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A novel solar panel cleaning mechanism to improve performance and harvesting rainwater

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ABSTRACT

First generation Photovoltaic (PV) systems need regular washing to avoid efficiency degradation. Dust deposition on the surface limits solar penetration into photovoltaics and consequently the PV output. Efficiency may fall by 50% after a month without cleaning the modules. This effect strongly depends on the area, being desert climates more problematic because of the proliferation of dust particles and eventual high wind speeds. This research aims to illustrate the idea of an innovative intelligent device with wide applications and advantages, which improves the efficiency of solar cells by a self-cleaning mechanism, keeping the temperature of solar cells from rising, recycling the cleaning water, and harvesting rainwater falling. In this research, an experiment was performed in the city of Salt (Jordan) to investigate the purification of solar cells at the energy production plant above the Najashi Mosque. To clean the dust periodically, an automated cleaner was installed that detects the dust on the solar panel and automatically cleans the module. Various cleaning methods were compared: manual cleaning, automatic cleaning, manual injection water, compressed air. Some outstanding features of the new proposal are identified, making it the ideal device for resolving cleaning difficulties, high temperatures, and increasing solar cell performance. It can be also utilized to gather rainwater by employing the vast areas of solar cells scattered over the world. The findings of this study may help in preserving the environment by harvesting sun and rainwater, enhancing PV efficiency, and achieving decarbonization in the energy industry.

1. Introduction

Renewable energy generation accounted for around 29% of global power generation in 2020 (Iea, 2021), with a two-percentage rise annually. Countries must dramatically increase the number of renewable energy installations in order to reduce global energy-related carbon dioxide emissions to zero by 2050 and ensure that the world has an equal chance of staying below 1.5 °C (Iea, 2021). To meet these goals, renewable generation generation should increase by 12% on average during the period 2021–2030, about twice as much as it did from 2011 to 2020 (Iea, 2021).

Solar energy refers to the $1.73 \cdot 10^{17}$ Watt-hour of solar power that reaches the Earth. Solar energy is used in two ways to improve our lives: solar heating and solar power. Direct conversion of solar energy to electricity is now widely recognized as a viable source of energy. Photovoltaic (PV) cells create energy through a process known as the photovoltaic effect (Roberts, 2019). Normally, the solar cell absorbs two-thirds of the sunlight that falls on the panel's surface, and one-third of the sunlight that reaches the panel's surface has a possibility of being reflected. The front glass is the heaviest element of the solar module and serves to protect and ensure the strength of the complete photovoltaic module while maintaining a high level of transparency. Depending on the type of glass used, the thickness of this layer might range from 2 mm to 4 mm. It is critical to maintain the cleanliness of this layer in order to benefit from its properties such as spectrum transmittance, and light transmittance (Svarc, 2020).

Renewable energy has the advantage of being environmentally friendly, which means that it is "non-harmful" to the environment. Furthermore, it is plentiful and a naturally occurring resource. Despite the development of new higher-performance materials, the major drawback of PV systems is their low efficiency in converting sunlight to electrical energy, where the highest reading of solar cell efficiency was

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31%.in thin film crystalline silicon (Bhattacharya and John, 2019).

Not all the bright radiation is converted into electric power by PV panels since most of it is wasted due to a variety of factors that influence panel efficiency. The primary elements that impact on the panel performance are dust deposition, high temperature, sunlight spectrum, panel orientation, and angle of inclination (Vidyanandan, 2017). This work is focused on dust depositions and how they affect the efficiency of solar panels. Fig. 1 shows the factors that mainly influence dust settlements (Mani and Pillai, 2010).

Frequently, dirt particles have a diameter lower than 10 µm, although this issue strongly depends on the location and environment (Maghami et al., 2016). Two factors influence the efficiency degradation. On the one hand, properties of dust include the dimension of particles, form, and color (Ghosh, 2020). Particulate matter is defined as dust particles and liquid mixtures suspended in air (PM). PM2.5 and PM10 are particulate matter of airborne dust particles with aerodynamic diameters of 2.5 µm and 10 µm, respectively. Getting rid of PM2.5 is even more difficult than getting rid of PM10. It was discovered that increasing the tilt angle of the PV results in less dust deposition, but light rain aids in greater dust settlement (Enaganti et al., 2022). In contrast, heavy rain and melting snow can be beneficial, removing partially or totally the dust accumulated in panels (Şevik and Aktaş, 2022). Soiling has a negative impact on economic revenues, not only because it reduces the amount of energy converted by PV modules, but also due to it introduces additional operating and maintenance costs, while also increases uncertainty in PV performance estimation, resulting in higher financial risks and prices imposed on factory developers. Contamination has been linked to energy reductions of more than 50% in the literature; it has been calculated that a 4% loss in worldwide yearly PV income can result in revenue losses of $109 per year (Smestad et al., 2020). To illustrate how the dust particles may be accumulated in solar panels, Fig. 2 shows various photographs taken in Al-Najashi mosque in the city of Al-Salt Jordan,)32°02′41.8″N 35°43′21.4″E). These panels were exposed to mineral dust and agricultural emissions, due to the nature of the geographical area.

The performance of PV modules in different places is affected by environmental variables that vary from place to place across the world. Solar radiation, wind velocity, rainfall, temperature, humidity, and the likelihood of dust present are all factors that might affect PV module performance (Mustafa et al., 2022). Although the effect of dust depositions may be observed worldwide, its effect is more notably in arid climates due to an increase in dust deposition in time, usually called pollution loss (Bubnova, 2016). The Middle East has the worst dirt build-up regions, with peak losses ranging from 10% to 70% (Ghosh, 2020).

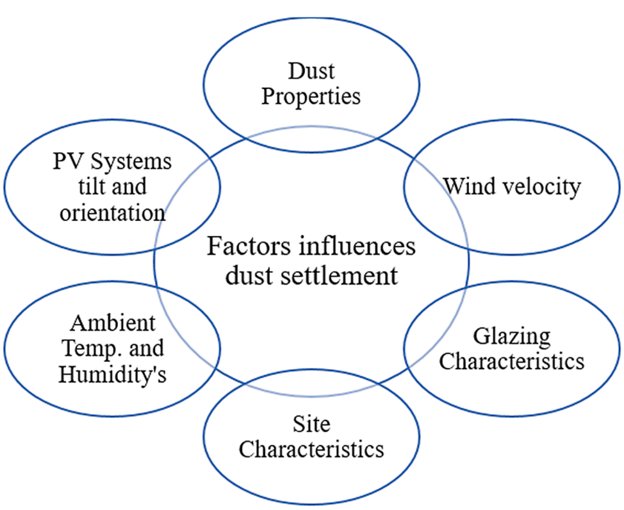

Fig. 1. Factors influencing dust settlements (().
adapted from Mani and Pillai, 2010

The photovoltaic system's economic and environmental benefits have made it the most sustainable clean energy alternative for poor nations to meet SDG-7. Aside from its low efficiency, which has been the topic of significant research throughout the world, dust has a direct impact on its performance (Chanchangi et al., Dec. 2021). For the varying amounts of ash deposited on the PV panel surface, they compared the power output drop of the intentionally polluted panel with the clean one control. The panel power output decreased by 2.3 %, 7.5 %, 17%, and 27 % for ash mass depositions of 0.63 g/m^2, 1.89 g/m^2, 3.15 g/m^2, and 3.78 g/m^2, respectively. Other studies showed that the efficiency of PV modules may decrease by 50% in some arid climate regions (Dacheng Li, 2021). Typically, solar panels are cleaned periodically by some qualified personnel using two different methods dry and wet cleaning, as dry cleaning is more common in desert and dry areas, and is often used due to lack of water or difficulty in accessing it. One of the disadvantages of dry cleaning is that it may cause scratches on the first glass layer in the solar cells, which causes permanent damage to the panels. As for wet cleaning, it spreads in areas where there is a nearby water source and in-home systems, with easy access to the panels for cleaning. Water or other cleaning fluids can be used, depending on the type of spots that are on the solar panels.

The major contribution of this study is the development of a pilot platform to improve photovoltaic system efficiency by cleaning solar cells in the simplest, cheapest, and safest method possible. This is accomplished by installing a light and intelligent system that performs soft self-cleaning as needed to repel all potential contaminants on the PV panel's surface. Furthermore, the method allows users to collect rainwater on the panel's surface and utilize it for irrigation or other purposes, improving the performance ratio and power output of the whole system. The controller, water pump, water gutter, pipes, reservoir, sprinklers, clamps, temperature sensor, and filters are among these components. The technology has no effect on the panels because it simply utilizes water to clean them, and it requires no more maintenance than replacing water filters on a regular basis.

The described mechanism aims to solve the cleaning problem definitively, with the possibility of using it in all places as an alternative solution to water shortages in the desert and dry areas, thus eliminating the method of dry cleaning by collecting rainwater and using it for cleaning and recycling cleaning water by passing it through dedicated filters, and it can also be used to exploit and clean existing solar cells. In difficult-to-reach places, such as tile roofs.

In the rest of this paper, Section 2 analyzes the effect of dirt on solar panels efficiency. Section 3 reviews some conventional cleaning methods, highlighting their main advantages and disadvantages. Section 4 analyzes the costs of cleaning solar panels. Section 5 describes in depth the proposed cleaning mechanism. This paper is concluded with Section 6.

2. The effect of dirt on solar panels efficiency

The efficiency of a solar panel is determined by various factors. In essence, it is based on how much incoming sunlight it can convert into useful power. But what elements go into determining the final conversion rate? When designing and manufacturing high-efficiency solar panels, researchers and manufacturers consider the following factors:

- Material - The kind of material (monocrystalline silicon, polycrystalline silicon, cadmium telluride, thin-film, and so on) influences how light is converted to electricity.
- Reflection – the efficiency of a solar panel may be reduced if the light is reflected away from it. The importance of the glass layer on top of silicon solar cells is due to this.
- Light wavelength/frequency - light is made up of photons, which vibrate at a variety of frequencies to produce the visible and invisible light released by the sun. Depending on their frequency and wavelength, some photons are reflected, some pass right through, and

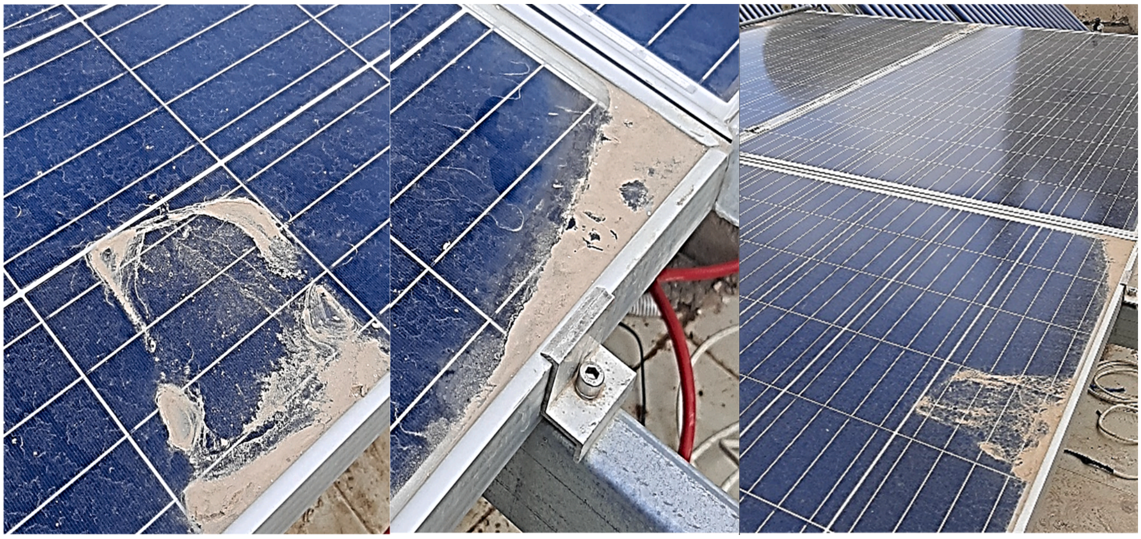

Fig. 2. Exemplary photographs of soiling mineral dust in Al-NAJASHI mosque, Al-Salt, Jordan.

others are absorbed when light strikes the surface of a PV cell. Some of the absorbed light may be converted to heat, while the remaining photons have enough energy to free electrons from their atomic bonds, resulting in an electric current.

- Positioning and angle - proper solar panel installation and an optimal angle are essential for capturing the most amount of sunlight. In this regard, Ghsoh (Ghosh and Neogi, 2017) conducted an experiment to investigate the effect of precipitation in eliminating dust from four glass panels set at different angles: 0, 90, 30, and 60°. The experiment found that rain water easily washes away dust accumulated on glass surfaces with an inclination of 30 and 60°, but rain water struggled to wash away dust placed on glass with an inclination of 0 and 90°.
- Temperature - the efficiency and energy of PV modules both decrease linearly with the operating temperature, according to a correlation between solar energy efficiency and energy dependence on temperature. As the ambient temperature rises, the power of the PV modules decreases by 0.5 %/°C, and the efficiency decreases by 0.05 %/°C (Li, Jul. 2021). And the efficiency of the dusty photovoltaic panels is measured, the average daily efficiency decreases in the range of 0.607% to 0.768%. During a 6-month experiment, the energy loss due to dust ranged from 8.140 kW/m^2 to 10.282 kW/m^2, which corresponds to the average daily loss due to dust accumulation of 1.03 and 0.82 USD per day.
- Climate - the effectiveness of your solar panels might be affected positively or adversely depending on where you live and the sort of weather you have.
- Shade - even a slight shadow on a single panel might reduce the overall efficiency of the system. It all comes down to turning more incoming sunshine into electricity in the end.

SunPower brand is the foremost effective solar panel on the market nowadays, with proficiency evaluations as tall as 22.8%, even though the bulk of panels have proficiency evaluations extending from 16% to 18% (Aggarwal, 2021). A wide range of research on the influence of dust has been undertaken across the world, although the environment and period are different. In important studies on the effect of dust on solar photovoltaics (Sulaiman et al., 2014). Fig. 3 represents the results of solar energy generation from solar panels in five distinct conditions: clean, talc, dust, sand, and moss. The experiment was carried out in a

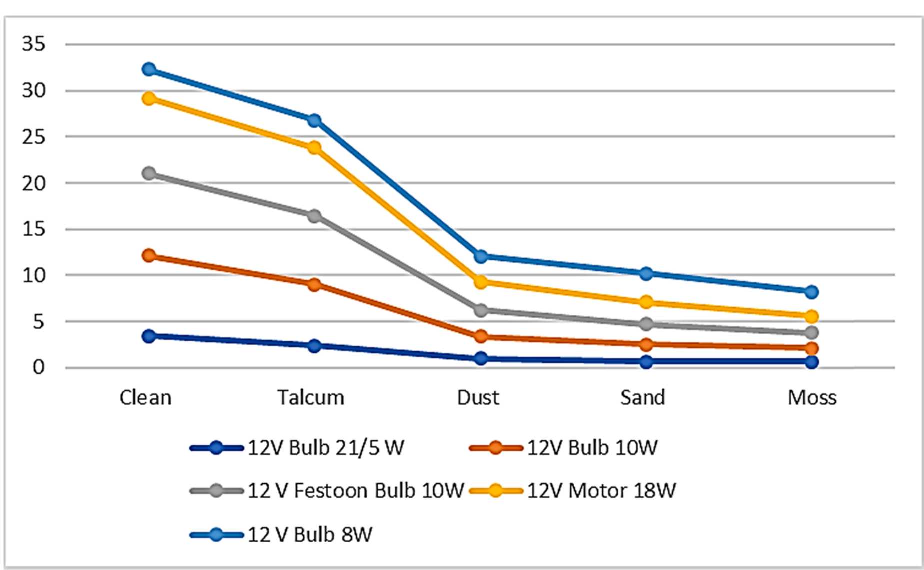

Fig. 3. Outcomes of generating solar energy from solar cells in five different conditions: Clean, Talcum, Dust, Sand, and Moss, respectively (Sulaiman et al., 2014).

laboratory by exposing the solar cells to the following light sources: 12 V Bulb 21/5 W, 12 V Bulb 10 W, 12 V Festoon Bulb 10 W, 12 V Motor 18 W, and 12 V Bulb 8 W.

The results of the above experiment prove that the generated solar energy decreases significantly during the accumulation of dirt on the surfaces of solar cells, as this dirt varies according to the surrounding environment.

Fig. 4 analyzes the yearly financial cost of efficiency loss due to dirt and dust accumulation for solar farms of various capacities. the amount of annual cost loss due to dust collection is projected to dramatically rise, especially for bigger solar farms. A simple calculation indicates that annual loss for an individual farm due to dirt collection might be in the hundreds of thousands of euros. As a result, selecting an appropriate and cost-effective cleaning process will boost maximum lower production while reducing environmental impact (Farrokhi Derakhshandeh et al., 2021).

The following equation is used to calculate the efficiency of the system (η):

$$\eta = \frac{P_{out}}{P_{in}} \tag{1}$$

where $P_{out}$and P_{in} represent the input and output power, respectively. The entire PV system (1) is related to cell efficiency (η_1), cell operating temperature (η_2), losses due to Joule effect on conductors as PV-transformer (η_3), inverter efficiency (η_4), maximum power point tracking (MPPT) (η_5), and finally panel soiling surface (η_6) (Farrokhi Derakhshandeh et al., 2021). Thus, the expression (1) may be further developed, as follows:

$$\eta_{pv} = \eta_1(t)\cdot\eta_2\cdot\eta_3\cdot\eta_4\cdot\eta_5\cdot\eta_6(t) \tag{2}$$

It is expected that η_{pv}fluctuates over time as a result of both cell degradation ($\eta_1(t)$) and dust accumulation ($\eta_6(t)$) during PV system operation (Farrokhi Derakhshandeh et al., 2021).

3. Conventional cleaning methods

Many studies on various techniques for cleaning PV panels with water have been conducted. Furthermore, considerable effort has been expended in the development of water-free approaches. Such integrated studies are rapidly becoming an important solution for producing more electricity and conserving water. Cleaning approaches can be broadly classified as follows after reviewing various studies.

3.1. Manual solar panel cleaning systems

Many methods can be used to clean solar cells besides manual cleaning, for example, natural cleaning (wind, rain, melting snow), water cleaning, hydrophobic surface, ultra-hydrophilic surface, and electrodynamic screen in photovoltaic cleaning (Jamil et al., 2017). Cleaning was traditionally done by humans. Manual cleaning has drawbacks such as the risk of employee injuries and panel damage, movement difficulties, and poor maintenance, etc. ***([22]). This technique needs many repetitions and can be time-consuming. If human labor is required to clean the surfaces, non-conductive materials such as brushes, cloths, and other tools should be utilized to avoid electrical damage and limit the danger of electric shock (Zahedi et al., 2021). The amount of water consumed is affected by environmental conditions. In the Middle East, for example, solar panels consume 0.5 L/m^2 (Jones et al., 2016) when cleaning large-scale PV power plants, such as MW PV power plants, manual cleaning requires more people, takes longer, and is difficult to clean all panels at once. Many water-based cleaning solutions for PV panels are being investigated, however, water is required for all of them. In this sense, it is not always possible to utilize that procedure worldwide due to difficulties to purchase water in some countries (Jaiganesh et al., 2022).

3.2. Vacuum cleaning

A vacuum suction cleaner is a device that employs an air pump to generate a partial vacuum to collect dust from carpets, windows, and other surfaces. The vacuum cleaner motor, which provides suction pressure, is usually supplied with an electrical feed. Essentially, the input power is transformed into the airflow and measured in air watts. Because physical motions on the panel with cleaner are unavoidable, thorough operator training is required. Scratches and dust build up over time, resulting in poor solar insolation absorption (Hudedmani et al., 2017).

3.3. Electrostatic precipitator

Without causing any physical contact, the electrostatic precipitator

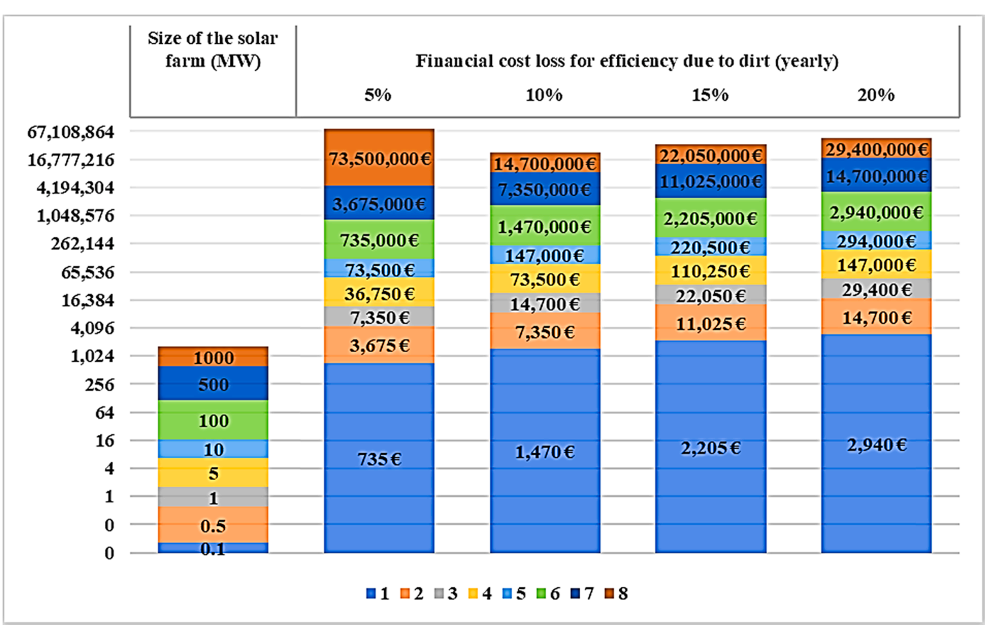

Fig. 4. Annual financial cost of efficiency loss due to dirt and dust accumulation, based on data from (Farrokhi Derakhshandeh et al., 2021).

(ESP) cleans and maintains the top surface of the panel. An ESP is a filtration device that removes microscopic dust particles from the surface of a solar PV panel using the force of an induced electrostatic charge. The electrodes of an ESP receive power through a relay when control signals after collecting the weight of the PV panel and comparing it to a specified value. The negative electrodes of the ESP establish a negative charge on the dust particles on the panels (Altıntaş and Arslan, 2021). This method is however not suitable for collecting gaseous contaminants, and it is not a safe method for dwellings since the panel may shake, loosening its attachment to the roof and causing damage if it falls.

3.4. Coatings with nanoparticles

Scientists of the International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI) unit of the Hindu Department of Science and Technology have developed a solar panel coating to prevent dirt from accumulating in harsh environments. In India, a combination of high temperatures, high humidity, and high pollution reduces PV panel efficiency. The nanoparticle-based technology repels dust so that it is easily washed off with water and is highly transparent so that the coating does not reduce panel efficiency.

Applying an additional coating to clean PV surfaces will not always boost its efficiency. Actually, an additional layer will diminish sunlight transmissivity. It is essential to remember that efficiency is only obtained when the dirt-induced lower light transmission is eliminated with the assistance of the coating. To keep the PV modules clean, it is necessary to wash them regularly.

3.5. Automatic wiper cleaning systems

To run the brushes or wipers, a set of mechanical devices like motors or robots is required, and to clean the PV panel surface, a water storage tank with sprinklers are used (Brahmbhatt, 2018). Power consumption of cleaning robots varies depending on the angle of the solar panel, wind speed, and thickness of the dirt layer. It has been proven that when the wind speed rises, the power consumption increases as well (Baloushi, 2018).

One of the solar cell cleaning tests carried out above AL-Najashi Mosque by the team of this study paper was an experiment employing one of the mechanical methods, in which automobile wipers were utilized for cleaning, as they usually show high efficiency, but on the other hand, some problems were found and observations like wipers do not cover the entire area of solar panels. In addition, the wiper blade must be tested every six months and replaced once a year, resulting in a comparatively high maintenance expense. The squeegee and metal wheels should be checked frequently to avoid problems such as skipping or scratching and the solar panels. Fig. 5 shows the wiper mechanism prototype used to clean the surfaces of solar panels, and Fig. 6 shows the 3D-CAD model for the wipers mechanism of a solar panel.

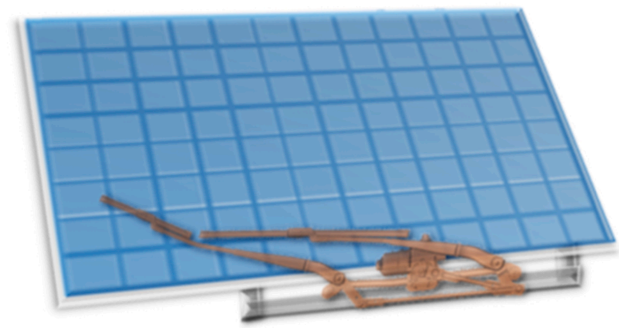

Fig. 6. Car wipers 3D CAD Model and simulation.

3.6. Robotic cleaning solutions

There are various industrial-grade robotic cleaning technologies available currently. Depending on factors such as cost, the convenience of usage, and performance rate. etc. Cleaning robots are commonly utilized. One of the most well-known is RobuGLASS, which uses a water-based technique to clean the entrance to the glass pyramid of the Louvre Museum in Paris, France (Sweezey, 2009). Cleaning robots must be operated on the surface of the solar panels to clean them. Photovoltaic panels, on the other hand, are slanted at an angle to increase solar radiation absorption. As a result, robots must have a method for committing to walking on the surface of the PV panel. There are two types of attachment systems created for robots to walk on sloping surfaces, some of the existing autonomous robots on the worldwide market are poor at cleaning solar panels due to their large weight and a place is allocated to the beginning of each row for the device to stand in without casting a shadow on the panels, and the device is programmed to move on each row of panels separately (Pickerel, 2017).

The advantages and disadvantages of the most prevalent cleaning technologies for solar panels are listed in Table 1. Observing this analysis, it can be concluded that the cleaning quality, labor risk, panel damage risk, water and electricity consumption, and cost of suppose the major issues in most of the existing cleaning technologies.

4. Cost evaluation of cleaning solar panels

Pollution is one of the factors affecting the operation and maintenance costs of PV panels. As a result, they must be considered, especially in desert areas. The cost of cleaning PV systems is mostly determined by the frequency with the economics of removing dirt and snow off PV systems (Stridh, 2012). In this regard, three different European areas were investigated in. The results of this research showed that there is no economic advantage to cleaning in Helsinki (Finland) and Stockholm (Sweden), however, there is an economic gain in places like Murcia (Spain) and Munich (Germany) (Zahedi et al., 2021), in which panels could be cleaned over a certain period depending on the month (Fathi et al., 2017).

Fig. 5. Cleaning solar panels by car wipers, a pilot project.

Table 1
comparison of cleaning technologies.

	Cleaned Surface Quality	Labors Injuries Risk	Electric Shock Risk	Panel Damage Risk	Water Wasting	Electricity Consumption	Cleaning Cost
Intelligent Cleaning	High	–	–	–	–	–	Low
Manual Cleaning	Visual Method	High	High	High	High	Low	High
Vacuum Cleaning	Visual Method	High	Low	High	Low	High	Low
Electrostatic Precipitator	Low	–	–	–	–	Low	High*
Automatic Wiper Cleaning	Low	Low	Low	High	Low	Low	High*
Coatings With Nanoparticles	Low	–	–	–	Low	–	High*
Robotic Cleaning Solutions:	High	Low	Low	High**	Low	Low	High*

Low cost = Electricity cost.
Medium Cost = Electricity + Water.
High cost = Electricity + Water + Labor cost.
* Capital Costs.
** Due to robot weight.

In Jordan, PV panels have an average daily cleaning cost of $ 0.212/kWp (Hammad et al., 2018), supposing over 900 €/per year for an average installation with 15–20 solar panels, assuming that if a company is hired to clean solar panels twice a month throughout the year, as usual. The cost varies from one home to another, based on factors such as the slope of the roof, the height of the house, and the size of the system (Hammad et al., 2018). The overall cost for various cleaning methods is determined using operational expenses, capital costs, and equipment lifespan, as shown in Table 2 and Figs. 7 and 8.

According to Table 2, the most expensive cleaning method is hiring a company to clean the panels regardless of the cleaning method, which costs around 60 €/panel annually, followed by manual cleaning with brushes and or wipers, which costs between 21 and 26 €/panel annually. In addition, it takes a long time and consumes a lot of energy. finally, the intelligent cleaning system has the lowest cost of any panels cleaning system, at 1.5 €/panel annually, which sets it apart from other solar panel cleaning systems, these findings demonstrate how combining a few strategies can make things easier and less expensive.

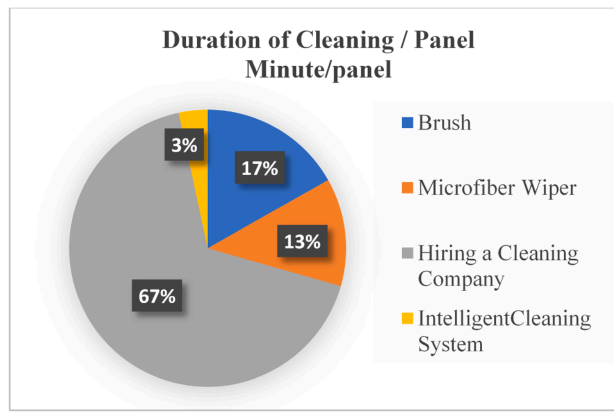

Fig. 7. Duration of cleaning panels (Al-Housani et al., 2019).

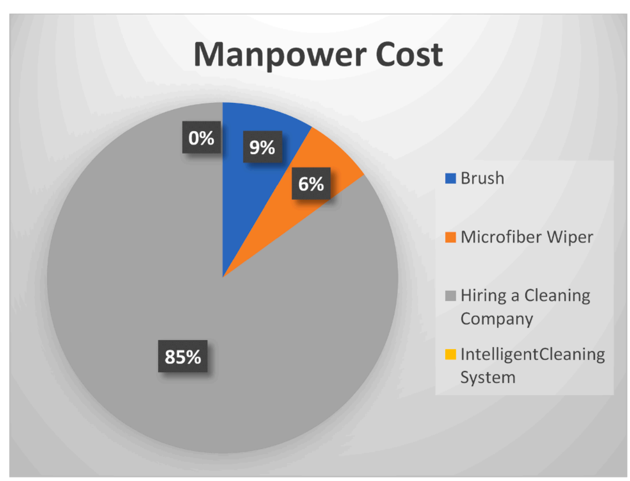

Fig. 8. Solar panel Manpower cost (Al-Housani et al., 2019).

5. The proposed cleaning system

Solar panel intelligent system cleaning, cooling, rainwater harvesting, and performance enhancement technology is an automated cleaning device used to solve the main two factors that limit PV system power generation the high PV temperature and the reduction in radiation on the solar panels due to soiling, in addition to the possibility of using the system in desert places that lack water, where the system can harvest rainwater in the winter and use it for cleaning at all times.

Table 2
Estimated cleaning PV panels cost in Jordan using different methods (Al-Housani et al., 2019).

Cleaning Equipment	Unit	Brush	Microfiber Wiper	Hiring a Cleaning Company	Intelligent System
Duration of Cleaning / Panel	Minute/ panel	1	0.75	4	0.2
Electricity Cost of Cleaning / Panel	€ /panel	0	0	0.000021	0.00001
Manpower Cost	€ /panel	0.25	0.19	2.5	0
Cost of One Cleaning / Panel	€ /panel	0.37	0.29	2.500021	0.00639269
Total Yearly Cost of Cleaning / Unit PV Panel	€ /Panel/ year	26.42	21.07	60	1.56

5.1. Foundations

The pilot system was installed on a part of solar panels with a capacity of 12 kWh, on the roof of the Najashi mosque in Al-Salt, Hashemite Kingdom of Jordan, the intelligent system was designed and developed to take advantage of the inclination of solar panels to collect rainwater in designated tanks through a gutter, then the water is from the rainwater tanks to the tank designated for cleaning the solar cells, which pumps water through pipes to the sprinklers and then is collected through the gutter to return to the designated tank for solar cells. Sprinklers put on the edges interfere with the spreading water, which therefore moves dust and heat away from the panel surface. The components are very durable and low-cost standardized items. Furthermore, the system can be built with a stationary duct assembly to bring water to the panel or as a movable set of equipment that can be moved to the cleaning and cooling site. This is dependent on the applications and the overall system cost.

The intelligent device may be mounted for any size or number of solar panels. Fig. 9 shows the three-dimensional model used to perform calculations to determine the water pump and air compressor capacities, as well as the number of sprinklers. Fig. 10 shows realistic photographs for the installed prototype.

As briefly explained above, the system that was implemented and developed was designed as a test field where more than one technology was integrated into the system, making it efficient, intelligent, environmental, economic, and many other features that make it superior to other cleaning systems. In three minutes, up to 95% of the dust from PV panel surfaces can be removed by this device.

5.2. System components

As briefly stated above, many built-in components make up the system that works harmoniously to ensure that the solar panels are clean at all times, these components are:

5.2.1. Air compressor, pipes and air nozzles

An air compressor with a 2 HP and a tank size of 36 L was used to produce 105 L per minute, connected to special pipes to clean the dust by blowing air through 3 mm diameter air holes installed on the roofs of the solar cells to clean the dust as an initial stage before operating the water sprinklers, but it was found to be ineffective after testing because the amount of air coming out of the holes was insufficient to remove the dust, in addition, the air compressor consumes a lot of electricity, making it uneconomical. Fig. 11 illustrates the air cleaning components utilized in the pilot project for an intelligent cleaning system.

Fig. 10. Intelligent cleaning system, pilot project.

5.2.2. Water pump

The water pump operates automatically by receiving a signal from the controller, which draws water from the tank and pushes it towards the sprinklers installed above the solar cells. The pump stops three minutes after all dirt and dust stuck to the solar panel body has been removed. A 0.5 CV water pump power was used, and the amount of electricity consumption when the pump is running for a full hour is estimated at 373 W or 0.373 kW, and this amount of electricity is sufficient to operate the system for a period of up to (a month), depending on the nature of the geographical area and the need for the frequency required to operate the system.

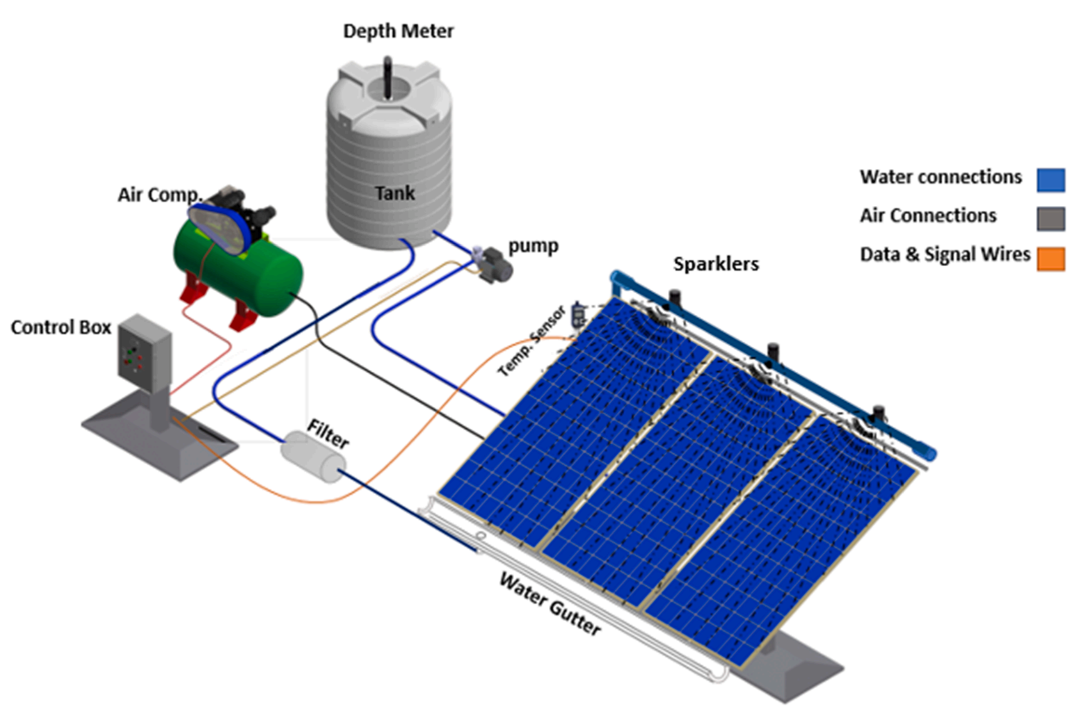

Fig. 9. Solar panel intelligent cleaning system, 3D CAD model.

Fig. 11. Air cleaning components utilized in intelligent cleaning system pilot project.

5.2.3. *Control unit*

The timer inside the control unit box has been programmed to send a signal to the water pump to work every 8 h for 3 continuous minutes)3 times per day(, which is enough time to clean the solar panels of dust or bird droppings before they stick and dry completely, as removing bird droppings becomes very difficult if they spend a long time on the surfaces of the solar cells. It is worth noting here that the geographical area must be studied before programming the system, as the type of dust and dirt that may accumulate on the surfaces of the solar cells can increase or decrease the time required for cleaning. It can also be linked to a thermal sensor installed on the roofs of the solar cells, which sends a signal to start the pump if its temperature rises above 45 °C. This will reduce its temperature and, as a result, increase its efficiency. Fig. 12 shows the control unit used in the project.

$$Working\frac{time}{year} = 3\ \ min{\cdot}3\ \ times{\cdot}365\ \ day = 3,285\ \ min/year = 54.75\ \ h/year$$

$$Yearly\ \ energy\ \ consumption = \frac{54.75h}{yeae}{\cdot}0.373Kw = 20.4\ \ kWh/year$$

5.2.4. *Temperature sensor*

The surface temperature sensor is installed on the back of PV modules to operate the system in an exceptional cycle if the panel temperature exceeds 30 °C. Although water affects the light-absorbing unit, the increase in energy yield can be obtained entirely by keeping temperatures below 30 °C.

5.2.5. *Water tank*

The water required to clean the solar cells is withdrawn through 200 L depicted in Fig. 13 below. In exchange, the tank is supplied with two water sources: rainwater from the roofs of solar cells and water recycled during cleaning, with 80% of the water that is pumped to clean the cells returning to the tank. The remaining 20% evaporates into the atmosphere.

5.2.6. *Sprinklers*

The sprinklers or water nozzle is a precise device that allows water to be dispersed in a mist, the flow rate is about 300 to 500 L/hour depending on the nozzle opening and water pressure. Nozzles serve three functions: they disperse a liquid across an area, they enhance the surface area of a liquid, and they provide an impact force on a solid surface (Schönenberger et al., 2022). Fig. 14 shows the water sprinklers used in the project.

5.2.7. *Water gutter*

To collect the water that fell on the surfaces of the solar cells, whether it was rainwater or cleaning water, the joints between the solar panels were sealed with adhesive tape, and a gutter was installed at the ends of the solar panels and connected to the other end with the water tank to capture every drop of water.

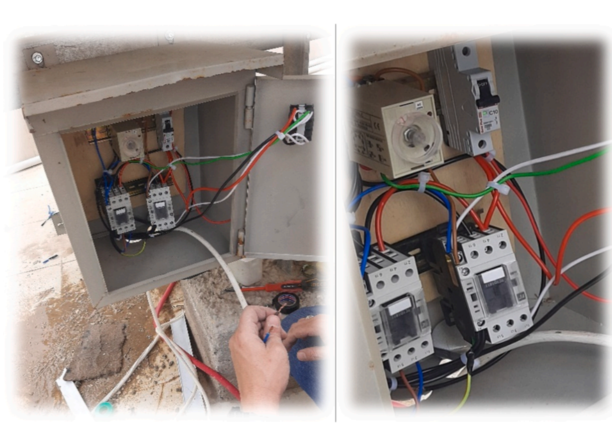

Fig. 12. Control unit utilized in the pilot project.

Fig. 13. Water tank used in the project.

Fig. 14. Water sprinklers used in the project.

5.2.8. *Water connections, filters, valves, mounting brackets, water depth sensor, electrical wiring. And many other components*

Cleaning sprinklers are mounted on variable-height bases to allow for easy adjustment of sprinkler heights. The water nozzles allow to change the spray angle, volume, and pressure of the water. This feature enables for the greatest cleaning outcomes. This is part of the design philosophy of investigating and identifying the most effective strategy to clean solar PV systems while consuming the least amount of energy and resources.

5.3. *Salient features of the proposed cleaning mechanism*

Some of the most salient features of the proposed cleaning system are numerated below. As seen, the investigated project overcomes most of the drawbacks of existing systems, especially regarding water consumption.

a. Rainwater harvesting
b. Recycle 80% of the cleaning water
c. The system does not require refilling.
d. Automatic on/off clean system.
e. No moving parts or robotic elements.
f. No manpower is required for cleaning.
g. The surface of the PV panel remains clean always.
h. It gives better efficiency compared to other traditional systems
i. The system can operate for many years before requiring maintenance.
j. Using the internet of things, the intelligent system can be monitored and controlled, such as turning it on and off, through a mobile phone.
k. The system cost is negligible when compared to manual, robotic, or any other system.

Nevertheless, it is worth mentioning that the system can be ineffective if it is used to clean old stuck dirt on solar panels such as old bird dropping, and water filters need to be replaced periodically according to the frequency of use.

6. Conclusions

This study is of particular interest to PV system researchers, designers, operators, and owners because it proposed a new technique to avoid reducing PV panel efficiency and the frequency of optimal cleaning using internet of thing connection, particularly in semi-arid and desert areas in general, and Jordan, the Middle East, and North Africa in particular. Depending on the type of dust, energy loss in fixed solar panels might be significant. Dirt and bird droppings create patches in the solar panel that impedes light and can cause the panel to shut down temporarily. Cleaning the solar water panel improves its efficacy by removing much of the dirt on the panel. Automatic cleaning was far less expensive and less laborious than human cleaning, especially in facilities with a high number of solar panels or panels that are difficult to access. Furthermore, regular cleaning guarantees that solar panels are always clean and extremely effective. Cleaning the panels helps increase the efficiency by removing much of the dust on the panels. Automatic cleaning costs were much cheaper and less challenging than manual cleaning, especially in solar panels plants or panels that are difficult to access. Furthermore, frequent cleaning ensures solar panels are clean and highly effective at all times.

Solar panels intelligent cleaning system can be relied on to clean the panels in all places and conditions, and help in harvesting rainwater and the results showed that there is a great potential to use the photovoltaic system in rainwater harvesting, as the water harvested can be used in the domestic water. Finally, rainwater may be harvested and stored on the rooftops of big buildings for use as residential water, industrial, toilet tanks, and landscape irrigation. Furthermore, collecting rainwater after heavy rains would help limit the amounts of water seeping into the network and the risk of floods.

This project has a wider future scope that focuses on the use of internet of things technologies connected to portable weather stations and cameras to detect climate conditions, this provides dust monitoring, enhanced analysis, and system control, which mandates an overall improved efficiency of the solar PV panel.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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