Proceedings of the 10th North American International Conference on Industrial Engineering and Operations Management, Orlando, Florida, USA, June 17-19, 2025

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/NA10.20250094
Published: June 17, 2025

Sustainable Solar Panel Cleaner: Optimizing Renewable Energy Through Automated Design

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Abstract

Current methods for cleaning residential solar panels involve manual labor, often requiring homeowners to climb onto their roofs, which poses significant safety risks. Accumulation of dust and grime on solar panels reduces their efficiency and overall energy output, affecting the ability to power homes. This inefficiency leads to economic and environmental opportunity costs. Homeowners currently have limited options with the top 3 being: hiring maintenance personnel, purchasing costly cleaning systems, or cleaning the solar panels themselves. An automated solar panel cleaning system could address these issues by providing a safer and more efficient solution. This system would maintain optimal performance, enhancing energy output and contributing to environmental sustainability by increasing the amount of clean energy in the power grid. As solar energy becomes a greener and better option moving forward, ensuring the efficiency of solar panels becomes a top priority for maximizing energy savings and reducing reliance on fossil fuels. Our project aims to design a cost-effective automated cleaning device for residential solar panels. This system will reduce safety risks, eliminate manual labor, and optimize the energy production of solar panels. This innovation could provide homeowners with a practical, low-maintenance tool to ensure long-term efficiency and economic return on their solar energy investments.

Keywords
Automated Solar Panel Cleaner, Gantry System, Solar Panel Efficiency.

1. Introduction
The current prevailing method for cleaning home solar panels is manual and requires people to climb up onto their roofs. This can be dangerous if homeowners are ill-equipped and not properly trained for this task. The impact of the issue is that dust and grime accumulation lead to decreased efficiency and lower overall output of energy. A lower power efficiency results in opportunity costs, ranging from the ability to sell surplus power back to the grid, saving power for future outages, or the inability to power current home appliances.

Stakeholders must either hire maintenance personnel to go up and clean the panels, purchase expensive cleaning technology, or manually clean the panels themselves, which can be dangerous for homeowners on a high roof. The introduction of an automated system will not only increase the efficiency of the solar panel system, but it will also decrease emissions of the general coal-powered grid connected to everyone's houses. This is due to the ability of solar panels to contribute to the power grid by selling surplus energy back to it. This means that– dependent on the usage and efficiency of the solar panels– a certain percentage of the power that the power grid provides will be coming from green sources.

The adoption of solar energy in residential homes has surged in recent years as homeowners seek sustainable and cost-effective energy solutions. However, the prevailing method for cleaning home solar panels remains manual, requiring individuals to climb onto their roofs to perform maintenance. This practice poses significant safety risks, especially for those who are not properly trained or equipped for such tasks. Falls from roofs are a leading cause of home-related injuries, highlighting the need for a safer alternative to manual cleaning.

Objectives

The goal of this project is to develop an automated solar panel cleaning device that is cost-effective and minimizes safety risks for homeowners. The device should require minimal maintenance while effectively cleaning the panels without causing any damage, thereby improving their efficiency. Additionally, it should be designed to be compatible with a wide range of residential solar panels, ensuring that it can be easily installed and used in as many homes as possible.

Problem Statement

Homeowners with solar panels are currently limited in the ways in which they can effectively clean their solar panels. Many often resort to manually climbing up to the roof to clean the panels by hand, which can be ineffective and dangerous, with many slip and fall hazards potentially occurring. There are two specific problems to address: 1) the lack of effective cleaning methods for a commercial audience. 2) Dust and debris accumulate over time, which results in proven efficiency losses. The reduced power output also forgoes the opportunity cost of selling surplus energy back to the grid, but this issue is not part of our main scope. While automated systems do exist for industrial applications, there has been no adaptation made for home applications.

2. Literature Review

Our topic for our senior design project is a home application of a solar panel cleaner. Throughout our research, we intended to prove that there is a need for our product on the market and to determine what competition already exists. After extensive research, we accomplished both of those objectives through review of academic articles and books. Initially, while researching, establishing an actual need for our product was essential, as without demand, there is no value in it. In a book titled *The Effects of Dust and Heat on Photovoltaic Modules : Impacts and Solutions*, the authors detailed that dust buildup and overheating can negatively affect the performance of solar panels if they are not addressed properly and regularly (Al-Ahmed 2022). This proves the need for an automated solar panel cleaner to exist. Currently, for home applications, manual cleaning is the main method. This leads to uneven cleaning, possible injuries due to the need to climb, and a physically demanding job brushing and squeegeeing the panels. An automated cleaning mechanism could effectively combat both effects without hindering the performance of the solar panels.

In literature, it is found that wet cleaning is a prominently effective method for solar panel cleaning applications. From Figure 1, the market clearly displays a lucrative market opportunity for wet cleaning PV panels compared to dry cleaning. This if further proven by our competitor's products, which involve a degree of water usage for their products to work effectively. During our research, we discovered that other people have attempted to make similar products to our proposed idea, even though they took a different approach (Saepul 2023). In this article, a prototype for a solar panel cleaning system is demonstrated both schematically and practically. However, there were some flaws in this design that we hope to address with ours. This design, which rests on top of the solar panel, only increased the overall efficiency 10 to 30% during testing. While this is technically impressive, the fact that it rests on top of the panel means that it blocks some of the cells, leading to a net loss in total output. Our proposed design, which retracts into a casing adjacent to the panel, should theoretically increase efficiency without hindering the output.

One of the most interesting designs from our competitors was the electrostatic repulsion device that needs 30% humidity to work effectively. It consists of a metal bar that passes over the panel, producing an electric field that charges dust particles as it goes, making the particles float away. It is a good concept, but it fails to explain where the energy to charge this device will come from, and if it needs to use the energy from the solar panels, then it is a very counterproductive device. Similar to the last two methods we have researched, this article discussed a self-cleaning robot for PV panels that uses a color monitoring system to detect dust particles. This addition to the mechanism can help add efficiency to the cleaning process by reducing or increasing the number of runs based on the level of dust. The system showed a 98% increase in efficiency on heavily dusted panels and a 68% increase on lightly dusted ones. This shows the effectiveness of the monitoring system. One of the drawbacks of Amin's design is that it has only been tested in a dry desert-like climate (Egypt). This can limit the market for potential buyers.

Another competitor to our product is a special hydrophobic nano-coating. The main leverage of this product is its ability to work without energy; the nanoparticles sit on the panel and any dust that accumulates on the panel can be rinsed off with water (rain). This results in a very low-maintenance product, but with only the nanocoating and a simple water rinse, roughly 74% of dust will be removed, which is still better than non-hydrophobic coated panels but cannot beat the effectiveness of manual cleaning (Tayel 2022). As a culmination of our research into the topic, several gaps were identified in the market that can be addressed by our idea. While many automated systems exist for industrial applications (such as solar panel farms), the prevailing method for cleaning home solar panels is obsolete and inefficient. These outdated processes can lead to decreases in efficiency and overall output.

Figure 1. Solar Panel Cleaning Market Projections

3. Design Development

In this table, we have identified all the fundamental needs of our design that must be implemented in order to function within its constraints. Additionally, we've also identified the wants and performance factors that would be a nice quality-of-life addition despite not being integral to the design. The main need of our product is to clean solar panels which is why it is identified first. Other important needs include safety, low power consumption, and material durability. Safety should always be implemented in the design of any product. In regard to ours, it must be able to withstand forces that could make it fall off the roof. We need lowered power consumption so we can actually justify the need for our product to increase solar panel efficiency. Material durability relates to the reliability of the materials to withstand harsh weather conditions. The wants we identified include ease of use, minimized storage space needed, and wireless activation/deactivation. Our design ideally requires little to no input from the homeowners to be switched on/off. It will also not require being stored regardless of the weather conditions outside. Remote control will most likely not be required as stated earlier.

Table 1. Customer Needs Priority Matrix

Customer Need/Feature	**Category**	**Feasibility**	**Importance**	**Cost Impact**	**Priority**	**Notes**
Clean	Need	5	5	Medium	High	Core Function

dust/debris						
Damage Control	Performance	5	5	Low	High	Product must not damage the solar panel
Ease of Use	Want	4	5	Medium	Medium	Product should not be technically complicated
Safety	Need	5	5	High	High	Should be low risk to end-users
Power Consumption	Need/Performance	5	5	High	High	Power drawn shouldn't exceed power saved
Space/Storage	Want	3	4	Low	Medium	Product should be sleek and not be overly large to draw attraction to the roof
Low Maintenance	Want/Excitement	2	3	High	Low	Lower maintenance means higher quality parts. This could increase cost impact
Software Integration	Want/Excitement	2	3	High	Low	Allow for control through an app. Not direly necessary but nice to have.

3.1 Preliminary Sketches

This sketch outlined the basic initial concept of our project. A simple, side-mounted mechanism that deployed water and sprayed the panels before squeegeeing the panel clean. Quickly after this sketch, we realized that this idea was infeasible since it would only be able to clean one panel, and homes tend to have an array of panels.

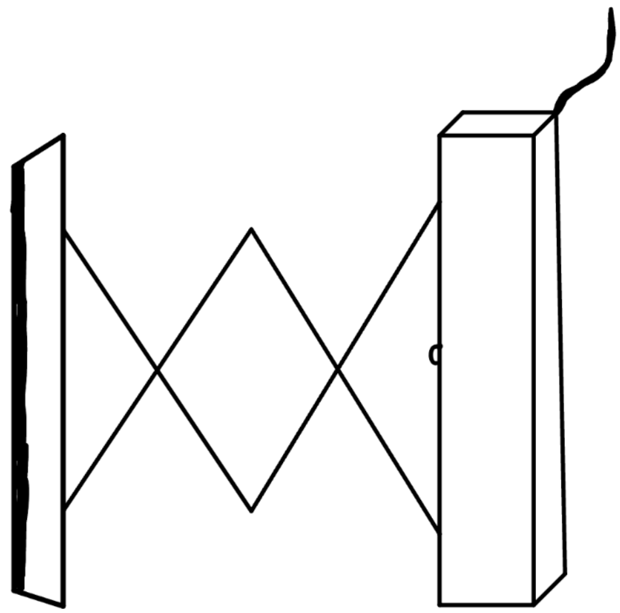

Figure 2. Initial Concept of Design

This is our first design addressing the problem of cleaning multiple solar panels in various configurations. However, utilizing telescoping arms can lead to stress failures.

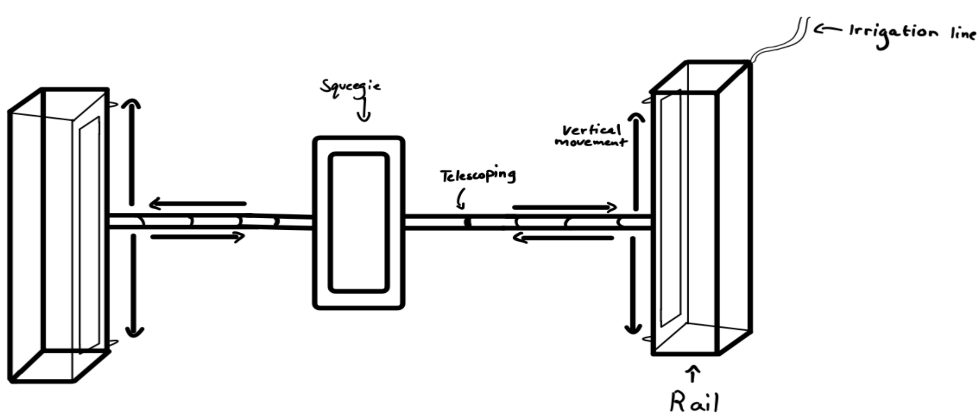

Figure 3. Updated Design Sketch

This is the most current design of our product. This design utilizes a gantry rail system to facilitate movement in all 4 cardinal directions while ensuring that the frame on which the cleaner is resting is not subject to breaking. This design also has a storage location for the cleaner to sit in when it is not in use.

3.3 Evaluating Alternatives

Based on the FMEA table below, we elected to go with the prevailing design which was the complete rail gantry system. This is because it had the lowest potential for major complications. Another reason is that we would only need to install one system to cover all the solar panels on any given roof compared to the other designs that would need multiple cleaners on every roof such as our initial design ideas. Not only does this reduce costs, it also makes the installation and maintenance process much easier to perform. The only reason why we needed to adjust design 2 was because we needed an area to store the sweeper/squeegee away after it had performed its function. The maintainability of the prevailing design helps us ensure the longevity of the product since it would just be one single unit with multiple components. In turn, this would increase the reliability of the product.

A major issue that we faced during the engineering design iteration process was determining the optimal solution for delivering the water to the surface of the panels. There were many practical and functional issues that were faced by earlier design iterations that would have negated many of the proposed benefits of the automated solar panel cleaner. In our final design, we believe we have addressed and effectively solved all of the previous issues with the introduction of a Ryobi water transfer pump. This pump will draw water from a water basin located on the side of the home and transfer water up onto the panels for watering and cleaning.

3.2 Failure Mode and Effects Analysis

Table 2. Failure Mode and Effect Analysis

Design 1 - Complete Rail Gantry system								
Process Step	Failure Mode	Effect	Severity	Cause	Occurrence	Detection	RPN	Recommended Action
Motor system	Motor overheats	Rails stop moving, system shuts down	9	Heavy rail and wiper mechanisms	4	4	144	Optimize overall weight of the gantry rails and wiper.
Linear actuators	Improper distance	Wiper may fail to travel certain distances and miss some areas of the panel.	7	Calibration of linear actuators to travel the correct distance to clean panel.	4	6	168	Correctly calibrate linear actuators and run tests.
Design 4 - Scissor Lift system								
Process Step	Failure Mode	Effect	Severity	Cause	Occurrence	Detection	RPN	Recommended Action
Wiper mechanism	Failure to cover larger surface area	Cleaning multiple panels will require multiple product installations.	7	Insufficient telescoping reach.	5	7	245	Attach multiple panel cleaners to cover more surface and angles.
Wiper mechanism	Scissor arm breakage	Wiper cannot move properly.	10	Harsh weather and long term mechanical stress.	3	5	150	Add extra protection or guards to stress points. Preventative maintenance.
Motor system	Motor overheats	Rails stop moving, system shuts down.	9	Heavy rail and wiper mechanisms.	4	4	144	Optimize overall weight of scissor arms.

Common FMEA for ALL designs

Process Step	Failure Mode	Effect	Severity	Cause	Occurrence	Detection	RPN	Recommended Action
Water compartment	Crack in compartmen t or hose	Insufficient water supply as well as wasting water.	8	Damage from force or debris. Mechanical stress on hose.	3	6	144	Quality material choice for hose and compartment.
Damage control	Solar panel damage	Function of panels amy be compromised.	10	Too much force applied from the wiper/brush. Material choice not suited for solar panels.	2	7	140	Use appropriate material for the wiper/brush. Ensure no other mechanical parts touch the panels.

4. CAD Design

Figure 4. Final Sketch

4.1 Simulation and Analysis

Based on the results of our stress analysis, we found that 10 N of force would cause a warping of the rubber material for our conveyor belts. This poses a problem for the functionality of our design. The best alternatives to address this issue would be changing the material, providing mechanical support around the conveyor, and increasing the elastic force to counteract the weight pushing down on the belt. The orientation of the belt could also eliminate the need for elastic force adjustments.

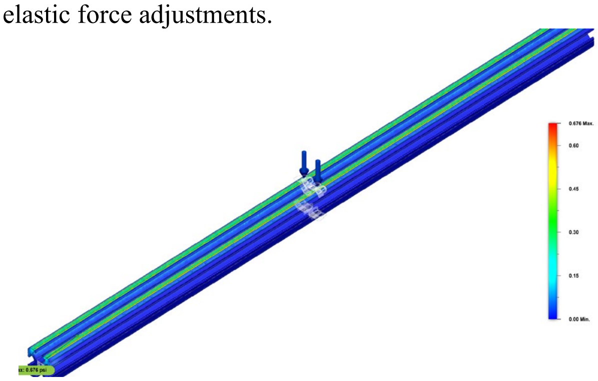

Figure 5. Current iterative design using Autodesk Fusion

From the thermal analysis, a temperature of 149 degrees Fahrenheit (or 65 degrees Celsius) could cause significant damage to rubber conveyor belts in several ways: accelerated aging process (which reduces mechanical properties), warping and alignment issues, decreased elasticity, and potential to melt. All issues can halt the functionality of the conveyor, so it is imperative to provide the necessary support or change to our current design to alleviate this issue.

The metal parts (aluminum T-slots and steel sprockets/mounting brackets) face no issues even at the temperature used in our thermal analysis. Plenty of research and examples of real-world applications have proven the strength and resistance of aluminum and steel in industry.

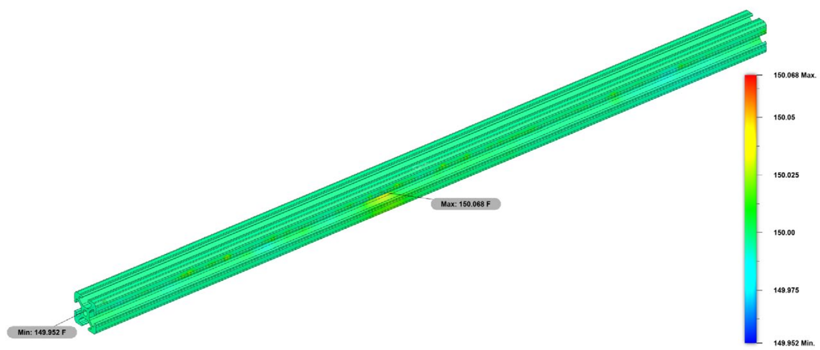

Figure 6. Stress Analysis Results

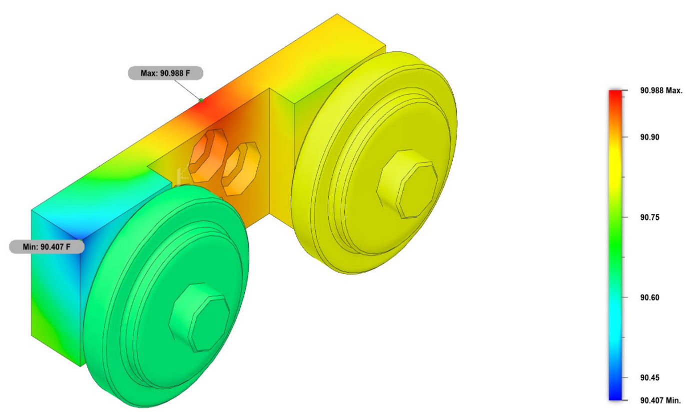

Figure 7. Thermal Analysis

5. Material Selection

For the frame, we've opted for 6063-T6 Aluminum due to its lightweight nature while having adequate strength. A 1010 series T-Slot is capable of withstanding 46 pounds before deflecting 1/10th of an inch. If 4 are connected into a secure table, it can withstand a maximum of 184 pounds (MotionAI). Aluminum was selected because it is lighter than steel while having similar strength and modulus capacities. In addition, this aluminum is corrosion-resistant and costs significantly less as well. When deciding on the motors that would facilitate the movement of the squeegee head, it was apparent that we would need a motor with sufficient torque to move the head the entire length of the solar panel. We had initially found a Nema 17 stepper motor, but after analysis, we opted to go with a Nema 34 high-torque motor to ensure that there is sufficient torque.

For safety reasons, the whole product as a package needs to be as lightweight as possible since it would be resting on a roof. The total weight of the frame would be around 8lbs. We also went with a rubber timing belt instead of chains. Although chains would require less maintenance over time, it is both heavier and more expensive upfront. These components make up the majority of the weight of the whole system. However, during the showcase, it may be considerably heavier due to all the supporting components that will be required to showcase the prototype such as the 5-gallon container, 12V battery, etc.

6. Testing and Prototyping

There are still questions that remain unanswered in this stage of the project. The goal is to have these questions answered during the testing and prototyping phase in order to ensure that there is no ambiguity should this reach a full production run. Currently, the main focus of testing is to determine whether the tensioned pulley system powered by the selected motors will be sufficient to sustain the movement of the squeegee. This will determine the validity of our design and help in cementing our selections in our Bill of Materials. Another aspect we seek to address in the testing phase is the water consumption. We already know that the power requirements are rather low, but actual testing will help in determining the amount of water used per panel and the amount of water used for an entire cleaning cycle. Since this project is centered around sustainability, we want to ensure that there is not an excess cost of water, because offsetting the energy savings by increasing the cost of water utilities would effectively render this project pointless.

7. Bill of Materials

This Bill of Materials is subject to change but currently encapsulates everything we believe will be needed to create this product. The initial total cost of materials (not factoring in true manufacturing costs) arrives at a total of **$829.00.** It is noteworthy that this is a prototype, and there are components in this bill of materials that will not be necessary if this were to be moved into a full production run. Mainly, there is a $139.99 cost associated with a solar panel that was purchased solely for testing and showcasing purposes. With this consideration, a more accurate cost than the one included here would be **$689.01**.

Table 3. Preliminary Bill of Materials

Item Name	Description	Quantity	Unit Cost	Shipping, Tax, etc.	Total Cost
Rubber Squeegee	Rubber Squeegee for cleaning Panel	1	$34.17	$10.98	$45.15
Arduino Controller	For Programming Motor	1	$48.35	$0.00	$48.35
Solar Panel	For showcasing	1	$139.99	$13.30	$153.29
12 V battery	Power Source	1	$75.99	$0.00	$75.99
Horizontal Frame	T-slot 60 inch aluminum	2	$23.79	$41.32	$88.90
Vertical Frame	T-Slot 36 inch aluminum	2	$15.39	$41.32	$72.10
Stepper Motor	Nema 34 High Torque	2	$69.98		$139.96
Back Support Plate	To facilitate movement	3	$13.99		$41.97
Irrigation Line		1	$15.99		$15.99
RYOBI Transfer Pump		1	$98.97		$98.97
5 Gallon Container	Water Basin	1	$14.35		$14.35
Pulley Timing Belt		2	$16.99		$33.98
		18.00			$829.00

7.1 Cost Analysis

In the current market landscape, the existing solutions for cleaning solar panels–as outlined earlier throughout this report–are costly, ineffective, inefficient, and dangerous. The main form of cleaning solutions is paid services where people physically climb onto the roof for cleaning. While there is no one set price for these services–as a result of competition in the marketplace–a range for this service is between $15 and $30 per panel (Cleaning 2024). Based on research that concluded that the average household in California has between 10 to 20 panels installed (Farmer 2024), costs for a biannual cleaning service can range from $300 to $1690.Based on these calculations, and the initial cost of materials being $689.01, a large lump sum cost is expected for the installation of our product. Assuming a total cost including installation of $2000, the product would recover its cost within as little as 2 years and as many as 7 based on the above ranges

8. Conclusion

This research successfully designed a cost-effective, automated gantry rail system to address the safety hazards and efficiency losses of manual residential solar panel cleaning. The selected design was chosen for its reliability and ability to clean an entire solar array with a single unit. Key findings from our analysis confirm the viability of using a lightweight aluminum frame and high-torque motors, while also identifying the rubber belt system as a potential weak point under thermal and physical stress.

The prototype's material cost is an estimated $689.01, with a cost-benefit analysis projecting a payback period as short as two years, confirming the design's economic feasibility. The crucial next step is the prototyping and testing phase, which will focus on validating the drive mechanism's performance and quantifying water consumption to ensure the system is both functional and sustainable. This device has the potential to provide homeowners with a practical tool to enhance the safety and efficiency of their solar energy investments.

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