



Review of Solar Panel Cleaning Technology

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How to Cite this Article:

KUMAR, A., SABLE, A., SAHARE, A., SONUNE, A. & ARSHAD, S. (2026). Review of Solar Panel Cleaning Technology. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(<i>03</i>).

<https://doi.org/10.55041/ijcope.v2i3.055>

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<https://doi.org/10.55041/ijcope.v2i3.055>

Abstract

lifting efficiency by nearly 19% less than in cooler months. Flat setups drop performance faster than those tilted near 40 °, thanks to steeper slopes using sunlight plus gravity to clear gunk naturally. Instead of Solar energy has rapidly emerged as one of the most significant contributors to the global transition toward sustainable and renewable electricity generation systems. This shift did not happen overnight; since tracking began, installations have climbed rapidly, hitting over thousand billion watts by 2022 alone. Growth continues to increase by approximately a quarter each year compared with previous years. Sunlight turned into power plays a significant role in how countries run their lights, machines, and homes. Attention has been focused on these systems as nations look beyond older fuels. However, there is a snag: when dust settles, dirt piles up, birds leave marks, or smoke coats the glass, the performance decreases significantly. These issues have led to efforts to find better cleaning methods, drawing insights from four core research papers and their supporting documents. Wiping by hand appears early, then shifting components take over, followed by unseen electrical forces, and robots inching across the panels like insects. Peering into tiny computer systems reveals Arduino chips communicating with programmable logic controllers, teaming with small gear-driven motors operating on direct current (DC). Harsh scrubbing cloths are slowly being replaced with blends of microfiber and nylon, which remove grime without scratching the surfaces. Sunlight-blocked ties are directly related to dust thickness: once the accumulation crosses 10 grams per square meter heading toward

38, the electricity output decreases anywhere from 13 % to nearly two-fifths. Deserts push it further; some sites lose 86 % under brutal conditions. Surprisingly, a smooth coat of fine grit often dims solar gain worse than chunky trash spread unevenly, casting shadows that heat cells internally and create hazardous zones within the modules. It turns out that where you are changes things; over half of the global dust trouble hits Asia, much like how seasons shift what happens on panels when cleaned in hotter months, guessing, experts compare gadgets such as Resola and Wash Panel through MCDA, judging actual outcomes in addition to cost, durability, and ease of use. Robots doing the job might cut upkeep spending sharply, sliding it from 5 % to only 2% within yearly site budgets. Still missing? Smarts tracks surface wear in real time. Next, independent scrubbers can be built for specific spots, sipping less water while standing firm against changing weather conditions for decades.

Keywords— Solar Photovoltaics, Soiling Losses, Robotic Cleaning, Multi-Criteria Decision Analysis (MCDA), Electrostatic Cleaning, Microcontroller-based Automation, Renewable Energy Maintenance, Environmental Impact of Dust, PV Efficiency Optimization



INTRODUCTION

Solar power is not near the edge of possibility. Driven by need rather than choice, the global grids are transforming rapidly. The rising pressure from increasingly hotter climates accelerates these changes. Energy hunger is also on the rise. Instead of waiting, nations should adopt cleaner strategies. Sunlight is the key: it is always there, gentle on the Earth, and cheaper every year. A quiet rise, then sudden surge: beyond 1000 gigawatts live online by 2022. This single year added nearly a quarter of their capacity. Solar panels capture sunlight from rooftops to deserts. Today, just under one in 20 bulbs glows because of this initiative. Lower installation costs are driving this growth. Government support for cleaner energy has gained momentum in many areas. Sunlight replaces fuel combustion, preventing 270 g of CO₂ from entering the atmosphere. For each additional kilowatt-hour sent to the European network, the emissions decreased by 238 g. This number reflects the balance achieved after considering hidden impacts. The manufacturing and installation of the panels released approximately 32 g/kWh. The actual climate benefit emerges when these upstream emissions are removed from total emissions. What remains is the true reduction that is made possible by this approach.

Still, even with those benefits, one big problem gets in the way - dirt building up on solar panels, often called soiling.

Research has shown that dust settling on these surfaces reduces their ability to convert sunlight into energy. Because dust sits there like a shield, less sunlight passes through the parts that generate electricity. Here is what happens underneath: dust grabs some of the sun's energy and turns it into warmth, yet another bit bounces away and is lost in the process. What finally arrives at the cell is just a slice of what started, meaning that much less fuel enters the system [3].

One study showed that dust might reduce panel performance by nearly half. Panels in deserts sometimes lose most of their power - up to 86 %—when grit builds up. Countries such as India face similar issues, especially

when tropical dust coats uncleaned panels for four weeks. What sticks to the glass depends heavily on the surroundings, such as storms, smog and damp air. When moisture lingers for too long, puddles form on the

surfaces. This wetness invites moss or microbes that cling tightly to the surface of the material. Cleaning these living layers requires significant effort, and the shadows they cast permanently harm cell function.

The location of a solar installation affects the rate of dirt accumulation, with dry areas collecting dust rapidly, and slope and sun position are also important factors. Near oceans, salty mist coats panels, sparking rust-like damage that reduces output by nearly half. Cities and factories leave behind grime glued by pollution, which is poorly washed away with water. Clean surfaces allow sunlight to be converted into power without waste accumulation.

A fresh look at solar panel cleaning draws from four key studies, piecing together the current reality and what might come next. This study focuses on the engineering ideas behind hand wiping, machine scrubbing, electric field dust removal, and robot cleaning. One method stood out during the careful analysis, showing clear advantages and disadvantages. Problems appeared only after breaking down each step, quietly pointing to the required corrections. Solar power lasting decades relies less on promises and more on solving real-world challenges in the system operation.

Detailed Review of Primary Research Papers

Although sunshine must reach solar panels without blockage for optimal functioning, dirt, wet air, or overcast skies usually hinder this process. Sunlight fades before hitting the cells when grime builds up across the panel face, resulting in reduced electricity generation. Previously, people wiped them by hand to address this issue; however, this was laborious, time-consuming, and resulted in inconsistent results. Because of these drawbacks, the idea of a self-running cleaner emerged, which reduces the frequency at which workers must intervene. A tiny built-in computer handles the cleaning, so people do not need to step on the delicate solar surfaces to check or maintain them. Because dirt blocks sunlight, wiping the panels occasionally helps them work better over time. This proves grime plays a clear role in how much power they produce.[1]

Usually powered by electricity, the cleaner turns steadily, thanks to a small motor that maintains its speed. Instead of harsh scrubbing, it relies on soft fabric pads made of fine fibers to safely lift dust. These cloths glide lightly across the glass, wiping grime off without leaving any marks. To avoid harm, the machine adjusts the pressure



and remains firm enough to function well. Smart wiring handles the operation of the unit and automatically feeds energy when required. This built-in logic means that it works consistently, even when no one is watching closely. The spinning motion is generated by the motor, which is transferred by a chain that turns the brushes steadily - no slips, no jolts. When thick layers of dust slow down the process, the power remains steady, keeping everything moving smoothly. Long hours pass like short ones, thanks to reliable force behind each turn.[1]

Starting mid-sentence sometimes works well for some authors. The cleaner is attached to a steady base that rolls over the solar panels via several wheels powered by strong but slow motors. Smooth movement occurs because jerky shifts can scratch the glass; therefore, it crawls carefully row by row. In addition, extra guiding rollers keep it lined up close to the panel border. Settings are scheduled through an automatic clock-like setup, and users select times such as every few hours or twice daily. Pushing the buttons handles activation and changes the frequency of the operation. Information is displayed plainly on a small screen. When the machine reaches the edge of a row, built-in sensors shut it down, and no human intervention is required to operate it. Instead of running on schedules, certain models check how dirty the panels are before starting up, thanks to sensor feedback; however, they often come with higher prices. Some robots clean without help but require power boosts every so often or someone to watch them nearby. Machines taking over scrubbing duties might lower upkeep spending while boosting the energy output across solar fields. On large sites, washing takes up much of the repair budget; smart bots cut these fees while adding features such as timed sprays, lens checks, and storm warnings. [1]

Cleaning solar panels is more important than many people realize, particularly in areas where older forms of power generation are common. Approximately 60 out of every hundred homes in remote areas still burn standard fuels, opening space for solar-based electricity. However, the performance of these systems is closely tied to the maintenance routines. During the first trials of grime buildup, scientists noticed tiny layers of dust blocking light flow. One percent dip in sunshine reached cells with only a slight dirt cover. Five percent vanished when filth thickened on the glass surfaces. Sandstorms leave thick dust layers on solar panels in arid regions. These deposits build up rapidly when the seasons change. Cleaning every so often keeps the performance stable. A small

amount of water was sufficient to wipe each of the surfaces. The efficiency remains stable if maintenance is performed regularly. Evidence supports this pattern in dry climates worldwide.[2]

Machines built for tough spots usually run on small computer brains tied to motor setups with internal gear. A spinning brush glides over the glass when the timer indicates so, owing to the settings being locked into the main box. Less hands-on work occurs because it runs by itself while keeping things clean. Studies have shown that when dust sticks for too long, energy production is severely affected. Near the middle of the planet, after 30 days without wiping, half of the power might vanish. Because of dust and grime, solar panels lose power over time, and machines that clean them help maintain a steady output, especially on large sites where people cannot easily reach every surface. A robot or automated brush might seem like an upfront cost, yet it often saves money down the road when measured against hiring crews year after year just to wipe glass by hand

Not every speck that lands on panels comes from city pollution; ash, grains of sand, bits of silica, chalky deposits, and even rust-colored earth accumulate over time. Sunlight struggles to penetrate when layers are built as films across the glass surface. Strong sunlight might shake loose some grime due to the warmth spreading under each panel; however, most dirt sticks around for longer than expected. Across deserts in the Middle East, researchers watched how slowly light dimmed behind grimy covers, dragging down electricity flow bit by bit. With more arrays popping up in dusty zones, wiping them clean by hand feels slower and less practical each year - a quiet push toward machines that scrub without needing someone to climb rooftops. [2]

By examining the cleaning of solar panels worldwide, researchers have determined the most effective methods, considering factors such as weather patterns, costs, tools, and maintenance requirements. Dust buildup varies by place, and Asia faces heavier losses than any other area, making up over 50 percent of the global output loss tied to grime. Behind it are Europe and Africa, which show much lower levels. This heavy load in Asia is mostly due to the presence of many solar farms, paired with air conditions that keep particles suspended for longer periods. Winds that pack a punch, when paired with parched air, whisk up dirt fine enough to ride the breeze until it lands on solar panels, blocking the sunbeams. Work probing how grime gums up these energy



harvesters? This is evident in places like Saudi Arabia, where stacks of papers have emerged from the deep exploration of the problem. [3]

Surprisingly, little dust was found to reduce solar panel performance by measurable amounts. Along the shorelines, panels often collect salty crusts that turn into light-blocking films when heated by sunlight. Instead of being washed away, grime from cities sticks hard, such as the smoky residue left behind after factory emissions pass through humid air. Separate studies have begun to track the behavior of various contaminants under real-world conditions. These tests revealed that some particles are more harmful than others, depending on their settlement locations. One gram of grime across a square meter can already tug light away from the solar cells. Around ten grams? The efficiency dipped to approximately 13 percent. Heavy buildup pushes losses to thirty-three percent. A faint, barely visible film still appeared in the power logs. In arid zones, daily harvests drop by over six percent when winds carry fine particles. Without wiping, the numbers increased weekly. Dust performs two functions: it soaks up rays like paper and bounces off rays at odd angles. The scattered shade affects the circuits differently depending on the layout. Panels wired side by side handled patchy dirt more smoothly than those wired end-to-end. [3]

To determine the best way to clean solar panels, experts have considered several factors, including speed, safety, cost, environmental impact, and simplicity. The hand-wiping, fog spray, drone with brush, electric dust shield, and robotic arm methods were tested sequentially. Robots built smartly tend to score better, mostly because they run alone without people stepping in every few minutes to correct them. However, some scientists have pointed out that there has not been enough research into automatic checks or self-cleaning tricks; more work must fill gaps regarding when exactly to wipe them next, as well as sharper guesses about dirt-cutting power over the years. [3]

Recently, studies have focused on developing new tools to keep solar panels operating for longer periods. When left unchecked, dirt, frost, and fallen leaves rapidly reduce the power output. Snow piles in chilly areas might crack glass fronts, and some crews apply alcohol mixes to prevent ice from forming. As water barely conducts electricity, it remains the top choice for safely washing the gear. Without the interference of leftover gunk

blocking the rays, basic H₂O is favored at many solar farms. [4]

Starting up when grime builds too high, smart cleaners now handle dusty solar panels where sand never stops falling. Dust detectors continuously monitor and update grime levels. Once these gauges confirm that the buildup has crossed a threshold, hidden motors wake up, spinning bristle wheels into motion without anyone pressing go. Movement kicks off in stages: first, the gunk shows up on the sensor readouts, then the scrubbers start rolling, and after that, the machine inches ahead as if it is pacing itself. Rolling slowly but steadily, it holds its line straight so that nothing is missed along the way. Midway through cleaning, the live sensor data showed a change in the amount of dust. When the robot nears a panel edge, the detectors trigger a halt, and the robot shifts its position before moving across the rest of the array. [4]

In addition to robots that clean panels, some methods aim to reduce the frequency with which people must wipe surfaces by hand. When it rains, certain surface treatments push water away or lay it flat, so the dust is washed off naturally. Instead of soaking in, the water beads up and drags the grime along if the coating repels the moisture. In contrast, when a layer resembles water, it spreads thinly and clears the muck without leaving streaks. Less upkeep means that the power output will remain steady for years. With sun-powered setups growing everywhere, smarter ways to keep them spotless—without spending too much or harming nature—are now key to ensuring that they deliver juice nonstop. [4]

[Detailed Technical Analysis of Cleaning Mechanisms](#)

Mechanical Removal of Dust (Brushing, Blowing, Vibrating, Ultrasonic)

Manual cleaning techniques involve the physical removal of accumulated dust, dirt, and other contaminants from surfaces using hand-operated tools, such as brushes, cloths, and vacuum devices. In certain situations, specialized instruments, such as scrapers, are employed to loosen and remove stubborn deposits through controlled mechanical action, thereby restoring surface cleanliness and improving operational performance. Wiping things down using fabric lifts tiny bits off flat areas, while brooms push scattered junk into heaps to be discarded later. Sometimes, people turn to pressure



washing, where strong jets of water blast stuck-on grime off surfaces without much effort.

Dust flies when a spinning brush strikes the surface of a solar panel. Bristles crafted from microfibers or gentle nylon are used for wiping the surface. Machines on rails often roll these cleaners across large setups. Power is generated using small electric motors designed to provide a steady turning force. Movement continues without stopping owing to the linked-motor design. Each pass removed the particles that had gathered since the last pass. Some models spin bristles using gear-driven circuits. Soft touch matters; therefore, scratches are avoided. Rotating units function optimally when the panels are stretched. The force levels were adjusted based on the dirtiness level. The cleaning rhythm matched the daily buildup pattern. The motion begins when the sensors detect sufficient dirt. The brushes were dropped only when necessary. The systems were reset after each round.

A sudden burst of air sweeps across the surface, lifting loose particles without using water to do so. Although efficient in saving liquid resources, it struggles with stubborn grime, such as dried waste from birds or thick layers of factory residue. In some cases, machines powered by pressurized wind show signs of doubling up, clearing debris, while lowering the panel temperature at the same time.

Shaking things up works when dirt clings too hard; tiny jolts or rapid pulses help shake the grime loose on solar surfaces [1]. When waves move at lightning speed, even specks too small to see break free, although the power demand increases [3].

Electrostatic Cleaning (Electrodynamic Screen Technology)

Not far beneath the glass, thin wires run across the screen like silent highways. These paths carry a pulse when the voltage jumps, which is sudden but soft. Instead of sticking around, dirt is lifted as if tugged by invisible hands. A ripple originating from charge shifts moves beneath it. This motion slides the particles away without any contact. Clear light returns where grime once held on.[3].

Some dust sticks initially and is pulled in by static energy. Once it touches the surface, it picks up a charge from the

glass. With this new charge, it is pushed off and lifted by matching the electrical pushes. Floating free occurs after the release of the object. The cycle repeats with fresh particles arriving.[1].

Water savings make this approach more effective in arid areas. However, the expenses incurred when setting up such systems are high. Its performance drops when it rains, and the electric charges stop working. Long-term reliability raises questions for users. A rating of 2.4 clearly reflects these drawbacks [3].

Water-based and Chemical Cleaning Methods (Pure Water vs. Alcohol)

However, water does most of the work when things are washed with it. Yet how it's used makes all the difference - pressure, temperature, timing must line up just right

Water without minerals was more effective than water with minerals. According to scientists, this prevents marks from appearing on panel surfaces. This type of water does not carry an electric current, thereby reducing the risk when washing. Consequently, the likelihood of electrical issues or rust formation is reduced.

When temperatures drop, alcohol-based cleaners are useful because they prevent water from turning into ice on solar panels. Ice buildup may crack parts over time; therefore, avoiding it is important. These solutions are effective even when a faint film remains after wiping the surface [4].

Spray nozzle systems operate through an array of nozzles controlled by a Programmable Logic Controller (PLC) to ensure coordinated water distribution. The nozzles are connected through a network of pipelines that draw water from concealed storage tanks. These tanks are equipped with level sensors that continuously monitor the remaining water quantity and transmit real-time feedback to the control system for efficient management of the water supply. When weather gear detects incoming rain by checking air weight, heat, dampness, breeze, and sun strength, the wash routine halts automatically. Each rinse phase lasted approximately half a minute. Power output climbs from roughly 140 watts to nearly 177 during operation. That jump means one-quarter more energy pulled in under real conditions.[3]



Robotic and Autonomous Systems (Rovers, Drones, Modular Robots)

Robots have grown more advanced because machines now handle tasks automatically

On solar farms, machines such as wash panels and Resola move by themselves across panels. Sinfonia's Resola stands out because it scores well (3.6) not just in one area but across several, such as its longevity and smooth operation. It can handle both wet and dry cleaning without requiring additional gear.

Floating above dusty solar panels, drones may soon whisk grime aside with rotor gusts instead of brushes. Some experiments have fitted them with misting tools, targeting rooftops that are seldom reached by people. Their ability to clean tough spots earns a 3.4 mark in the rating system.[3].

A single robot changes shape when needed and adapts to different panel sizes. One piece connects here, and another shifts there; each adjustment occurs without extra tools. Shape matters less now because it builds itself around whatever structure appears. Some setups take longer, although each version fits exactly where it is placed. Flexibility comes from within, not from manually swapping parts.

Environmental and Technical Factors Affecting PV Efficiency

Quantitative Impact of Dust Density and Pollutant Type

As dust accumulates on panel surfaces, the intensity of incoming sunlight decreases, significantly affecting energy conversion efficiency. This relationship is critical because reduced solar irradiance directly lowers the power output and overall system performance of PV systems. Power drops sharply as more dust settles, based on findings reviewed by Najmi and Rachid 13% vanishes when it hits 10 grams per square meter. Weight slips away under that mark, quietly but sure 20 g/m²: 25.4% loss

Pollution at 38 grams per square meter cuts performance by 38 %. Along the coastlines, salt spray triggers corrosion, sometimes reducing output by nearly half. Instead of being easily rinsed off, industrial grime clings

tightly and requires more than just plain water for cleaning. In hot zones, red dirt and fine sand are frequent problems. Each contaminant behaves differently under sunlight exposure.

Shading Dynamics and Circuit Configurations (Series vs. Parallel)

When shadows fall, power output changes - how much depends on how the circuits are set up

When solar panels are connected in series, even a single row of shaded or darkened cells can reduce the current flowing through the entire panel string. Because the same current passes through all the panels in a series configuration, the performance of the entire chain is limited by the weakest or most obstructed section. Although freewheeling diodes allow electricity to detour around blocked sections, the total output still depends on the lower flow of the weakest link [3].

Dust Density (g/m ²)	Efficiency Loss (%)
10	13
20	28
38	38

When solar panels are connected in parallel, shading on a single module primarily reduces the power output of that specific panel, whereas the overall array voltage remains relatively stable. Consequently, localized dust accumulation or partial shading has a limited impact compared to series-connected configurations, where shading on one panel can significantly affect the performance of the entire string [3].

Weather can sometimes shape how surfaces collect moisture. The angle of a slope affects wetness by altering sun exposure. When air holds more water, materials remain damp for a longer period. Morning droplets are formed more easily on cool nights. Seasons shift these patterns with temperature variations.

Dust accumulation increases more rapidly when variations in atmospheric humidity occur, because changes in moisture levels influence particle adhesion and surface deposition rates. Wind speed affects the movement of grit. Hot days can cause particles to stick more. What happens outside shapes what is settled inside the body. Seasonal swings tilt the balance each month



Most flat solar panels collect more dust than sloped panels. When set low, they lost approximately 2.2 % energy. Panels angled at 40 °drop that loss to just over half a %. Sloped positions allow gravity to slide dirt away from the surface. Dust slips easier when the surface points upward.[3].

Foggy air often causes dust to stick to solar panels, using moisture as a glue-like layer. When dew settles, it traps dirt that clings more strongly than dry dirt. Puddles invite green scum or fuzzy fungus to grow in corners where the sun does not reach. Cleaning those spots takes extra scrubbing compared to smooth areas.[3].

Most of the benefits are observed in summer. Bright sunlight plus layers of dust make washing panels worth +18.3%. In winter, the boost drops slightly to +13.3%, yet still clears stubborn messes like bird waste and bugs. When harvest time rolls around, gains shrink a bit more. Cloudy skies during those months tend to limit how much extra power cleaning brings.[3].

Geographic Variations and Specific Pollutant Impacts

Half the world's trouble with dusty solar panels happens in Asia, yet Europe still makes up a large chunk near twenty-five percent. Research into grime cutting power output, That's dominated by Saudi Arabia - more papers come from there than anywhere else. Fastest growth in setting up solar farms now pushes hardest across Asian landscapes. Most of those setups rise in bare, arid zones, places where wind and dirt meet often. Panels sit exposed, gathering specks fast when nothing blocks the open air. As a result, these areas experience greater soiling issues, which can significantly reduce solar energy output if proper cleaning and maintenance strategies are not implemented. Africa contributed 12%, followed by North America, which contributed 5%. South America followed closely behind, with 4%. Australia accounted for only 1% of the total. These trends are closely associated with the geographic distribution of solar installations and the prevailing arid conditions of the surrounding terrain. Regions with extensive solar farm development and consistently dry landscapes are more susceptible to such effects.[3].

Comparative Analysis and Decision Support Systems

Multi-Criteria Decision Analysis (MCDA) Framework

To assist decision-makers, Najmi and Rachid employed a Multi-Criteria Decision Analysis (MCDA) approach that systematically evaluates alternatives based on key factors such as operational effectiveness, safety, cost, durability, environmental impact, and user-friendliness. This structured method ensured a balanced and objective selection. Each approach gets a mark from 1 up to 5, then the total grade shows up as an average

Cleaning Method	MCDA Score
Resola	3.6
Wash Panel	3.4
Drone	3.4
Water Spray	3.4
Manual	3.2
Truck	3.2
EDS	2.4

·Resola robot (Sinfonia): 3.6 (Excellent balance of efficiency and durability)

·Wash Panel robot: 3.4

·Water Spray systems: 3.4

Starting off, drone cleaning scores 3.4—decent reach, though power runs short. Despite solid access, flight time is a hindrance. Reaching tight spots works well until the juice fades. A fair mark comes from the usable design minus the energy limits. Short sessions okay, longer ones fail on charge

Water use here is high. Risk level sits at 3.2. Cleaning by hand takes more time. This approach uses additional resources. Waste builds up faster. Efficiency drops with each round

·Truck-mounted cleaning: 3.2

A screen that uses electric currents to repel dust - its effectiveness sits around 2.4 because it wears down fast and costs too much [3].



Qualitative and Quantitative Comparison of Methods

Most of the time, machines clean more often, are safer, and handle bigger jobs better than humans. Cleaning by hand requires many workers and poses risks; however, robots deliver steady outcomes every run. However, buying automation gear is expensive, which prevents small setups from using it. Dust brushes work fine on light dirt, though they fail when grime sticks hard.[3].

Cost-Benefit and Economic Feasibility Analysis

Choosing how to clean often comes down to what matters most: saving money now or getting more power later. Because manual methods require people and water, they start cheap but become expensive over time. Even so, automated options require more spending initially but pay off more quickly on large solar sites. Since machines cut down work needs and boost output, upkeep expenses might drop from 5% to just 2% of the whole project's price.[1],[3].

Identification of Research Gaps

Looking closer, a few key holes show up in today's studies. Currently, most setups run on schedules rather than actual needs. When dust gathers and the power drops, cleaning is performed at fixed times. Smarter tools can monitor performance shifts and provide weather clues. Only then would the maintenance kick in. That change saves effort without losing efficiency.[3].

Smart solar panel cleaning technologies have been predominantly tested and implemented in Asia. In contrast, research efforts in other regions, such as Africa and South America, remain largely theoretical, with limited large-scale practical validation. Real tests could help tackle local grime better.[3].

Few studies have noticed how dust settles slowly on panels, yet it chips away at the power. When rain fails to wash the grime off, the output dips without any warning. Forecasting these slips helps crews to act before small issues grow into larger problems. Weather patterns leave traces in performance logs if someone knows where to look for them. Over time, even a slight buildup forces tough choice regarding cleaning schedules.

The following aspects stand out. Determining the optimal cleaning frequency of solar panels is challenging,

primarily due to the scarcity of comprehensive cost-versus-gain studies. Long-range numbers missing make it hard to balance maintenance spending with actual power gains. When storms hit hard, some cleaning methods wear down faster than others. However, their performance under inclement weather conditions remains uncertain. Real-world testing and more on-site proof are needed before they can be considered reliable in harsh climates. However, this remains unclear [3].

Future Scope and Recommendations

In the future, robotic cleaning systems may require minimal human supervision as they become capable of autonomously adapting to different types of solar panels and environmental conditions. Further advancements may focus on reducing the size of these robots and simplifying their mobility mechanisms, making them more efficient, flexible, and practical for large-scale deployment in solar power installations. [3][1].

Dust on solar panels in arid zones needs removal - but skipping water is key. Down the line, electric fields might handle grime more effectively. Where humidity runs low, blowing air could become the go-to fix. Panels facing brutal sunlight stand up better if their EDS layers are built stronger.[3].

The sensor module was automatically activated in response to variations in the solar irradiance. Photovoltaic panels continuously monitor and evaluate their power output throughout the operational cycle to maintain optimal performance and efficiency. Cleaning begins only if the dust blocks a significant amount of light. The sun angles guide the responses of the systems. Each move is determined by a real number. The efficiency drop signal indicates that it is time.

Panels now wear tougher skins - coatings designed to repel grime while laughing off harsh sun, endless rain, or bitter cold [4].

A mix of washing plus checking at once - like adding cameras or drones - works alongside weather-driven cleaning rules.[1].



CONCLUSION

When grime gathers on solar panels, energy drops sharply - more than half in some cases. Little by little, the gunk builds up, so you might not realize how much juice is vanishing. Still, fresh fixes are arriving to tackle those losses. Instead of people, robots take on cleaning duties, moving across surfaces at any hour. Equipped with smart sensors and adaptive code, they tweak their moves while going. Every drop of rinse water circulates again. Weather predictions shape when things happen. Because of how land behaves - like how wind moves or how loose the sand is - they adapt. Even though certain spots haven't been checked yet, methods keep getting better. Soon enough, many locations could handle cleaning on their own, without prompts. Stillness isn't waiting - it means something is shifting. When conditions shift, steady focus matters more than sudden brilliance. Tools change - how we care for them needs to as well. Performance that lasts appears quietly when effort stays consistent.

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