltage closely follows the available sunlight. However, on September 3, when the net is applied, we see a moderate reduction in PV voltage, indicating that even lighter forms of shading, such as a net, can still reduce PV system efficiency.

Combined Analysis:

- Impact of Small Liner (26.08, 28.08): The graphs show that even a small liner significantly reduces PV voltage, even when solar radiation is optimal. This suggests that partial shading from small objects or debris can have a large impact on system performance.
- Removal of Liner (27.08, 01.09): The days without shading show a much closer match between PV voltage and solar radiation, indicating optimal performance when there is no shading.

- Net Impact (03.09): The net applied on September 3 introduces some shading but does not reduce PV voltage as severely as the liner did, suggesting that less opaque objects (such as a net) allow more sunlight to pass through and have a smaller impact on efficiency.

Key Insights:

- Partial Shading Effect: The small liner caused a significant reduction in PV voltage, even though only a portion of the panel was covered. This confirms that PV panels are highly sensitive to shading, and even small shadows can lead to a disproportionate drop in performance.
- Net vs. Solid Shading: The net, while still reducing efficiency, had a less dramatic effect compared to the small liner, suggesting that semi-transparent shading (such as dust or smoke) may have a lesser impact than more solid obstructions.
- Optimal Performance Without Shading: On days with no liner or net (August 29–31 and September 1), the PV voltage aligns well with the global radiation, confirming that the PV panel performs optimally when fully exposed to sunlight

The net introduced on September 3, 2024, in the second graph, had a moderate shading effect on the photovoltaic (PV) panel, resulting in a noticeable but less severe reduction in output compared to the small liner that was applied earlier on August 26 and 28.

Detailed Effects of the Net:

1. **PV voltage Decrease**:

On September 3, when the net was applied, the PV voltage (blue line) dropped, though not as drastically as when the small liner was used. The voltage is lower than the preceding days (August 29 - September 1), where the PV system was exposed to full sunlight.

The PV voltage under the net was still capturing a substantial amount of sunlight but not at the optimal level that was seen on days without shading. The voltage line is somewhat smoother but does not reach the peak values seen on previous days.

2. **Global Radiation Remains High**:

The global radiation (GR W/m², yellow line) stayed high, peaking around 700–800 W/m², indicating that there was still plenty of sunlight available. However, the PV system was unable to fully convert this available energy into electricity due to the partial shading caused by the net. This suggests that while sunlight is penetrating the net, it is diffused or scattered, reducing the PV system's efficiency.

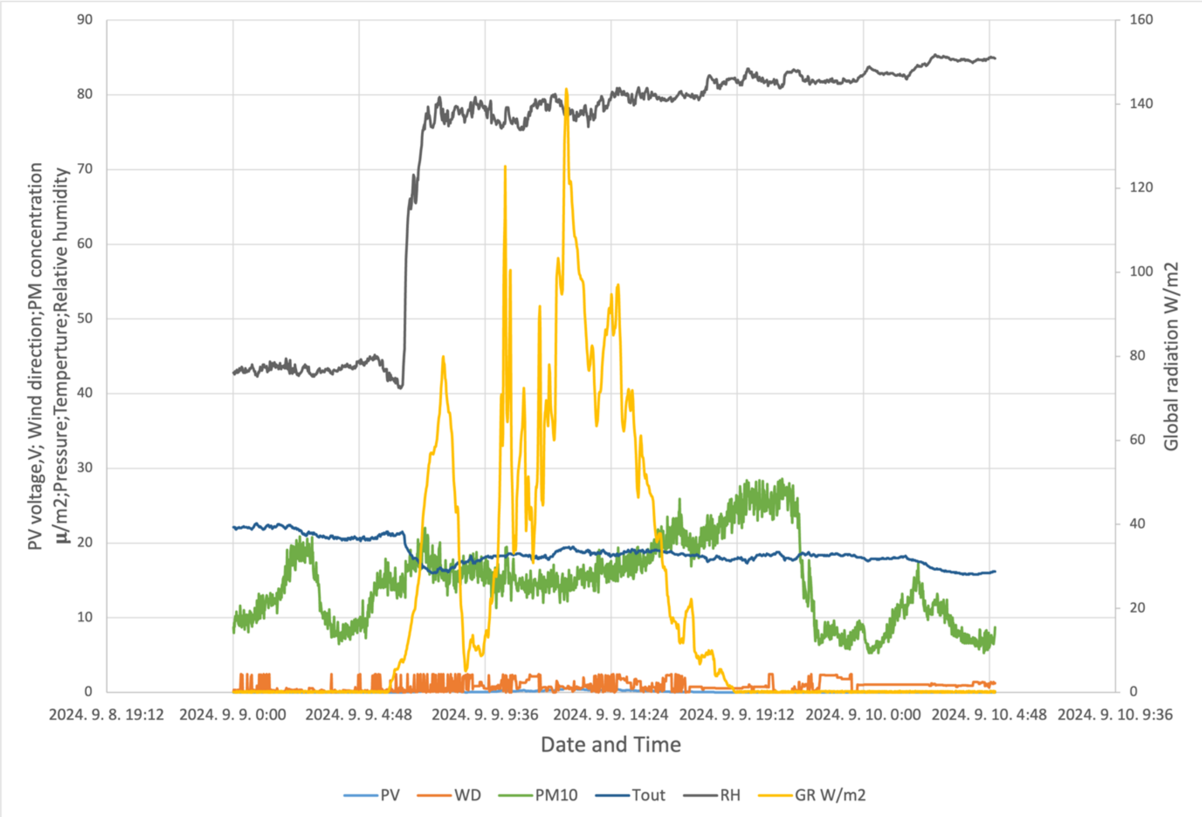
3. **Comparison to Small Liner**:

When comparing the effect of the net to the small liner (on August 26 and 28), the net caused a smaller drop in PV voltage. The small liner caused a much more significant reduction in PV voltage, almost flattening the blue line even during peak sunlight hours. This indicates that lighter, more transparent shading (such as a net) allows more sunlight to reach the panel compared to solid shading (like the liner), though it still leads to some efficiency loss

Conclusion on Net Impact: The net on September 3 had a moderate impact on the PV panel's performance by introducing partial shading. While the PV voltage was lower than on unshaded days, the effect was not as severe as the solid liner. This shows that semi-transparent or diffused shading, such as from a net, reduces energy voltage, but the system can still generate a reasonable amount of power, unlike when solid shadows are cast.

4.5 Impact of Environmental Factors and Rain on PV Performance

Figure 18 Effect of rain and environmental factors on PV performance (September 9 - 10, 2024)



Analysis of Environmental Impact on PV Performance During September 9-10

This section explores the influence of a rain event observed from September 9 to September 10 on the performance of photovoltaic (PV) systems. By analyzing various environmental parameters such as particulate matter, humidity, solar irradiance, temperature, and wind direction, insights can be drawn into how natural weather events impact PV output.

The Impact of Rain on Particulate Matter (PM) Levels

Following the rain on September 9-10, there is a noticeable reduction in particulate matter (PM2.5 and PM10) levels, indicative of the "washing effect" where rain cleanses the air and removes dust from the PV panel surface.

This has consequences for PV performance since the level of PM has been reduced. Dust and particulates can block sunlight, thus the irradiance that falls onto PV cells will be impaired. Cleaning the PV panel by rain ensures more sunlight gets through to the panel increasing the efficiency.

In the areas that are prone to dust or particulate matter, rain can wash off the dust on the PV panels and therefore improving the efficiency temporarily because of cleaner surface. This is especially important for dry climates with irregular rainfall because as studies have shown PV performance may increase within the same day after rain.

Humidity Spikes During Rain

A related finding is that RH increases dramatically during the rain event and then gradually decreases as the rain ceases. There is high humidity during the rain period.

Excessive humidity affects the PV panel surface and causes condensation that may temporarily block the panel from sunlight. However, the continuous rain may counter act this by ensuring that the surface is clean at all the time. Both relative humidity and rainfall are assumed to reduce the amount of airborne and surface dust, and hence their combined presence should result in lower values of dust concentration.

This correlation between rain and humidity shows that rain has a two-way effect on PV performance. Even though the high humidity that is associated with rain leads to condensation, it also improves the particulate clearance making the environment better. These results imply that in humid and rainy environments, PV systems are less affected by particle shading.

Solar Irradiance Reduction During Rain and Rapid Recovery Post-Rain

Dark grey thick clouds during the rain reduce the amount of solar radiation incident on the PV system (GR W/m²). Nonetheless, irradiance levels are known to rise quickly as soon as rain stops.

This brief decrease in irradiance shows how PV systems are affected by clouds that are usually followed by rain. This is evident by the fast power output improvement in the post-rain period to demonstrate that PV systems can adapt to the changing weather conditions to produce power at the right time when the sun comes out.

In seasonal regions with unreliable weather conditions, the fast response of the PV system to varying irradiance underlines the need to integrate dynamic forecasting to enhance PV generation forecasting. This indication clarifies the need for adaptive monitoring systems in the PV installations affected by weather conditions.

PV voltage Response to the "Cleaning Effect" of Rain

After the rain event, PV voltage shows a significant increase which can be attributed to the so-called “rain washing” effect. Rains wash off the dust that may have piled up on the panel surface thus improving on the light-trapping mechanism.

This self-cleaning mechanism is particularly useful in areas with high levels of dust deposition, in which rain may be utilized as a temporary means of improving the efficiency of photovoltaic panels without the need for intervention by human beings.

This paper identifies how rain has a positive effect on PV voltage to guide maintenance in dusty regions. Rainfall can wash off dust from the panels thus decreasing the frequency of cleaning and hence the cost of maintaining such panels in such areas.

Temperature and Humidity Effects Post-Rain

The rain event also has the effect of cooling the environment, by lowering and stabilizing the temperature. As PV panels usually have higher performance at lower temperatures, such cooling effect may enhance the efficiency of PV systems.

It is well understood that high temperatures are detrimental to the performance of PV panels, and hence the rainfall may assist in mitigating this effect, especially with high irradiance levels following rain.

In the arid regions, rainfalls are beneficial in two ways; they cool the environment and wash the panels. This cooling may prove useful in preserving the efficiency of PV during periods when temperatures usually decrease panel efficiency.

Wind Direction and Particulate Dispersion

It is possible to identify some relation between wind direction (WD) and changes in particulate matter. Before the rain, changes in direction may have resulted to the formation of particulates which could be easily washed away by the rain.

Wind direction affects the spread of dust and debris around the PV panel surface and hence affects the performance of the system. There are certain wind conditions that might cause particulate levels to increase thus increasing the dust deposition on the PV surface and thus decreasing the PV efficiency.

This means that the wind flow patterns, and particulate dispersion can be useful in PV system maintenance, particularly in areas that are characterized by high dust incidence depending on the wind direction. Rain events can be therefore considered as a part of the natural cleaning process, which helps to remove particulates that are brought in by some wind conditions.

Conclusion

The analysis of this period reveals several insights into the impact of rain and environmental factors on PV performance:

- **Natural Cleaning Effect:** Rain removes particulate matter from the surface of PV panels meaning the panels receive more direct sunlight and produce more energy after rain.
- **Humidity and Condensation:** Humidity is useful in the removal of dust during rain since water may for a while affect the panel's transparency.

- **Cooling and Irradiance:** This is because rain creates a cooling effect which results to high PV efficiency notably after periods of high irradiance recovery.
- **Wind and Dust Patterns:** Changes in the wind direction may result to high particulate matter before rain and a rain wash, hence creating a cycle effect on the PV performance.

These results show that PV system performance is significantly influenced by environmental conditions. In climates with seasonal rains, PV efficiency may benefit from periodic natural cleaning and cooling events. This understanding could contribute to more efficient maintenance schedules and adaptive forecasting models for PV systems in variable environments, particularly in areas with similar climatic conditions to those studied here.

5. Conclusion

This thesis has critically assessed how different conditions that prevail in the environment and influence the PV systems' performance including particulate matter, shading, rainfall, wind, and temperature. We have established the most important findings and recommendations derived from the findings and the data analysis through the course of the research in the areas of photovoltaic application and operation in various environmental conditions.

The research shows the fact that smoke and particulate matter affect the efficiency of PV panels in a major way. These experiments also indicated that not only did smoke particles block direct sunlight, but they also accumulated on PV surfaces as dust, which also decreased output. These results should be particularly useful in regions with intense dust or pollution, in which PV systems cleaning may be needed. For those not able to clean as often there are options like anti-soiling together with self-cleaning technologies to be considered.

Concerning shading, the analysis showed that shading impairs the performance of PV systems greatly, even partial shading caused by minor objects or debris on the surfaces, or by buildings and trees. Interestingly, both small and large shading areas had a profound impact on the output implying that even partial shading is destructive to the energy production. Such processes as selection of location, orientation of PV panels, and application of devices and equipment such as micro-inverters or optimizers could reduce negative effects of shading and increase efficiency.

Rain events naturally clean PV surfaces, temporarily increasing efficiency by removing accumulated dust. Rain not only restores panel clarity but also provides cooling, which is particularly beneficial for efficiency in hotter climates. The findings suggest that in regions with seasonal rain, such natural cleaning can partially reduce the need for manual or automated cleaning interventions, making PV systems more cost-effective over time. However, in arid climates with minimal rainfall, proactive cleaning solutions remain essential to maintain optimal performance.

Wind direction and speed play an influential role in dust accumulation patterns on PV panels. Understanding these local wind dynamics can inform placement strategies and influence maintenance routines, such as placing panels away from areas with high wind-driven dust flow. The study also found that wind could provide a cooling effect, which offsets temperature rises in PV panels, contributing to a minor yet positive effect on efficiency, especially in regions with high ambient temperatures.

Higher temperature holds a disadvantage in the efficiency of PV because the electrical resistances of PV cells rise. This study supports the hypothesis that going beyond the best temperature levels can lead to low production. But still, the effect of rain or wind is to some extent alleviated by evaporation, especially in the hot climate. Next-generation PV systems should consider integrating passive or active cooling features to mitigate the impacts of temperature on system performance in any weather condition.

The conducted experiments show that the performance of the PV system depends on the climatic conditions and stresses the need for appropriate management strategies. For instance, in areas with high dust levels and low water frequency, it is necessary to clean the surface by hand or through machines. On the other hand, in areas that are characterized by seasonally predictable rainfall, then natural cleaning is used. The sensitivity of PV panels to even small levels of shading indicates that installations should ensure the panels receive direct sunlight, and wind analysis may be useful in determining the best placement to reduce dust buildup.

Future work may also examine other forms of automated adaptive maintenance like the use of robotic cleaning or monitoring systems that use sensors to decide when cleaning is necessary based on the current environmental conditions. Furthermore, future studies on the anti-soiling coatings and advanced cooling mechanisms may lead to greater improvement in PV efficiency in different climates.

In conclusion, this thesis provides insights into the effects of environmental factors on PV systems and recommendations for improving the performance of these systems in the real world. This makes it possible to control the performance of the PV system according to the prevailing environmental condition and at the same time enhance the life expectancy of the PV systems. These findings could be useful for the further promotion of solar energy, especially in areas with problematic weather conditions.

6. Summary

This thesis aims to examine the impact of environmental factors on the performance and efficiency of photovoltaic (PV) systems, with primary consideration being on particulate matter, wind, shading and temperatures, Photovoltaic or PV technology that harnesses energy from the sun to produce electricity is widely embraced due to its renewability. Nevertheless, practical situations present several issues with PV efficiency, including dust, smoke, temperature variations, and shading by nearby objects.

This is followed by a review of the literature reviewing the history and growth of PV technology, the environmental benefits of its use, and the effect of various environmental factors. It reviews current knowledge about the impact of conditions such as dust deposition, shading and heat on the PV system performance and the ideas that have been put forward to address these issues.

The research methodology used in the present study is experimental research and observation of the environment. For instance, controlled smoke tests were carried out to explore the impact of particulate matter on PV efficiency; it was noted that small particulate matter hampers the PV's ability to gather and convert sunlight to energy. Similarly, shading tests demonstrated that partial shading could form current barriers in PV cells that reduces the cell efficiency and sometimes may result in cell cracks. Temperature variations were also incorporated into the analysis, and it was found that high temperatures impact PV performance by raising the electrical resistance of the cells.

As a conclusion of these experiments, we can state that environmental conditions play a major role in the PV system's efficiency. The thesis provides several suggestions for preventing these effects, namely better panel tilt, cleaning regimens, shade assessment, and upgraded materials and tactics, for instance, self-cleaning coatings, microinverters, and cooling systems. The following are strategies that may be taken to improve the performance of PV systems about environmental factors to encourage the utilization of solar energy in various environments.

In conclusion, this thesis offers practical implications for improving PV systems' performance in the context of environmental conditions. The outcomes of this work will be useful to engineers, scientists, and policymakers involved in the design, construction, and operation of PV systems to increase their performance, durability, and productivity across the world. As future research and development work progresses, these findings can help expand the application of PV technology and play a very important part in meeting sustainable energy objectives and combating climate change.

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