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Design and Development of A Portable Solar Panel Cleaner With Dry and Wet Cleaning Systems

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ABSTRACT: Solar panels (PV modules) are a popular alternative energy source. The outer layer of toughened glass protects the solar cells from heat and weathering. The cleanliness of the surface has a significant impact on energy conversion, as dirt and dust can hinder the absorption of solar radiation. This study aimed to design, develop and analyse a solar panel cleaner using innovative wet and dry cleaning technologies. The design process resulted in detailed equipment specifications. Key components were assembled and tested for functionality. The dry cleaning system uses a rotating brush (three-cycle mops) connected to a DC motor. The wet cleaning system uses a nozzle at the end of the tool to deliver pressurised water from a DC pump connected to a water tank. The prototype was field-tested to assess the effectiveness of wet and dry cleaning methods on solar panels. The solar panel cleaner can be used for both wet and dry cleaning. Future improvements may result in an aesthetically pleasing, durable, effective and efficient solar panel cleaner.

KEYWORDS: solar panel cleaner, portable, rotary brush, wet cleaning, dry cleaning, performance

I. INTRODUCTION

The sun has been mankind's oldest source of energy. It is an inexhaustible, immense resource. The Sun radiates a total energy of 3.8 x 10^{20} MW, with its surface emitting 63 MW/m². This energy is scattered in all directions, and about 1,7 x 10^{14} kW of solar radiation reaches the Earth (Duffie & Beckman, 2013). Although only 30% of this energy reaches the surface of the planet, the solar radiation received in just half an hour could potentially meet the Earth's annual energy needs (Kalogirou, 2009). The growing global demand for renewable energy has driven the rapid expansion of solar power plant installations. Solar panel technology plays a critical role in capturing clean and sustainable solar energy (Susilo et al., 2022; Sudarsono et al., 2023).

Solar panels convert photon energy from the sun into electrical energy, but their performance is inherently affected by external weather conditions (Asrori et al., 2020). Fluctuations in solar radiation, climate, wind speed and weather patterns can all affect the surface temperature of the panel and ultimately the power generated by the photovoltaic cells (Asrori et al., 2019; Chukwuagu et al., 2023). In addition, outdoor solar panel installations are inevitably exposed to contaminants such as dust, leaves, bird droppings and air pollution. These materials can accumulate on the surface of the panel, blocking sunlight from reaching the photovoltaic cells and reducing energy output (Boottarat et al., 2023).

Solar panel cleanliness is crucial for optimal energy output. Dust, dirt, and other contaminants can significantly diminish efficiency, sometimes by as much as 30%. In recent years, innovative solar panel cleaning methods and technologies have emerged to address these issues. Advanced cleaning solutions are now available to maintain the highest possible efficiency and performance of solar photovoltaic (PV) systems. The loss of efficiency due to fouling is a significant threat to the viability (plant factor) of solar power plants. Researchers are actively investigating efficient solar panel cleaning technologies to mitigate this problem and improve the overall performance and lifetime of solar power systems (Hachicha et al., 2023).

The development of solar panel cleaning methods and technologies can be broadly described as follows:

A. Traditional Methods.

Traditional solar panel cleaning methods typically involve manual cleaning with water, a brush, and sometimes a mild detergent. This approach is widely used and effective for removing dust, dirt, bird droppings, and other contaminants. However, large-scale water usage can be problematic in arid regions, such as deserts.

B. Modern techniques.

Advanced solar panel cleaning technologies include robotic systems that automate the cleaning process for large-scale installations. These robots employ brushes, jets, or ultrasonic vibrations to efficiently remove dirt. Moreover, drones equipped with cleaning tools provide a viable solution for hard-to-reach areas or expansive roof surfaces. Although drone technology can be cost-effective in certain scenarios, weather conditions can present challenges.

C. Emerging Technologies.

Researchers are exploring self-cleaning coatings for solar panels inspired by biomimetic technology. These coatings utilize hydrophobic or superhydrophobic materials that repel water and prevent dust and dirt from adhering, mimicking the self-cleaning properties of lotus leaves or butterfly wings. Additionally, researchers are investigating nanoparticle-based coatings that can be applied to both traditional tempered glass and other solar panel materials, offering dirt-repellent and self-cleaning surfaces. Furthermore, some researchers are developing ultrasonic cleaning methods that utilize high-frequency sound waves to remove contaminants without the need for water or abrasives.

C. Future Trends.

The rapid advancement of information technology offers the potential for more effective, efficient, and cost-effective solar panel maintenance. Deep Machine learning (DML), artificial intelligence (AI), and Internet of Things (IoT) technologies can be leveraged for predictive maintenance. By analyzing data from sensors and other sources, these technologies can predict when cleaning is necessary, optimizing maintenance schedules.

Solar panel cleaning methods and equipment have evolved significantly in the past decade. While dry and wet cleaning remains the primary approaches, advancements in technology have introduced manual, mechanical, and automated options. Automated cleaning methods, such as those using robots and drones, are becoming increasingly popular due to their efficiency and scalability.

Researchers have investigated dry cleaning methods for solar panels, developing equipment that utilizes rotating brushes to effectively sweep away dirt and dust. These dry cleaning techniques have demonstrated significant efficacy in removing contaminants from solar panel surfaces. Fatima et al (2020) present the design and implementation of an automated dry cleaning system for solar panels using a microfibre brush driven by a DC motor, with an additional motor for machine movement and an ultrasonic sensor to detect panel edges. His research successfully demonstrated the design and implementation of a low-cost automated dry cleaning system for solar panels, providing a potential solution for maintaining solar panel efficiency without the use of liquids.

Zhang et al. (2021) investigated the impact of dust on solar panels and emphasized the importance of mechanical cleaning using brush filaments. Their study analyzed the cleaning force exerted by nylon brush filaments, establishing a mechanical model to understand the interaction between filaments and dust particles. The researchers discovered that the normal force exerted by dust particles and the cleaning force is influenced by the filament's deflection angle, axial displacement, and radial displacement. They determined that nylon brush filaments with a length of 20 mm, a diameter of 0.3 mm, and an axial displacement of 13-15 mm offer optimal cleaning performance for solar panels. These findings can inform the design of new cleaning tools to enhance dust removal efficiency.

The rotary brush cleaning systems offer a viable solution for maintaining optimal energy production from solar panels. Several studies have developed automated systems utilizing rotary brushes to efficiently remove dust and dirt from solar panels, thereby enhancing panel efficiency. These cleaning robots are designed to follow a guided path, ensuring thorough cleaning of the entire solar panel system (Ölmez et al., 2021; Ren et al., 2022; Shariful et al., 2022; Osawal et al., 2023).

The efficiency of rotary brush cleaners has been influenced by design parameters such as brush angle, rotation frequency and power consumption. Studies have demonstrated their reliability and effectiveness for dry cleaning various surfaces (Najmi et al., 2023). Simulations and small-scale tests have confirmed their ability to remove dust and significantly increase energy yield. Commercial options include telescopic poles with brushes and water pumps, stationary robots with dry and wet cleaning capabilities, and mobile cleaning systems with robotic arms, as shown in Figure 1.

Figure 1. Solar panel cleaning robot with brushing system (Najmi et al., 2023).

Furthermore, the researchers developed a cost-effective wet cleaning method that utilizes vacuum cleaners and pressurized water pumps to remove dust from solar panels. This approach not only removes contaminants but also provides a cooling effect, potentially enhancing panel efficiency by reducing operating temperatures.

Sugiartha et al. (2020) conducted a laboratory study to investigate the effectiveness of a semi-automatic wiper control system for cleaning solar panels (Figure 2). A DC motor powered the wiper, which was used to sweep the panel surface after spraying a controlled amount of water. Experimental tests were conducted to evaluate the performance of the solar panel under clean and dusty conditions, including output voltage, current, power, and efficiency. The results demonstrated that repeating the wiper sweep 10, 20, and 30 times restored 57.0%, 79.1%, and 86.7% of the initial clean surface performance, respectively.

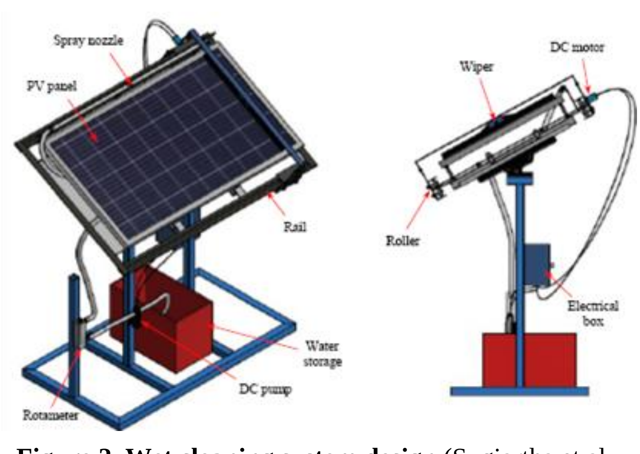


Figure 2. Wet cleaning system design (Sugiartha et al., 2020)

Kasim et al (2021) conducted an experimental study to analyse the power efficiency of solar generation systems.

This study compared the performance of a solar panel system exposed to dust with a clean panel surface. The automatic water spray cleaning system using Arduino runs for 30 minutes every week for six months. Cleaning starts one day a week in the early morning to reduce water evaporation. The system pumps enough water to clean an area of 14 m^2 with automatic control.

Despite the proven advantages and disadvantages of different solar panel cleaning technologies, several factors affect their effectiveness. Cost is an important consideration, as high-end PV cleaning equipment can be expensive. This initial investment may not be feasible for small PV operators (below 100 kWp). Given the prevalence of rooftop solar installations in Indonesia, the development of affordable cleaning equipment is the goal of this research.

II. MATERIALS AND METHODS

2.1 Methods

The prototype of the solar panel cleaner was designed and assembled in the Mechanical Engineering Production Workshop at the State Polytechnic of Malang. CATIA V6 software was used to create the design and working drawings for this portable device. The manufacturing process started with a design analysis and calculation phase. The Pahl-Beitz design method, which includes task planning, product concept design, embodiment design and detailed design, guided this process (Asrori et al., 2022). Following the design phase, the tool was machined and assembled. The 3D design is illustrated in Figure 3, with detailed specifications provided in Figure 4. In addition, the prototype will be tested for performance in real experimental research conducted outdoors (real environment) to collect real research data in the field.

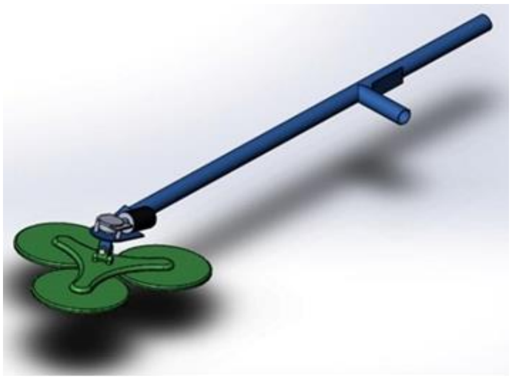


Figure 3. Design of a portable solar panel cleaner

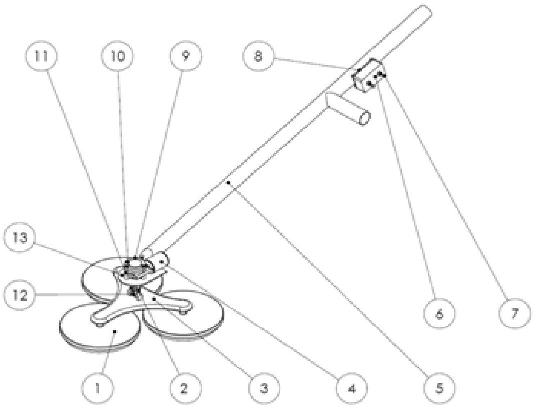


Figure 4. Part of Portable solar panel cleaner

2.2 Materials

The technical specifications of the solar panel cleaning equipment components (Figure 4) are detailed in Table 1.

Table 1. Parts of the solar panel cleaning equipment

No.	Part Name	Tech. Specifications
1	Cycle Mop	Plastic, ϕ 265 x 35 mm
2	Top Joint	ST 37, 65 x 35 x 15 mm
3	Bracket Mop	Aluminium, 280x310x40 mm
4	DC Motor	12 V/3 A/30 W
5	Main Frame	Galvanize, ϕ 48 x 1375 mm
6	Box Panel	Plastic, 110 x 70 x 50 mm
7	Switch on/off	Toggle Type
8	Box Panel Cap	Acrylic, 110 x 70 x 7 mm
9	Hex Nut	M5 x 0,8
10	Gear Box Cap	ϕ 72 x 15 mm
11	Gear Box	Reduction Ratio 20:1
12	Bottom Joint	Plastic, 30 x 25x 50 mm
13	Bracket DC Motor	ST37, 150 x 115 x 5 mm

The wet cleaning system also includes other components, as illustrated in Figure 5. These components include a water pump, a water tank, a nozzle, a hose assembly, and a pump control switch.

Figure 5. Components for the wet cleaning system

III. RESULTS AND DISCUSSION

3.1 Assembly of the solar panel cleaning device

The components are installed sequentially, beginning with the rotary mop, electric motor, and other supporting equipment. Figure 6 illustrates the installation of cables and rotary mops on the solar panel cleaner.

Figure 6. The rotary mop, cable, and hose system are assembled into a unit

The water hose connecting the pump to the nozzle is integrated into the cleaner's stick. A 12V/32Ah battery powers the rotary mop motor and the pressurized water pump system. For convenience, the water tank and battery are housed in a rucksack for easy carrying during cleaning operations (Figures 7 and 8). The prototype is assembled and tested to ensure that all components function correctly.

Figure 7. Installing the battery in the rucksack

Figure 8. Installation of a water tank in a ruckpack

The designed prototype, shown in Figure 9, consists of a Ø24 x 1310 mm galvanised steel solar panel cleaning rod. The dry cleaning system consists of 3 circular mop rotation systems with a two-speed control system for low and high rotation speeds. The wet cleaning system includes a nozzle for spraying pressurised water.

Figure 9. Prototype of solar panel cleaner

3.2 Production Cost and BEP Analysis

Production cost analysis is a detailed examination of all costs incurred in the production process. This analysis provides a clear understanding of the cost structure and helps companies identify areas for cost reduction and make informed decisions about pricing, production volumes and resource allocation. Break Event Point (BEP) analysis is a financial tool used to determine the sales volume required to cover all costs and make no profit or loss (Lau, 2020). It helps companies identify the minimum level of sales required to break even and assess the financial viability of a project or product. Production cost analysis therefore provides the essential data required to calculate BEP. By understanding the fixed and variable costs associated with production, companies can accurately determine BEP.

A. The production cost

The manufacturing cost estimate includes all expenses associated with producing the solar panel cleaner devices, such as design, materials, machining, labour, and assembly costs. The variables used for cost analysis are listed in Table 2.

Table 2. Production cost of a portable solar panel cleaner

No.	Variables Cost	Total Cost (Rp)
1	Design	500,000
2	Raw materials	1,183,650
3	Machinery process	92,000
4	Operator	235,000
5	Electricity consumption	200,000
6	Workshop rental	100,000
7	Assembly	160,000
	Total cost	2,470,650

Therefore, the total cost of manufacturing a solar panel cleaning tool is Rp. 2,470,650.

B. The selling price

The selling price of the portable solar panel cleaner is calculated based on the total cost of production, value-added tax (VAT) and the desired profit margin. Assuming a VAT rate of 11% and a desired profit margin of 20%, the estimated selling price per unit is Rp. 3,300,000.

C. The Break-Even Point (BEP)

The BEP analysis is used to determine whether it is feasible to mass-produce and sell 30 units of this device. To calculate the break-even point, it is critical to accurately estimate the fixed and total variable costs associated with producing and selling the device. The basic formula for calculating BEP in units is shown in Eq. 1.

$$BEP\ (in\ units) = \frac{FC}{P/unit - VC/unit} \qquad (1)$$

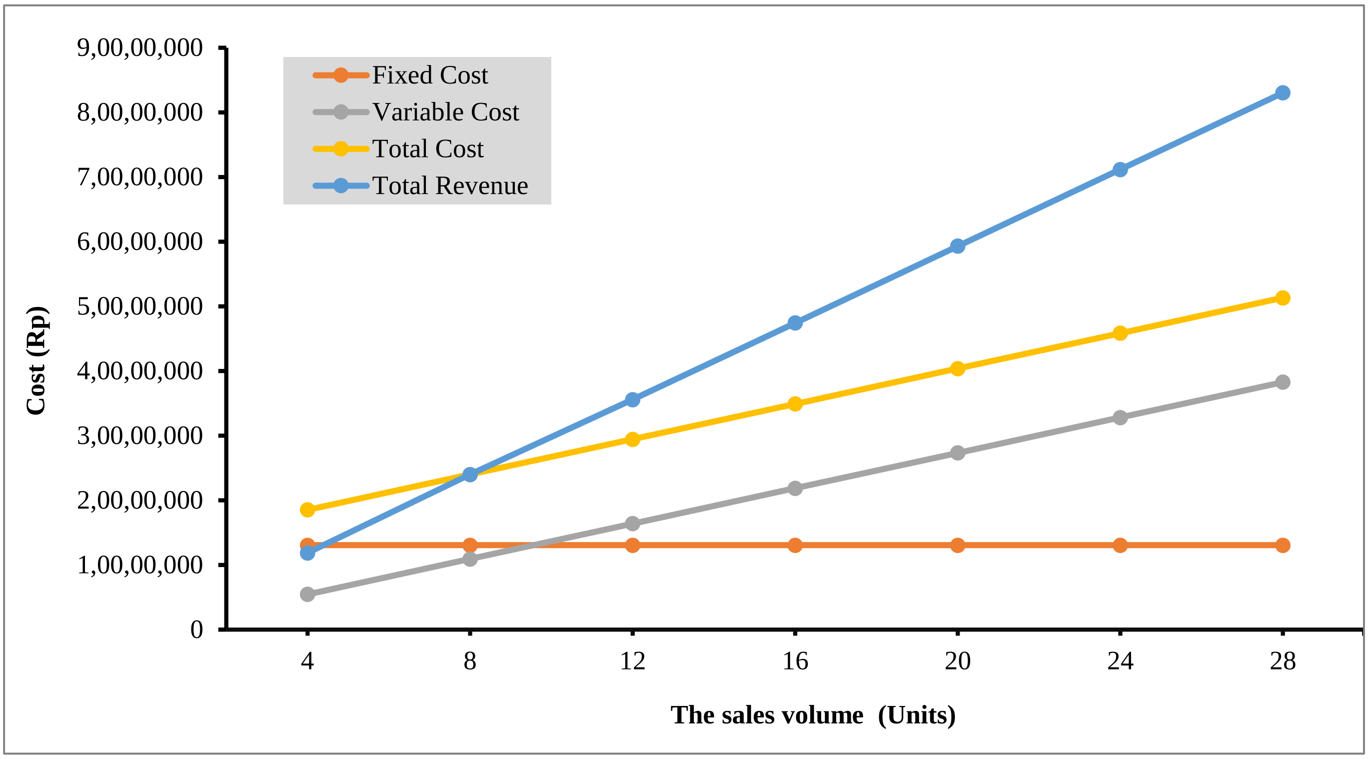
where *FC* is the fixed cost, *P* is the selling price and *VC* is the variable cost.

Table 3 below shows the BEP cost of selling solar panel cleaning tools, assuming production of 30 units.

Table 3. Cost types in BEP analysis

Fixed Cost		Variable Cost	
Components	Cost (Rp)	Components	Cost (Rp)
Machine rental	2,700,000	Electricity	6,000,000
Design	500.000	Raw materials	35,000,000
Operator salary	7,050,000		
Workshop rental	2,800,000		
Total cost	13,050,000	Total cost	41,000,000

According to Table 3, the variable cost per unit (VC) for producing 30 units is Rp. 1,366,667. Consequently, based on Equation 1 and the data in Table 3, the break-even point for the production of portable solar panel cleaners is approximately 8 units. In addition, the estimate of the BEP is presented in the graph in Figure 12.



3.3 Prototype Performance Test

Prototype performance tests were conducted using two methods: dry cleaning (Figure 11) and wet cleaning (Figure 12). The tests were carried out on the solar roof area of the Mechanical Engineering Building at the State Polytechnic of Malang, located at the following coordinates: Latitude: 7.943° S; Longitude: 112.613° E. The surface area of each cleaned solar panel was 1722 x 1134 mm (435 Wp).

A. Dry Cleaning Method

Figure 11. Prototype performance testing for dry cleaning method

Dry method testing was conducted on solar panels contaminated with dust flex and bird droppings (Figure 12). The blue circles in the image indicate the presence of these contaminants.

Figure 12. Condition of the solar panel surface before cleaning

As shown in Figure 13, the dry cleaning process was incomplete, leaving residual bird droppings (indicated by blue circles) and dust on certain areas of the solar panels.

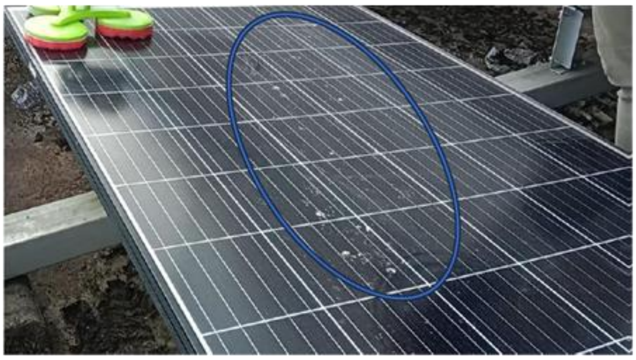


Figure 13. Solar panel surface after using a dry cleaning method

While dry cleaning is effective for certain types of soiling, it may not be optimal for removing stubborn dust from solar panel surfaces. Therefore, in some cases, dry cleaning may be less effective than other cleaning methods.

B. Wet Cleaning Method

The wet cleaning process commences by affixing a three-circle sponge pad to the solar panel's surface. Upon activation, the electric motor initiates rotation at the desired speed, concurrently activating the water pump to deliver pressurized water through the nozzle (Figure 14). The surface of the solar panel is then cleaned using a glass-wiping motion, as illustrated in Figure 15.

Figure 14. Prototype performance testing for wet cleaning method

Figure 15. Process for cleaning solar panels using the wet method

The wet cleaning method effectively removes bird droppings and stubborn dust from the solar panel surface, as shown in Figure 16. The estimated cleaning time for a 435 Wp solar module with a surface area of 2 m² is approximately 1 minute.

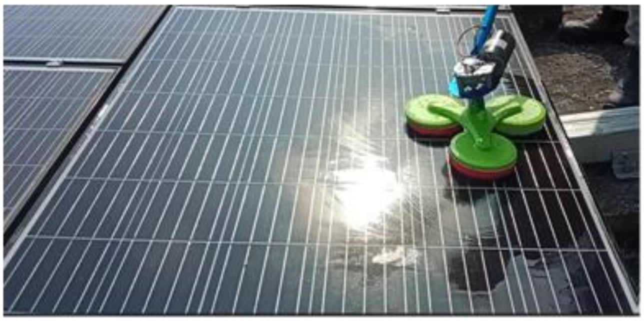


Figure 16. Condition of solar panel surface after combination cleaning

A combined dry and wet cleaning approach offers optimal results for solar panel maintenance. Dry cleaning effectively removes coarse dust particles, like sand, from the panel's surface. Following dry cleaning, the wet method addresses any remaining dirt. Additionally, the combined method effectively eliminates bird droppings, stubborn dust, and other contaminants, leaving the solar panel clean and debris-free.

The advancements in solar panel technology and the development of new materials necessitate concurrent progress in cleaning methods. Ongoing research ensures that cleaning technology keeps pace with the advancements in solar technology. Solar installations in different locations will encounter various challenges, such as dust storms, bird droppings, algae growth, or limited water resources. Some of these factors will require customized cleaning solutions and methods. Therefore, it is crucial to develop cost-effective cleaning methods that can provide a solution for low-capacity solar power plants (Mondal et al., 2018; Kazem et al., 2020).

Future development of this prototype will focus on improving its functionality and design, particularly for electric motor mounts, which require more sophisticated solutions. The battery's power source could be extended by integrating a solar panel directly into the cleaner devices.

IV. CONCLUSION

The portable solar panel cleaner prototype offers both wet and dry cleaning options. The wet cleaning system features a spray nozzle with an integrated pump for precise water delivery. The water tank and electronics are conveniently housed in a backpack. For optimal cleaning, the dry cleaning method can be used initially to remove loose debris, followed by wet cleaning to tackle stubborn stains and residue. This dual-cleaning approach is particularly beneficial in dusty environments where solar panel efficiency can be significantly compromised.

The estimated production cost of one automatic solar panel cleaner is Rp 2,470,650, with a selling price of Rp 3,300,000 per unit. Therefore, a total of 8 units must be sold to reach the break-even point (BEP).

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