JJMIE

Volume 14, Number 3, September. 2020
ISSN 1995-6665
Pages 279 - 287

Jordan Journal of Mechanical and Industrial Engineering

Systematic Approach for Selecting a Cleaning Method to Solar Panels Based on the Preference Selection Index Approach

Mohammed Said Obeidat*, Esra'a Mohammad Al Abed Alhalim, Bilal Raif Melhim

Department of Industrial Engineering, Jordan University of Science and Technology, PO Box 3030, Irbid 22110, Jordan

Received June 19 2019 *Accepted August 8 2020*

Abstract

Policymakers have become eager to move towards sustainability recently due to the growing costs of electricity and concerns about the environment. Environment friendly and economical energy sources, such as solar power, are being introduced at increasing rates. Photovoltaic (PV) panels are considered an important method of harnessing solar power. Although solar energy is one of the most efficient renewable and sustainable sources of energy, the accumulation of dust and debris on even one panel in a PV array reduces the efficiency of energy generation, thus highlighting the need to keep the surfaces of PV panels clean. Several methods can be used to clean PV panels, such as Heliotex technology, electrostatic cleaning, the use of self-cleaning glass, automatic cleaning and manual cleaning. The Preference Selection Index (PSI) multi-criteria decision-making approach is used in this study to compare these cleaning methods. Data were collected via a survey of solar energy experts in Jordan to enable a comparison of these cleaning methods, and several attributes were considered. After the initial PSI analysis, a follow-up sensitivity analysis was conducted that involved removing the cost attributes. The results showed that the best method was manual cleaning. The results of the sensitivity analysis confirmed that manual cleaning is the method most often preferred by experts.

Keywords: Energy; Cleaning; PV Panel; Multi-criteria Decision Making; Preference Selection Index;

1. Introduction

Global demand for resources has been growing rapidly, which has created pressure on the manufacturing sector to generate new products and develop technologies. These requirements are reflected in the amount of the energy required. The world relies heavily on oil, which is expensive, and causes environmental problems, and is non-renewable. This combination of disadvantages has forced countries across the world to shift to new, alternative energy sources. Renewable sources of energy are those that are not depleted by continuous usage, do not contribute to environmental pollution in terms of greenhouse gases, and do not pose health hazards [1]. Renewable energy systems are an essential alternative energy choice and are considered the first step in the industrialized building system construction industry [2]. These energy sources, and especially solar, biomass and wind, are now playing an important role in the economics of energy production and are improving the quality of the environment [3]. Projects involving renewable energy, and especially photovoltaic (PV) systems, can result in crucial savings in terms of the energy consumed in a building [4]. Countries around the word have implemented plans to increase the share of renewable energy sources and reduce greenhouse gas emissions [5].

Decision making and judgments are essential aspects of the average person's daily life. Human judgment has received considerable attention, both within and outside of the psychological sciences [6], [7], [8]. For some decisions, a single criterion may be the major focus of the decision makers, while other decisions are made based on multiple criteria simultaneously. Multi-criteria decision-making (MCDM) tools are used to evaluate candidate alternatives for the purpose of ranking, choosing or sorting based on a number of qualitative and/or quantitative criteria, and are associated with different measuring units [9]. Multi-criteria decision analysis can be applied to numerous types of complex decision. The Preference Selection Index (PSI) is one of the primary MCDM approaches that can help a decision maker to reach the optimal decision. Other MCDM approaches include the Analytic Network Process (ANP), Elimination and Choice Expressing Reality (ELECTRE), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), grey theory and the Analytic Hierarchy Process (AHP).

This paper provides a systematic procedure for selecting the best cleaning method for PV panels, using an approach based on PSI. Experts in the field of solar energy were asked to voluntarily answer a survey that described the most

* Corresponding author e-mail: msobeidat1@just.edu.jo

frequently used cleaning methods and included several attributes related to the cleaning of PV panels.

2. Literature Review

2.1 Solar Energy and the Cleaning of PV Panels

One of the largest challenges of the modern world involves how to meet the required demand for energy in a sustainable way [10]. This rise in energy demand is a result of the growing population and increases in prosperity levels [11]. Solar energy is considered one of the best alternatives of the various types of renewable energy sources which entails the conversion of the sun's rays into electrical energy. A solar or PV cell is a device that converts sunlight into electricity [12]. As the sun is the source of solar power, this form of electrical power is cleaner and less expensive than fossil fuels [13]. Solar cells are made from semiconducting materials, and to be able to absorb sunlight, these materials must have specific characteristics.

PV panels are currently the most widely used renewable energy source. There are several factors that can significantly affect the maximum efficiency of a PV installation, including the geographic location (latitude and solar insolation) and the design of the installation (tilt angle, altitude and orientation). Other factors can also significantly affect the performance (efficiency), such as the accumulation of dust and debris [14]. Mani and Pilli (2010) studied the impact of dust on PV systems; they identified various factors responsible for the settling of dust on PV panels, and suggested some solutions to reduce this accumulation [14].

There are two key cost drivers related to the use of PV cells that affect all stakeholders: the efficiency and the degradation rate [15]. The efficiency of a PV cell refers to the conversion of sunlight into electrical power, and concerns how this relationship evolves over time, while the degradation rate is a quantification of how the electrical power declines over time [15]. The latter is extremely important, as a higher degradation rate means that a lower level of power is produced, thus reducing future cash flows [16].

The conversion efficiency of a solar cell is defined as the percentage of the solar energy falling onto a PV device that is converted into electricity [17]. This efficiency is one of the main factors that can affect the selection process of a type of solar cell. Most of the sunlight that reaches a PV cell is lost rather than converted into electricity [17]. Several factors can affect the conversion efficiency, including the wavelength, recombination, temperature and reflection. These factors must be considered when designing a PV system to achieve higher efficiencies.

In any PV installation, the engineers focus on the design (tilt angle, altitude and structure) in order to harvest the maximum solar radiation. However, they may overlook the practicalities of a site, such as the deposition of dust, water, salt, or bird droppings [14]. These phenomena, when combined with losses in wires and inverters, can reduce the efficiency of a module by 10–25% [14].

Dust is defined as a solid particle with a diameter less than 500 µm. It is generated in the atmosphere from different sources, such as wind, vehicular movement, pollution and volcanic eruption. The accumulation of dust on PV panels is characterized by two important factors that influence each other: the properties of the dust (such as its size, weight, shape, chemical and biological properties and electrostatic properties), and the local environment (such as human activities, environmental characteristics including the orientation and height of the installation, and weather conditions) [14].

Mani and Pillai (2010) performed a study that had two phases. In phase one, they primarily studied the impacts of the characteristics of solar systems, such as the tilt angle and glazing, on dust accumulation. In phase two, they studied the effects of dust deposition via an experimental investigation. They suggested several solutions to the problem of dust on solar panels in relation to the geography of the installation; for example, dry tropical regions with temperature ranges of 20–49°C, annual precipitation greater than 150 cm and in latitude ranges of 15–25° north and south are prone to dusty desert environments and dust storms, and PV systems in these areas should be cleaned at a minimum of weekly.

Appels et al. (2013) studied the effects of dust settlement on PV modules that are installed at an optimal tilt angle with regular rainfall in Belgium. Their methodology was as follows: (i) a spectrometer was used to examine the relationship between the decrease in transmittance and the decrease in the output power of a PV module; (ii) a scanning electron microscope was used to examine dust samples; (iii) several prototype coatings were introduced to determine whether they reduced the power loss of the output; and (iv) the effects of dry residue on PV modules were studied [18]. The results showed that the accumulation of dust on PV modules in Belgium was responsible for consistent power losses in the range 3–4% after dust saturation over three or four weeks. Rainfall had a limited effect on power losses for small dust particles (2–10 µm), but had a better effect in terms of washing away large dust particles. A special coating was shown to be a solution for this issue, although it was not cost-effective [18]. Appels et al. (2013) also suggested regular cleaning with soft tap or demineralized water.

The use of hydrophobic coatings on photovoltaic modules is another method of cleaning them [19]. High temperatures and dust storms are the most frequent factors that reduce the maximum performance of PV modules in Middle East and North Africa [19]. These can reduce the maximum output power by 16.2% and the short-circuit current (I_{sc}) by 6.6% [19]. In addition, dust settlement on PV modules induces a hotspot phenomenon, which increases the temperature of the PV module, thus reducing its efficiency. Fathi et al. (2017) applied a self-cleaning hydrophobic nano-coating to a PV module and measured its output performance. They found that the hydrophobic coating, which was a cost-effective method, increased light transmittance and reduced the temperature of the PV module, meaning that the output power losses were reduced [19].

Moharram et al. (2013) studied the effect of cleaning PV modules using a non-pressurized water system and a surfactant. Their objective was to remove dust from PV modules using these two methods, as they are the least costly and the most energy-efficient approaches. The experiment used a 14 kW PV system and consisted of three stages: no cleaning; cleaning with non-pressurized water;

and cleaning with anionic and cationic surfactants. They found that the accumulation of dust on PV modules (i.e. no cleaning) significantly reduced the efficiency, the non-pressurized water system was insufficiently strong to improve the efficiency of the PV modules compared to regular water, and a mixture of anion and cation surfactants was the best method of removing dust sticking to the modules [20].

A superhydrophobic and water-repellent coating offers a further method of self-cleaning for PV panels. Park et al. (2011) studied a micro-shell array that was fabricated on transparent and flexible polydimethylsiloxane (PDMS) layers. This method was compared to a non-superhydrophobic coating on PV modules. The results showed that this was an excellent water repellent, and lower dust accumulation was seen for a superhydrophobic PDMS at a contact angle that was higher than 150°, with a hysteresis level of less than 20° [21].

Chaichan et al. (2015) studied the effects of pollution and cleaning on PV modules in Baghdad, Iraq. Their experiment was conducted in outdoor conditions in order to investigate the impact of air traffic pollution on highways on the performance of PV panels. Three polycrystalline panels were installed at a tilt angle of 30° towards the south. Natural cleaning conditions, such as rain and wind were the main cleaning methods for the first panel, while the second panel was designed to collect pollutants such as dust, bird droppings and to preserve them by being covered during cloudy and rainy weather. The third panel was cleaned by alcohol with 99% purity before each measurement was taken. The experiment was conducted for a period of two months during the winter. The results showed that the cleaned panel had an average efficiency of 4.82%, the naturally cleaned panel 3.233%, and the polluted panel 1.749% [22]. The second phase of the study by Chaichan et al. (2015) involved evaluating the best cleaning method for PV panels. The same polycrystalline panels were tested for two further months. The first panel was cleaned with deionized distilled water, the second was cleaned with alcohol and the third with sodium surfactant. The results showed a reduction in the efficiency of the PV panels of about 0.1% for alcohol, less than 1% for sodium surfactant and about 14% for deionized distilled water. Distilled water failed to clean the PV panels due to the small particles, and especially nano-scale carbon, that were stuck to them [22].

Sayyah et al. (2015) introduced a new cleaning method to reduce soiling of a PV module using an electrodynamic screen (EDS) in an environmentally-controlled test chamber. The EDS system was composed of two stacked layers of transparent dielectric coating, which covered the PV glass. The results showed that 90% of I_{sc} was restored from its original value after several cycles, which enhanced the efficiency of the module. However, coagulations of dust were observed on some PV surfaces after using the EDS method. The authors stated that this dust coagulation was acceptable because its availability, the PV module can use the light scattered from dust particles [23].

Biris et al. (2004) studied the effect of removing dust particles from a PV module using an EDS. Their experiment involved applying an AC signal to a shield consisting of parallel wires. The electrodes were embedded into a polymer film to prevent any spark between them. A wide range of amplitudes and frequencies was applied, and it was found that the EDS was able to remove dust particles and prevent them from re-accumulating; however, this depended on the amplitude and frequency of the voltage. The researchers concluded that increasing the amplitude of the voltage led to greater removal of dust particles, and that the 5–15 Hz frequency range was optimal [24].

2.2 Multi-criteria Decision Making

MCDM aims to assist decision makers in selecting the best option from many feasible alternatives [25]. MCDM approaches are designed to identify the most preferred alternative by grouping the available alternatives into a limited number of categories and ranking these alternatives in order of preference. MCDM approaches have been used in a wide range of areas according to the nature of the decisions to be made. Examples of MCDM approaches include PSI, AHP, ANP, ELECTRE, TOPSIS and grey theory. The aim of these widely used decision-making approaches is to break complex decisions down into smaller parts, which can be analyzed separately and then recombined into a weighted score [26]. The following is a brief description of the most commonly used MSDM approaches.

The ANP method is used in models with clear dependencies. It is a general class of decision-making approaches that deals with complex interdependencies among different attributes or elements [27], [28]. It provides a framework for dealing with decisions without the need for assumptions about the interdependence between elements at higher and lower levels, or between elements at the same level [29], [30]. The ANP method uses a network rather than a hierarchy of different levels [29], [30]. It has been applied to decisions in fields, such as product design, equipment replacement, and energy policy planning [31]. ANP has also been applied in the evaluation and selection of projects [32], supply chain management [33], performance management [34], environmental issues [35], strategy selection [36] and manufacturing systems [37]. If there are dependencies between the criteria, a fuzzy ANP might be a good choice [38].

ELECTRE methods (I, II, III, IV, IS, and TRI) have been chosen as the best methods by pairwise comparison of alternatives within the decision problem [9]. Examples of studies that have used ELECTRE methods include evaluating an action plan for the diffusion of renewable energy technologies at a regional scale [39], supporting decision makers with different value systems [40], solid waste management [41], choosing materials under weighting uncertainty [42] and the planning of water resources [43].

Grey theory is one of the MCDM approaches used to study the uncertainty of systems, and is a superior approach that can provide a mathematical analysis of systems with uncertain information [44], [45], [46]. In this theory, a system is referred to as 'white' if its information is known completely, 'black' if its information is unknown, and 'grey' if it is partially known [46]. Researchers have used grey theory in several fields, for example in medicine [47], economics [48], supplier selection [46], the environment [49] and airline networks [50].

AHP is an appropriate approach for decisions under conditions of certainty, where a judgment is quantified using a systematic procedure and used as a base for making an optimal decision [51]. It is a structured technique that applies both psychology and mathematics to make complex decisions [52]. The priority levels of the decision criteria are evaluated and determined [53], and complex decisions are made by quantifying non-numeric factors related to the decision, such as the ideas, emotions, feelings, expectations, etc. of people involved in the decision [51]. A pairwise comparison matrix is constructed for all the factors considered in the decision process [54]. There are four main components of an AHP model that enable a decision to be made in a structured manner and to enhance the process of generating priorities [55]. These components are: (i) the definition of the decision problem; (ii) the construction of a decision hierarchy; (iii) the construction of pairwise comparison matrices; and (iv) the use of the priorities computed from the comparison matrices to weight the priorities of the elements [55]. Over 150 applications of the AHP approach are available, and these can be categorized into 10 areas: allocation, selection, benefit-cost, evaluation, development and planning, ranking and priority, forecasting, decision making, medicine and quality function deployment [56]. One example of the application of AHP in the solar energy sector is the research reported in [57], which investigated the connection between regional factors and the attractiveness of investing in the production of solar energy.

The TOPSIS approach is a straightforward one that generates two alternative solutions: a positive ideal solution and a negative one. In TOPSIS, the selected alternative must simultaneously have the minimum geometric distance from the positive ideal solution and the maximum geometric distance from the negative ideal solution [58], [59], [60]. A decision matrix and a normalized decision matrix are constructed using accurate scores that each alternative receives from all criteria [60]. The negative and positive ideal solutions are found by considering all attribute rates. The order of preference of the alternatives is determined by comparing the distance coefficient of each alternative. Applications of TOPSIS include financial investment decisions such as highway buses outranking [61], [62], identifying new active investment opportunities [63], operations management, for example in decision problems related to supplier selection in the manufacturing industry [64], the selection of production processes for semiconductors [65] or the selection of material for metallic bipolar plates for a polymer electrolyte fuel cell [66], water management [67] and evaluating the service quality of public transportation [68].

The PSI method is a direct decision-making method that requires fewer and simpler calculations than the other MCDM approaches [69]. This approach relies on statistical concepts without the need to weight the considered attributes [27]. The methodology consists of defining the problem goal, formulating a decision matrix of alternatives and criteria, normalizing the decision matrix, computing the preference variation value, determining the overall preference value, obtaining the preference selection index and ranking alternatives in ascending or descending order to facilitate the interpretation of results [70].

2.1.1. PSI Details

PSI is a new approach that was proposed in [70]. Unlike other MCDM methods, this technique does not require the user to give an importance between attributes. A PSI value is calculated for each alternative, where the best alternative is the one with the highest value. This method can be illustrated using the following steps [70]:

- Step I: Identification of the objective and determination of all possible criteria and the measures and alternatives to be studied.
- Step II: Formulation of the decision matrix. Let A be a set of alternatives, where A= {Ai for i= 1, 2, 3, . . ., n}, *C* a set of decision criteria where *C*={C_j for j = 1, 2, 3, . . . , m} and X_{ij} the performance of alternative A_i when it is studied with criterion C_j. As a result, a decision matrix can be created as shown in Table 1.

Table 1. Decision matrix X_{ij}

Alternatives (A_i)	Criteria (C_j)				
	C_1	C_2	C_3	…	C_m
A_1	X_{11}	X_{12}	X_{13}	…	X_{1m}
A_2	X_{21}	X_{22}	X_{23}	…	X_{2m}
A_3	X_{31}	X_{32}	X_{33}	…	X_{3m}
…	…	…	…	…	…
A_n	X_{n1}	X_{n2}	X_{n3}	…	X_{nm}

- Step III: Normalization of data, i.e. transforming the values in the decision matrix to the range 0–1. In the case of a positive expectancy (i.e. profit), the normalization formula will be as follows:

$$R_{ij} = \frac{X_{ij}}{X_j^{max}}, \quad (1)$$

while for a negative expectancy (i.e. cost) the normalization formula is:

$$R_{ij} = \frac{X_j^{min}}{X_{ij}}, \quad (2)$$

where X_{ij} are the attribute measures (i = 1, 2, 3, ..., N and j = 1, 2, 3, . . . , M) in the decision matrix.

- Step IV: Calculation of the preference variation value (PVj), which is determined for each attribute using the following equation:

$$PV_j = \sum_{i=1}^{N}[R_{\text{ij}} - \overline{R_J}]^2, \quad (3)$$

where $\overline{R_J}$ is the mean of the normalized value of attribute j and is calculated as follows:

$$\overline{R_J} = \frac{1}{N}\sum_{i=1}^{N} R_{\text{ij}}\,. \quad (4)$$

- Step V: Computation of the deviation (Φ) in the preference value (PVj) for each attribute, using the following equation:

$$\Phi = 1 - PV_j\,. \quad (5)$$

- Step VI: Computation of the overall preference value (Ψ) for each attribute as follows:

$$\Psi_j = \frac{\Phi_j}{\sum_{j=1}^{M}\Phi_j}. \quad (6)$$

The overall summation of the preference value of all attributes must give a value of one.

- Step VII: Computation of the preference selection index (Ii) using the following equation:

$$I_i = \sum_{j=1}^{M}(R_{ij} \times \Psi_{\text{j}})\,. \quad (7)$$

- Step VIII: Finally, alternatives are ranked based on the Ii value, where alternatives with the highest value are selected first.

3. Methodology

The main objective of this paper was to compare the most widely used methods of cleaning PV panels. The PSI MCDM approach was used to find the optimum cleaning method based on certain attributes. Five cleaning methods were compared: Heliotex technology (automatic cleaning and washing without using brushes), electrostatic cleaning, self-cleaning glass (nano-coating), automatic cleaning (by robot, dry or wet wipers and water spray) and manual cleaning (by water spray, dry or wet wipers and rotary brushes). Several relevant criteria were considered in the PSI, including the cleaning time, initial cost, running cost, efficiency, time between cleanings and safety. Data were collected via a survey that was distributed in interview format to PV experts in Jordan. The PSI method was applied twice, in two phases. In the first phase, all the abovementioned criteria were considered in a comparison of the five different cleaning methods, while in the second phase, the cost attributes were removed, and a sensitivity analysis was carried out.

4. Data

Data on the cleaning methods were collected using a survey of Jordanian experts in the field of solar energy. The average of the responses was considered for the PSI analysis, as shown in Table 2, which contains the decision matrix of the PSI.

5. Results and Discussion

In this section, the eight steps of the PSI method described in Section 2.2.1 are applied. Table 2 shows the decision matrix for selecting the most preferred cleaning method based on the PSI approach. The data in the decision matrix were normalized as shown in Table 3, following Step III in Section 2.2.1. In this step, the cells representing the initial cost and the running cost were normalized using Equation 2, by dividing the minimum value in each column of the decision matrix by the value in each cell of the decision matrix in the corresponding column. This was not the case for the data normalization in the remaining columns of the decision matrix; each cell in these columns was divided by the maximum value in the corresponding column using Equation 1. The mean of each attribute ($\bar{R}_j$) was calculated as shown in Table 3, by taking the average of all the normalized values in each column using Equation 4.

Table 4 summarizes the following quantities for each attribute: (i) the preference variation value (PVj), calculated based on Equation 3; (ii) the deviation (Φ) in the preference value (PVj), calculated based on Equation 5; and (iii) the overall preference value (Ψ), calculated based on Equation 6.

Table 2. Responses collected from PV experts (decision matrix)

Alternatives (cleaning methods)	Attributes					
	Cleaning time	Initial cost	Running cost	Efficiency	Time between cleanings	Safety
Heliotex technology	6.33	6	5.33	5.67	5	5
Electrostatic cleaning	5.5	9	6.67	5.33	5.5	6.33
Self-cleaning glass (nano-coating)	4.5	9	4	6.67	4.5	8
Automatic cleaning (robot, dry or wet wipers and water spray)	7.33	7.67	6.67	7	5.33	6.67
Manual cleaning	8.33	4	7	7.33	5.67	5.33

Table 3. Normalized data

Alternatives (cleaning methods)	Attributes					
	Cleaning time	Initial cost	Running cost	Efficiency	Time between cleanings	Safety
Heliotex technology	0.7599	0.6667	0.7505	0.7735	0.8818	0.6250
Electrostatic cleaning	0.6603	0.4444	0.5997	0.7272	0.9700	0.7913
Self-cleaning glass (nano-coating)	0.5402	0.4444	1.0000	0.9099	0.7937	1.0000
Automatic cleaning (robot, dry or wet wipers and water spray)	0.8799	0.5215	0.59970015	0.9549	0.9400	0.8338
Manual cleaning	1.0000	1.0000	0.5714	1.0000	1.0000	0.6663
$\bar{R}_j$	0.7681	0.6154	0.7043	0.8731	0.9171	0.7833

Table 4. Values of PVj, Φ and Ψ for each attribute

Measures	Attributes					
	Cleaning time	Initial cost	Running cost	Efficiency	Time between cleanings	Safety
PVj	0.12992	0.21781	0.12911	0.05538	0.02668	0.08833
Φ	0.87009	0.78219	0.87089	0.94462	0.97332	0.91167
Ψ_j	0.16255	0.14613	0.16270	0.17647	0.18183	0.17032

Table 5 shows the last step in the PSI calculations in which the index (I_i) was calculated for each alternative using Equation 7. Table 5 shows that the maximum I_i value was achieved for manual cleaning (0.40807), followed by Heliotex technology (0.34928), self-cleaning glass (nano-coating) (0.32647), automatic cleaning (0.31853) and then electrostatic cleaning (0.27412). The maximum value indicates the most preferred alternative, i.e. manual cleaning in this case.

6. Sensitivity Analysis

In this section, the PSI method was applied again to compare the five cleaning techniques with same attributes as used in the first PSI calculations; however, in this case, the attributes related to the cost of the cleaning method (the initial cost and the running cost) were removed to ensure that the decision was not biased. This experiment was conducted in order to compare only the techniques themselves. Table 6 shows the last step of the PSI calculation for the purposes of sensitivity analysis, in which the index (I_i) is calculated for each alternative after removing the cost-related attributes. The maximum value of I_i is still found for manual cleaning, followed by automatic cleaning, Heliotex technology, electrostatic cleaning and then by self-cleaning glass (nano-coating).

7. Conclusions

In this paper, five methods of cleaning PV panels were compared, based on six attributes of these cleaning techniques. The cleaning methods were Heliotex technology, electrostatic cleaning, self-cleaning glass (nano-coating technique), automatic cleaning (robot, dry or wet wipers and water spray) and manual cleaning. The attributes considered here were the cleaning time, initial cost, running cost, efficiency, time between cleanings and safety. The PSI MCDM technique was used as a novel tool to evaluate the cleaning methods. Solar energy experts in Jordan were asked to fill in a survey, and their judgments were used as input to the PSI approach.

The results of the PSI method indicated that the most suitable cleaning technique was manual cleaning, followed by Heliotex technology, self-cleaning glass (nano-coating), automatic cleaning and then electrostatic cleaning. A sensitivity analysis was conducted to measure the efficiency of the PSI approach when some attributes were removed. The two attributes related to the cost of the cleaning method (the initial and running costs) were removed, and the new results showed that manual cleaning remained the best cleaning method, followed by automatic cleaning, Heliotex technology, electrostatic cleaning and then by self-cleaning glass (nano-coating).

8. Limitations

The data used in this paper were collected from solar energy experts in Jordan. This means that the results may be influenced by conditions in Jordan, such as the weather, temperature, humidity, customs, man hour rate, technology level, etc. Hence, the criteria considered here, and the respective opinions of these experts may vary with differences in conditions related to the country, the cost of technology, and other factors. The results from this paper can therefore be applied in other countries, taking into consideration their local conditions.

Table 5. Computation of the preference selection index (I_i)

Alternatives (cleaning methods)	Attributes						I_i
	Cleaning time	Initial cost	Running cost	Efficiency	Time between cleanings	Safety	
Heliotex technology	0.1235	0.0974	0.1221	0.00175	0.00023	0.00427	**0.34928**
Electrostatic cleaning	0.1073	0.0650	0.0976	0.00376	0.00051	0.00001	**0.27412**
Self-cleaning glass (nano-coating)	0.0878	0.0650	0.1627	0.00024	0.00277	0.00800	**0.32647**
Automatic cleaning (robot, dry or wet wipers, water spray)	0.1430	0.0762	0.0976	0.00118	0.00010	0.00043	**0.31853**
Manual cleaning	0.1625	0.1461	0.0930	0.00284	0.00125	0.00233	**0.40807**

Table 6. PSI (I_i) for sensitivity issues

Alternatives (cleaning methods)	Attributes				I_i
	Cleaning time	Efficiency	Time between cleanings	Safety	
Heliotex technology	0.1787	0.0025	0.00033	0.006171	**0.1877**
Electrostatic cleaning	0.1553	0.0054	0.00074	0.000016	**0.1615**
Self-cleaning glass (nano-coating)	0.1271	0.0005	0.00401	0.011577	**0.1430**
Automatic cleaning by (robot, dry or wet wipers and water spray)	0.2070	0.0017	0.00014	0.000628	**0.2094**
Manual cleaning	0.2352	0.0041	0.00181	0.003373	**0.2445**

References

[1] G. Boyle, Renewable Energy: Power for Sustainable Future, 3rd ed., United Kingdom: Oxford University, 2004.

[2] B. Hassan and M. Beshara, "Using Renewable Energy Criteria for Construction Method Selection in Syrian Buildings," *Jordan Journal of Mechanical and Industrial Engineering,* vol. 13, no. 2, pp. 125-130, 2019.

[3] A. Herzog, T. Lipman, J. Edwards and D. Kammen, "Renewable Energy: A Viable Choice," *Environment: Science and Policy for Sustainable Development* , vol. 43, no. 10, pp. 8-20, 2001.

[4] M. Al-Widyan, I. Soliman, A. Alajlouni, O. Al Zu'bi and A. Jaradat, "Energy Performance Assessment of a Non-domestic Service Building in Jordan," *Jordan Journal of Mechanical and Industrial Engineering* , vol. 12, no. 2, pp. 69-5, 2018.

[5] M. Bürer and R. Wüstenhagen, "Which Renewable Energy Policy is a Venture Capitalist's Best Friend? Empirical Evidence from a Survey of International Cleantech Investors," *Energy Policy,* vol. 37, no. 12, pp. 4997-5006, 2009.

[6] N. H. Anderson, "Functional Measurement and Psychophysical Judgment," *Psychophysical Review,* vol. 77, no. 3, pp. 153-170, 1970.

[7] R. M. Dawes, "A Case Study of Graduate Admissions: Application of Three Principles of Human," *American Psychologist,* vol. 26, no. 2, pp. 180-188, 1971.

[8] J. Louviere, "Predicting the Evaluation of Real Stimulus Objects From Abstract Evaluation of Their Attributes: The Case of Trout Streams," *Journal of Applied Psychology,* vol. 59, no. 5, pp. 572-577, 1974.

[9] T. Özcan, N. Çelebi and S. Esnaf, "Comparative Analysis of Multi-criteria Decision Making Methodologies and Implementation of a Warehouse Location Selection Problem," *Expert Systems with Applications,* vol. 38, p. 9773–9779, 2011.

[10] I. Dincer and C. Acar, "A Review on Clean Energy Solutions for Better Sustainability," *International Journal of Energy Research,* vol. 39, no. 5, pp. 585-606, 2015.

[11] J. Lange, J. Hilgedieck and M. Kaltschmitt, "Renewable Resources of Energy for Electricity Generation-Development Trends and Necessities Within the Overall Energy System," *Jordan Journal of Mechanical and Industrial Engineering,* vol. 13, no. 3, pp. 207-220, 2019.

[12] O. o. E. E. a. R. Energy, "Solar Photovoltaic Technology Basics," 2013. [Online]. Available: https://energy.gov/eere/solar/articles/solar-photovoltaic-technology-basics. [Accessed 28 January 2018].

[13] A. Herzog, T. Lipman, J. Edwards and D. Kammen, "Renewable Energy: A Viable Choice," *Environment: Science and Policy for Sustainable Development* , vol. 43, no. 10, pp. 8-20, 2001.

[14] M. Mani and R. Pillai, "Impact of Dust on Solar Photovoltaic (PV) Performance: Research Status, Challenges and Recommendations," *Renewable and Sustainable Energy Reviews,* vol. 14, no. 9, pp. 3124-3131, 2010.

[15] D. Jordan and S. Kurtz, "Photovoltaic Degradation Rates: An Analytical Review," National Renewable Energy Laboratory, Golden, CO, United States, 2012.

[16] W. Short, D. Packey and T. Holt, "A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies," National Renewable Energy Laboratory , Golden, Colorado, United States , 1995.

[17] O. o. E. E. &. R. Energy, "Solar Performance and Efficiency," 2013. [Online]. Available: https://energy.gov/eere/solar/articles/solar-performance-and-efficiency. [Accessed 6 2 2018].

[18] R. Appels, B. Lefevre, B. Herteleer, H. Goverde, A. Beerten, R. Paesen, K. De Medts, J. Driesen and J. Poortmans, "Effect of Soiling on Photovoltaic Modules," *Solar Energy,* vol. 96, pp. 283-291, 2013.

[19] M. Fathi, M. Abderrezek and M. Friedrich, "Reducing Dust Effects on Photovoltaic Panels by Hydrophobic Coating," *Clean Technologies and Environmental Policy,* vol. 19, no. 2, pp. 577-585, 2017.

[20] K. Moharram, M. Abd-Elhady, H. Kandil and H. El-Sherif, "Influence of Cleaning Using Water and Surfactants on the Performance," *Energy Conversion and Management,* vol. 68, pp. 266-272, 2013.

[21] Y. Park, H. Im, M. Im and Y. Choi, "Self-cleaning Effect of Highly Water-repellent Microshell Structures for Solar Cell Applications," *Journal of Materials Chemistry,* vol. 21, no. 3, pp. 633-636, 2011.

[22] M. T. Chaichan, B. Mohammed and H. Kazem, "Effect of Pollution and Cleaning on Photovoltaic Performance Based on Experimental Study," *International Journal of Scientific and Engineering Research,* vol. 6, no. 4, pp. 594-601, 2015.

[23] A. Sayyah, M. Horenstein and M. Mazumder, "Performance Restoration of Dusty Photovoltaic Modules Using Electrodynamic Screen," New Orleans, LA, 2015.

[24] A. Biris, D. Saini, P. Srirama, M. Mazumder, R. Sims, C. Calle and C. Buhler, "Electrodynamic Removal of Contaminant Particles and its Applications," Seattle, Washington, 2004.

[25] T. Erden and M. Z. Coskun, "Multi-criteria Site Selection for Fire Services: The Interaction with Analytic Hierarchy Process and Geographic Information Systems," *Natural Hazards and Earth System Sciences,* vol. 10, pp. 2127-2134, 2010.

[26] R. Al-Aomar, "A Combined AHP-Entropy Method for Deriving Subjective and Objective Criteria Weights," *International Journal of Industrial Engineering: Theory, Applications and Practice,* vol. 17, no. 1, pp. 12-24, 2010.

[27] R. Attri and S. Grover, "Application of Preference Selection Index Method for Decision Making Over the Design Stage of Production System Life Cycle," *Journal of King Saud University – Engineering Sciences,* vol. 27, pp. 207-216, 2015.

[28] H. Abu Qdais and H. Alshraideh, "Selection of Management Option for Solid Waste from Olive Oil Industry Using the Analytical Hierarchy Process," *Journal of Material Cycles and Waste Management* , vol. 18, pp. 177-185, 2016.

[29] T. Saaty, "Fundamentals of the Analytical Network Process," Kobe, Japan, 1999.

[30] T. L. Saaty and L. G. Vargas, Decision Making with the Analytic Network Process: Economic, Political, Social and Technological Applications with Benefits, Opportunities, Costs and Risks, New York: Springer, 2006.

[31] J. Sarkis, "Evaluating Environmentally Conscious Business Practices," *European Journal of Operational Research*, vol. 107, no. 1, pp. 159-174, 1998.

[32] L. Meade and J. Sarkis, "Analyzing Organizational Project Alternatives for Agile Manufacturing Processes: An Analytical Network Approach," *International Journal of Production Research* , vol. 37, no. 2, pp. 241-261, 1999.

[33] L. Meadea and J. Sarkis, "Strategic Analysis of Logistics and Supply Chain Management Systems Using the Analytical Network Process," *Transportation Research Part E: Logistics and Transportation Review,* vol. 34, no. 2, pp. 201-215, 1998.

[34] M. Yurdakul, "Measuring Long-term Performance of a Manufacturing Firm Using the Analytic Network Process (ANP) Approach," *International Journal of Production Research,* vol. 41, no. 11, pp. 2501-2529, 2003.

[35] A. Güngör, "Evaluation of Connection Types in Design for Disassembly (DFD) Using Analytic Network Process," *Computers and Industrial Engineering,* vol. 50, no. 1-2, pp. 35-54, 2006.

[36] G. Büyüközkan, C. Kahraman and D. Ruan, "A Fuzzy Multi-criteria Decision Approach for Software Dvelopment Strategy Selection," *International Journal of General Systems,* vol. 30, no. 2-3, pp. 259-280, 2004.

[37] D. Tesfamariam and B. Lindberg, "Aggregate Analysis of Manufacturing Systems Using System Dynamics and ANP," *Computers & Industrial Engineering,* vol. 49, no. 1, pp. 98-117, 2005.

[38] O. Yilmaz, B. Oztaysi, M. Durmusoglu and S. Oner, "Determination of Material Handling Equipment for Lean In-Plant Logistics Using Fuzzy Analytical Network Process Considering Risk Attitudes of the Experts," *International Journal of Industrial Engineering: Theory, Applications and Practice,* vol. 24, no. 1, pp. 81-122, 2017.

[39] M. Beccali, M. Cellura and M. Mistretta, "Decision-making in Energy Planning. Application of the ELECTRE Method at Regional Level for the Diffusion of Renewable Energy Technology," *Renewable Energy,* vol. 28, no. 13, p. 2063–2087, 2003.

[40] J. C. Lopez and E. Gonzalez, "A New Method for Group Decision Support Based on ELECTRE III Methodology," *European Journal of Operational Research,* vol. 148, pp. 14-27, 2003.

[41] M. Rogers and M. Bruen, "A New System for Weighting Environmental Criteria For use within ELECTRE III," *European Journal of Operational Research,* vol. 107, no. 3, pp. 552-563, 1998.

[42] A. Shaniana, A. Milanib, C. Carsona and R. Abeyaratnec, "A New Application of ELECTRE III and Revised Simos' Procedure for Group Material Selection under Weighting Uncertainty," *Knowledge-Based Systems,* vol. 21, no. 7, p. 709–720, 2008.

[43] P. A. Raj, "Multicriteria Methods in River Basin Planning: A Case Study," *Water Science and Technology,* vol. 31, no. 8, pp. 261-272, 1995.

[44] D. Ju-Long, "Control Problems of Grey Systems," *Systems & Control Letters,* vol. 1, no. 5, pp. 288-294, 1982.

[45] J. Deng, "Introduction to Grey System Theory," *The Journal of Grey System,* vol. 1, no. 1, pp. 1-24 , 1989.

[46] G. Li, D. Yamaguchi and N. M., "A Grey-based Decision-making Approach to the Supplier Selection Problem," *Mathematical and Computer Modelling,* vol. 46, p. 573–581, 2007.

[47] H. Wei, .. Lin, Y. Zhang, L. Wang and Q. Chen, "Research on the Application of Grey System Theory in the Pattern Recognition for Chromatographic Fingerprints of Traditional Chinese Medicine," *Chinese Journal of Chromatography,* vol. 31, no. 2, pp. 127-132, 2013.

[48] C. Huang, C. Lu and C. Chen, "Application of Grey Theory to the Field of Economic Forecasting," *Journal of Global Economics,* vol. 3, no. 1, 2014.

[49] T. Pai, K. Hanaki, H. Ho and C. Hsieh, "Using Grey System Theory to Evaluate Transportation Effects on Air Quality Trends in Japan," *Transportation Research Part D: Transport and Environment,* vol. 12, no. 3, pp. 158-166, 2007.

[50] C. Hsu and Y. Wen, "Application of Grey Theory and Multiobjective Programming Towards Airline Network Design," *European Journal of Operational Research,* vol. 127, no. 1, pp. 44-68, 2000.

[51] H. A. Taha, Operations Research: An Introduction, 9th ed., New Jersey: Pearson, 2011.

[52] K. Venkataraman, B. Vijayaramnath and S. Kannappan, "Comparative Analysis of AHP and ANP Model for Lean Production System Justification," *Applied Mechanics and Materials,* vol. 591, pp. 197-201, 2014.

[53] A. Acar, İ. Önden and K. Kara, "Evaluating the Location of Regional Return Centers in Reverse Logistics through Integration of GIS, AHP and Integer Programming," *International Journal of Industrial Engineering: Theory, Applications and Practice,* vol. 22, no. 4, pp. 399-411, 2015.

[54] M. Obeidat, T. Qasim and A. Khanfar, "Implementing the AHP Multi-criteria Decision Approach in Buying an Apartment in Jordan," *Journal of Property Research* , vol. 35, no. 1, p. 53–71, 2018.

[55] T. L. Saaty, "Decision Making with the Analytic Hierarchy Process," *International Journal of Services Sciences,* vol. 1, no. 1, pp. 83-98, 2008.

[56] O. S. Vaidya and S. Kumar, "Analytic Hierarchy Process: An Overview of Applications," *European Journal of Operational Research,* vol. 169, no. 1, pp. 1-29, 2006.

[57] N. Apostolopoulos and P. Liargovas, "Regional parameters and solar energy enterprises: Purposive sampling and group AHP approach," *International Journal of Energy Sector Management* , vol. 10, no. 1, pp. 19-37, 2016.

[58] J. M. Benítez, J. C. Martín and C. Román, "Using Fuzzy Number for Measuring Quality of Service in the Hotel Industry," *Tourism Management,* vol. 28, no. 2, pp. 544-555, 2007.

[59] A. Assari, T. Maheshand and E. Assari, "Role of Public Participation in Sustainability of Historical City: Usage of TOPSIS Method," *Indian Journal of Science and Technology,* vol. 5, no. 3, pp. 2289-2294, 2012.

[60] R. Karim and C. L. Karmaker, "Machine Selection by AHP and TOPSIS Methods," *American Journal of Industrial Engineering,* vol. 4, no. 1, pp. 7-13, 2016.

[61] C. Feng and R. Wang, "Considering the Financial Ratios on the Performance Evaluation of Highway Bus Industry," *Transport Reviews,* vol. 21, no. 4, pp. 449-467, 2001.

[62] M. Janic, "Multicriteria Evaluation of High-speed Rail, Transrapid Maglev and Air Passenger Transport in Europe," *Transportation Planning and Technology* , vol. 26, no. 6, pp. 491-512 , 2003.

[63] G. Kim, C. Park and K. Yoon, "Identifying Investment Opportunities for Advanced Manufacturing Systems with Comparative-integrated Performance Measurement," *International Journal of Production Economics,* vol. 50, no. 1, pp. 23-33, 1997.

[64] J. Vimal, V. Chaturvedi and A. K. Dubey, "Application of TOPSIS Method for Supplier Selection in Manufacturing Industry," *International Journal of Research in Engineering & Applied Sciences,* vol. 2, no. 5, pp. 25-35, 2012.

[65] O. Chau and C. Parkan, "Selection of a Manufacturing Process with Multiple Attributes: A Case Study," *Journal of Engineering and Technology Management,* vol. 12, no. 3, pp. 219-237, 1995.

[66] A. Shanian and O. Savadogo, "TOPSIS Multiple-criteria Decision Support Analysis for Material Selection of Metallic Bipolar Plates for Polymer Electrolyte Fuel Cell," *Journal of Power Sources,* vol. 159, no. 2, pp. 1095-1104, 2006.

[67] B. Srdjevic, Y. Medeiros and A. Faria, "An Objective Multi-Criteria Evaluation of Water Management Scenarios," *Water Resources Management,* vol. 18, no. 1, p. 35–54, 2004.

[68] A. Dehghani, "A Hierarchical TOPSIS method based on type-2 fuzzy sets to evaluate service quality of public transportation," *International Journal of Industrial Engineering: Theory, Applications and Practice,* vol. 24, no. 5, pp. 505-525, 2017.

[69] K. Maniya and M. Bhatt, "An Alternative Multiple Attribute Decision Making Methodology for Solving Optimal Facility Layout Design Selection Problems," *Computers & Industrial Engineering,* vol. 61, no. 3, pp. 542-549, 2011.

[70] K. Maniya and M. Bhatt, "A Selection of Material Using a Novel Type Decision-making Method: Preference Selection Index Method," *Materials & Design,* vol. 31, no. 4, pp. 1785-1789, 2010.