

Article

Photovoltaic Modules' Cleaning Method Selection for the MENA Region

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Abstract: Photovoltaic (PV) systems are important components of the global shift towards sustainable energy resources, utilizing solar energy to generate electricity. However, the efficiency and performance of PV systems heavily rely on cleanliness, as dust accumulation can significantly obstruct their effectiveness over time. This study undertook a comprehensive literature review and carried out multiple interviews with experts in the PV systems field to propose a map for selecting the optimal PV cleaning method for PV systems within MENA region. These factors, covering meteorological conditions, the local environment, PV system design, module characteristics, dust deposition attributes, exposure time to dust, and socio-economic and environmental considerations, were employed as criteria in a Multi-Criteria Decision-Making (MCDM) model, specifically, an Analytic Network Process (ANP). The results indicate that partially automated cleaning is the most suitable method for existing utility-scale PV projects in the MENA region. The findings provide robust guidelines for PV system stakeholders, aiding informed decision-making and enhancing the sustainability of PV cleaning processes.

Keywords: photovoltaic (PV) systems; maintenance or PV cleaning methods; Multi-Criteria Decision-Making (MCDM) model; Analytic Network Process (ANP)



Citation: Abuzaid, H.; Awad, M.; Shamayleh, A. Photovoltaic Modules' Cleaning Method Selection for the MENA Region. *Sustainability* **2024**, *16*, 9331. <https://doi.org/10.3390/su16219331>

Academic Editor: Cristina Ventura

Received: 8 April 2024

Revised: 16 September 2024

Accepted: 28 September 2024

Published: 27 October 2024



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1. Introduction

Photovoltaic (PV) systems serve as a predominant renewable energy source worldwide for generating electricity [1]. This predominance stems from several factors, including the abundant availability of solar irradiance [2], consistent reduction in PV modules and installation prices [3], minimal maintenance required compared to other renewable energy resources, positive environmental impacts [4], ongoing enhancement in PV modules' efficiency [5], feasibility and profitability considerations, and support from numerous federations and governmental authorities [6]. According to the latest report from the International Energy Agency (IEA) [7], PV solar energy contributed to approximately 75% of renewable systems' capacities in 2023, with projections indicating further growth in the coming years, leading to a record of 96% of solar and wind capacities installed by 2028, with around 80% of this capacity being attributed to PV solar, as illustrated in Figure 1 [7].

Nevertheless, numerous factors influence the performance of PV systems, including meteorological factors that vary depending on the geographical location, PV system design features, PV module characteristics, cleaning methods employed during operation and maintenance, and the reliability of supporting equipment such as inverters and controllers [8]. It is confirmed by a great amount of research that dust accumulation has the most significant impact on PV module performance, with the potential losses in output power exceeding 50% due to accumulated dust and resultant soiling losses [9].

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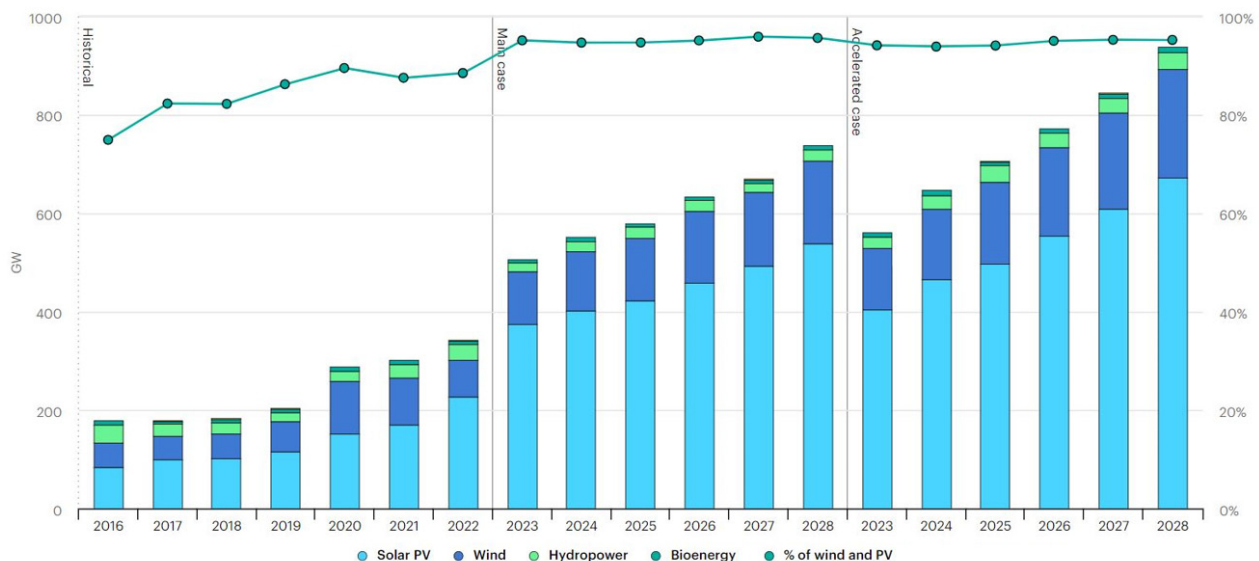


Figure 1. Installed and projected capacities of renewable energy by technology 2016–2028 [7].

Moreover, there exists a significant correlation among these factors [10]. For instance, wind speed can affect the deposition of dust on PV modules [11], and higher ambient temperatures have an adverse impact on PV module performance. Similarly, the type and characteristics of dust depositions influence the dust accumulation process and may impact the selection of appropriate PV cleaning methods [12]. Likewise, the efficiency of PV cleaning methods is highly influenced by the predominant weather conditions, PV systems design parameters, dust deposition attributes, and PV module characteristics [13].

Examining dust distribution globally reveals that the Middle East and North Africa (MENA) region exhibits the highest concentration of dust particles [14]. The worldwide Particulate Matter (PM_{2.5}) concentration, as captured by the National Aeronautics and Space Administration (NASA) [15], indicates that the Sahara Desert and the Arabian Peninsula, which account for the major areas of the MENA region, emerge as the areas with the highest concentration of dust due to the massive desert in this region [16].

Furthermore, the MENA solar PV market, valued at USD 5.33 billion in 2022, is anticipated to expand at a strong Compound Annual Growth Rate (CAGR) of approximately 24% from 2023 to 2030 [17]. Accordingly, it is vital to shed light on this very important region and comprehend the influence of all factors on the PV system performance during operation and maintenance.

PV cleaning stands out as a primary maintenance activity for PV systems [18], necessitating a robust selection of suitable cleaning methods that consider all factors influencing their performance and dust accumulation of dust on PV modules while also addressing the associated interdependencies and correlations among these factors. In addition, the chosen method should align with relevant sustainability indicators to enhance socio-economic and environmental benefits.

Building upon this context, this study aims to determine the most suitable cleaning method for PV systems within the MENA region by using a Multi-Criteria Decision-Making (MCDM) technique that can address the complex interdependencies among the factors influencing PV cleaning and dust accumulation on PV modules. To achieve the aim of this study, the following research questions are posed:

- How do relevant influential factors affect PV cleaning techniques and dust accumulation on PV modules?

- What are the current PV cleaning methods? How do they align with sustainability pillars?
- Which socio-economic and environmental factors are relevant to the PV cleaning process within the MENA region?
- What is the ranking of current cleaning techniques within the MENA region?

The novelty of this research lies in its contribution to synthesizing all factors influencing the efficiency of PV cleaning, dust accumulation of PV modules, and their relationship with sustainability pillars, with a particular focus on the MENA region. The involvement of experts who are specialized in the PV industry from various MENA countries enriches this research, providing a robust decision-making tool for assessing PV cleaning methods and selecting the optimal method for utility-scale PV projects. To the best of the authors' knowledge, this research marks the first comprehensive attempt in this area, potentially paving the way for future research.

The structure of this paper is organized as follows: Section 2 summarizes the literature review findings, and Section 3 presents the methodology employed in this study. Following this, Section 4 shows the results obtained, leading to Section 5 for the discussion. Finally, Section 6 presents the conclusion and recommendations for future research.

2. Literature Review

PV systems' cleaning is essential for maintaining and enhancing PV module performance throughout its lifespan. It aids in preventing excessive degradation caused by dust accumulation and its consequent adverse impacts [19]. Therefore, a comprehensive understanding of how various factors affect dust accumulation on PV modules and the efficiency of different cleaning methods is necessary. Moreover, given the MENA region's importance as a future hub for PV system installations [20], it becomes crucial to provide a guide for selecting the most suitable PV cleaning technique. The subsequent sections offer a comprehensive literature review to address the initial three research questions.

2.1. Influential Factors Impacting PV Cleaning Techniques and Dust Accumulation on Modules

Given the fact that PV systems are typically installed outdoors, they are inevitably vulnerable to different weather conditions, which can affect their performance [21], along with other factors related to the design, installation, and operation of PV systems, and the following subsections explain them further.

2.1.1. Meteorological Factors

A great number of studies have investigated the impact of several meteorological factors on PV system performance [8,22]. Among these factors, solar irradiance stands out as particularly crucial, serving as an engine for PV module performance, with higher irradiance levels correlating to increased PV performance [23]. On the other hand, higher ambient temperatures can lead to decreased PV voltage and, consequently, decreased PV performance [24]. This impact is highly noticeable in arid regions characterized by high ambient temperatures and frequent sandstorms [25].

Likewise, high relative humidity levels contribute to the formation of an adhesive dust layer on PV modules, negatively impacting overall PV performance [26]. Also, wind speed and direction influence the accumulated dust on PV modules and consequently impact PV system performance [22]. Moreover, adequate rainfalls accompanied by sufficient solar irradiance can enhance the efficiency of PV systems and promote natural cleaning processes [27].

2.1.2. Dust Depositions Attributes

Undoubtedly, dust accumulation has the most adverse impact on PV modules' performance, a consensus supported by several studies [8]. Interestingly, different attributes of dust depositions have different impacts on PV systems' performance and the efficiency of PV cleaning methods [19]. For example, the weight of dust is an influential factor [28]; as it increases, the density of dust accumulation on PV modules (g/m^2) increases, leading

to a considerable decrease in PV module performance [29]. Likewise, the electrostatic properties of dust deposition accelerate its accumulation on PV modules due to adhesive forces between the dust and the PV module's surface [30], resulting in preventing the solar irradiance from reaching the module and consequently reducing the output power [31].

On the other hand, small dust depositions pose a greater challenge than large ones, as they tend to accumulate more rapidly and form a dust layer on PV modules [32]; removing it with natural cleaning techniques is inadequate due to the strong adhesion between the particles and the modules [33]. In addition, a higher moisture content in dust depositions leads to more losses in the PV module's performance [34], and necessitates thorough cleaning to remove the mud layer and restore the performance [35]. Moreover, different morphologies of dust deposition impact dust accumulation and PV module performance differently [33]; particles with spherical or elliptical shapes have a more adverse impact on dust accumulation and PV module performance due to their lower optical and transmittance properties [36].

Furthermore, the color of accumulated dust depositions affects the transmittance and PV module performance; darker depositions correspond to more performance losses [37]. Finally, the chemical composition of dust depositions yields varying impacts on PV modules performance [29].

2.1.3. PV System Design

The design of a PV system encompasses multifaceted factors such as system size, available installation area, budgeted capital costs, accessibility, PV module technology, and prevailing meteorological conditions [38]. Accordingly, understanding how these design elements contribute to dust accumulation is crucial for determining suitable cleaning methods during the project's lifespan [39]. For instance, installation settings including tilt angle, azimuth angle, and elevation significantly influence dust accumulation in PV modules [40]. PV systems with higher tilt angles are less prone to dust accumulation compared to those with flat or lower tilts [41]. However, this comes with a counter impact on the generation efficiency, the need for structural modifications, associated additional costs to accommodate higher tilt angles, and land utilization issues due to increased shading areas throughout the day [42].

Additionally, the size of the PV system plays a vital role in the initial selection of PV cleaning methods [43]. Decision-making regarding suitable cleaning methods for utility-scale PV systems requires thorough considerations compared to small-scale residential systems [44]. Also, different installations necessitate different cleaning methods; these types include ground-mounted systems [45], rooftop systems with flat or tilted bases (corrugated sheet) [39], pole-mounted systems like street-lighting units [46], car-parking systems [26], and floating systems [47].

2.1.4. PV Module Characteristics

PV module characteristics have an impact on dust accumulation and are interrelated with other influential factors such as installation settings and meteorological conditions. These characteristics include the material type of the front surface of PV modules, which includes glass, epoxy, and plastic, each with its unique optical attributes influencing dust accumulation tendency, where glass surfaces are particularly effective in preventing dust accumulation compared to epoxy or plastic counterparts [48]. In addition, the application of anti-reflective or anti-soiling coatings reduces the potential for dust accumulation [49]. Furthermore, the aluminum frame of the PV module may contribute to non-uniform dust distribution, resulting in significant losses in output power [50].

Moreover, the type of PV technology has been identified as an influential factor in performance degradation due to dust accumulation, as several studies have indicated that monocrystalline PV modules are more sensitive to dust accumulation compared to polycrystalline PV modules, resulting in greater losses under similar conditions [19]. Also,

the surface roughness of PV modules impacts dust accumulation of dust, as rough and adhesive surfaces tend to accumulate more dust.

Additional influential factors include the local environment and its associated dust sources, which stem from various anthropogenic, agricultural, or industrial activities and their relevant pollutants [51]. Furthermore, the proximity to dust sources is vital [52], especially for PV systems installed near manufacturing plants that emit substantial dust particles into the atmosphere during the production process, such as cement production plants [53]. Lastly, the duration of exposure to dust increases the severity of the impact on PV module efficiency, with prolonged exposure leading to the formation of hot spots and rapid degradation in PV module performance.

2.2. Current Methods and Techniques for PV Module Cleaning

Maintaining PV modules clean is important for optimizing their performance during their operation, enhancing their transmittance, and avoiding their fast degradation [54]. Selecting the suitable cleaning method is reliant on several factors, including PV module attributes, meteorological conditions, PV system design, economic considerations, etc. [13]. Figure 2 illustrates the current PV cleaning methods, and the subsequent sections investigate these methods in more detail.

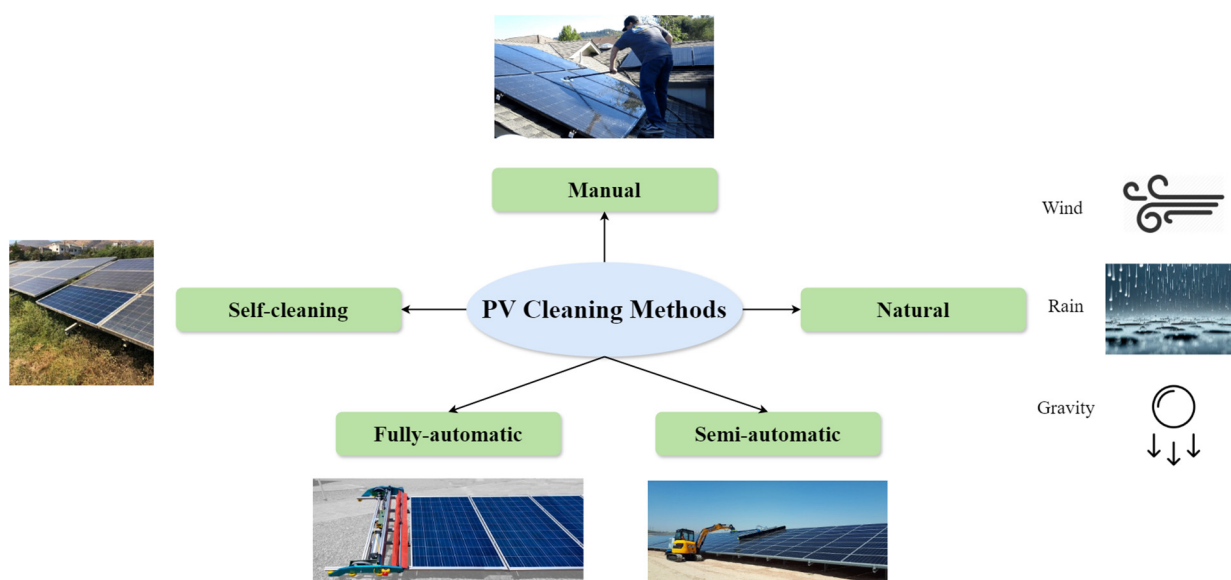


Figure 2. Current PV cleaning techniques.

2.2.1. Natural Cleaning

Cleaning PV modules through natural processes is largely reliant on environmental conditions and factors beyond human control, making it a challenging method to depend on solely [31]. The effectiveness of natural cleaning is influenced by various meteorological and design factors, including wind speed, humidity, tilt angle, and the types of dust depositions present [55]. However, this method proves to be highly effective in regions with lower dust levels, such as Europe, Canada, and the USA [56].

Rain, as a natural cleaning agent, is largely dependent on geographical location and seasonal changes [57], making it an unreliable method for consistent dust removal. Nonetheless, light rain can even contribute to the formation of a mud layer, negatively impacting the transmittance of PV modules [9]. Wind can be effective in removing accumulated dust, but its impact varies depending on wind speed, direction, and particle size, making it an unreliable cleaning method [31].

Gravity also plays a role in dust removal, with efficiency linked to the tilt angle and the characteristics of dust particles [58]. Similarly, snow can act as a natural cleaner when it gently washes over tilted PV modules [9], but heavy snowfall can lead to partial or full

coverage of the modules, reducing their performance and potentially causing cracks and damages [59].

The advantages of natural cleaning methods include being cost-free, environmentally friendly, and requiring no maintenance. However, they are seasonally volatile, location-dependent, and unreliable, with effectiveness influenced by multifaceted factors [60]. Hence, there are uncertainties and risks associated with relying exclusively on natural cleaning processes.

2.2.2. Self-Cleaning

Self-cleaning techniques demonstrate a passive approach to maintaining PV module cleanliness [61]. It involves applying a specialized layer to the front surface of PV modules, serving as an anti-reflective or anti-soiling layer, thus eliminating the need for human or machine interference [62]. Another approach, Electrodynamic Screens (EDS), utilizes rows of parallel transparent electrodes within the dielectric film to remove accumulated dust [63]. This method achieves impressive dust removal efficiency that exceeds 90% [64]. However, EDS integration during the manufacturing phase poses challenges such as the risk of Paschen breakdown and high costs, limiting its compatibility with existing PV systems and large-scale installations [65].

Coating PV modules with anti-reflective materials during manufacturing has also shown effectiveness in preventing dust accumulation. Studies have explored various coatings, with hydrophilic nanostructure coatings demonstrating superior efficiency and resistance to dust accumulation [66]. However, such coatings are vulnerable to deterioration from prolonged exposure to sunlight [67]. Additionally, the piezoelectric effect can be employed to induce mechanical vibration for dust depositions for effective cleaning [68]. While self-cleaning methods offer benefits such as reduced labor and water usage, their integration into the manufacturing process and uncertainties regarding efficiency and lifespan present challenges in their widespread adoption [65].

2.2.3. Manual Cleaning

Manual cleaning involves labor-intensive processes, utilizing tools like mops or brushes to remove dust from the surface of modules [67]. The frequency of manual cleaning depends on the tilt angle of the modules, local environment, meteorological conditions, and PV system design [69]. This method is feasible for small-scale PV systems and can be executed in dry or wet modes, with dry cleaning being more cost-effective due to lower water supply expenses [70]. Yet, wet cleaning offers higher efficacy, though it carries risks such as potential module surface scratching, especially when using degraded brushes, and the formation of hotspots during cleaning in high temperatures [71].

2.2.4. Automated Cleaning

Automated methods reduce human interference by employing specialized machinery like robotics, wipers, or drones to clean PV modules automatically [72]. These tools can be programmed to execute cleaning cycles based on pre-scheduled timings, sensor inputs, or immediate commands for wet or dry cleaning, often connected to water supplies for enhanced cleaning efficiency [73].

However, integrating water-based cleaning into automated systems requires additional water management considerations including water collection, storage, and disposal [9]. Also, partially automated cleaning techniques provide a cleaning method that needs human interference to operate the machine, supervise the process, provide feedback, and make decisions related to the cleaning process [74].

Moreover, drones have been employed in automated cleaning, offering wide-range surveillance, reduced reliance on humans, data logging advantages, and scalability. Nevertheless, their adoption is restrained by the associated power requirements, high capital costs, and limited flight durations [75]. Additionally, innovative methods like using re-

turned air from air conditioning systems for dust removal present sustainable alternatives but may not be sufficient, especially when wet methods are required [76].

Timing is critical for water-based cleaning to avoid thermal shock during hot daytime and elevated module temperatures, especially in arid regions [76]. For some pollutants and dust depositions, special detergents or solutions are used to improve cleaning efficiency [31]. While semi-automated cleaning methods involve some human interference for monitoring and maintenance purposes, both automated and semi-automated techniques are complex, costly, and present uncertainties regarding their reliability and efficiency [77].

2.3. Photovoltaic Systems in the MENA Region: PV Capacities, Climate Challenges, and Associated Costs

This section sheds light on the MENA region, which holds pivotal importance in PV systems' utilization to produce electricity, while addressing the various challenges affecting their effectiveness and feasibility. The subsequent sections discuss the capacity of PV systems, the climate-related challenges, and the cost associated with cleaning these systems in the MENA region.

2.3.1. PV Systems' Capacity in the MENA Region

Countries in the MENA region have set ambitious targets for renewable energy, which describe a robust roadmap for the expansion of PV solar projects [20]. Figure 3 shows the installed and targeted capacities of PV systems across the MENA countries, sourced from governmental entities and international reports for each country [78].

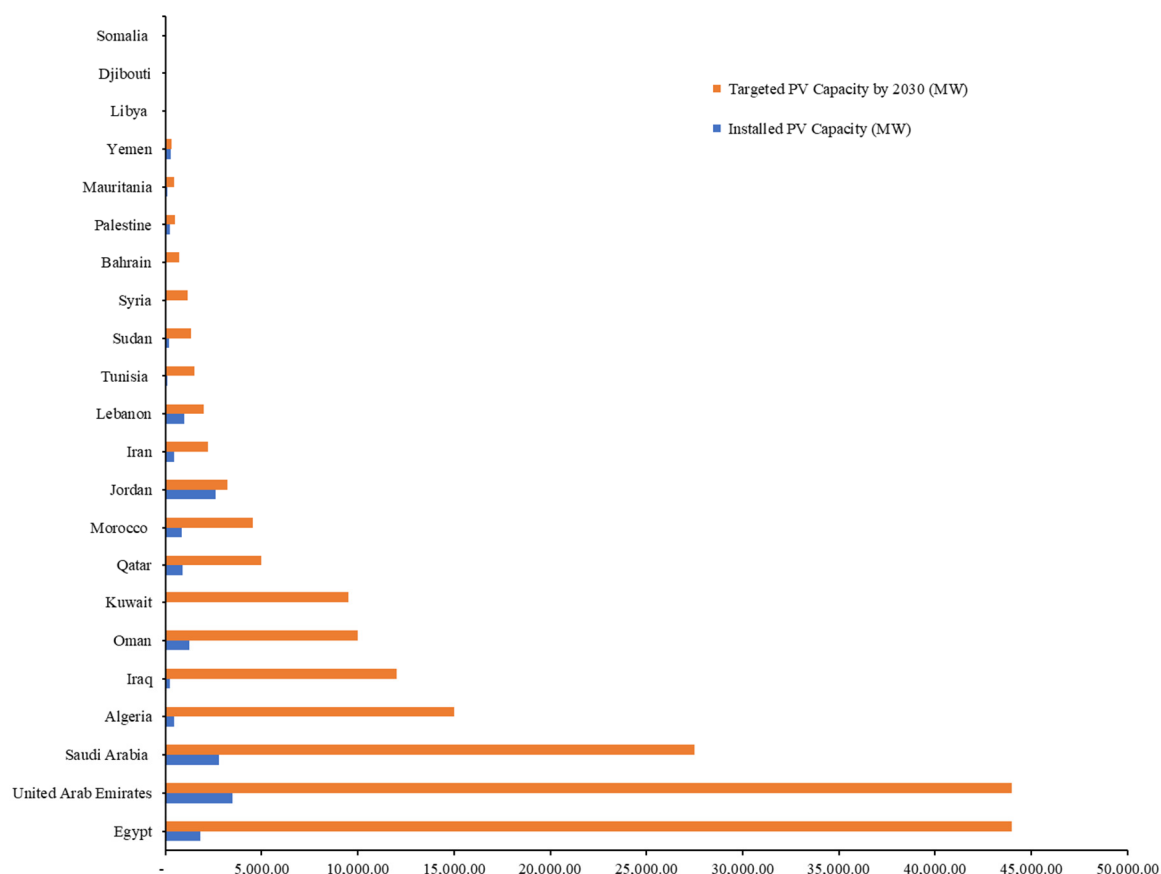


Figure 3. Installed and targeted PV capacity in the MENA region [78].

2.3.2. Climate-Related Challenges in the MENA Region

The MENA region has one of the globe's most abundant levels of solar radiation [79,80], as illustrated in Figure 4 [81]. It receives approximately 25% of all solar energy reaching

the earth's surface [82]. Hence, if fully exploited, the potential solar energy in the MENA region could fulfill at least half of the electricity demand worldwide [82]. Solar irradiance contributes to the increased viability of PV systems in the region given the significant positive impact of solar radiation intensity on their PV system's performance. On the other hand, the region is one of the most vulnerable in the world to the consequences of climate change, experiencing higher temperatures, floods, rising sea levels, air pollution, droughts, and intense water scarcity [83].

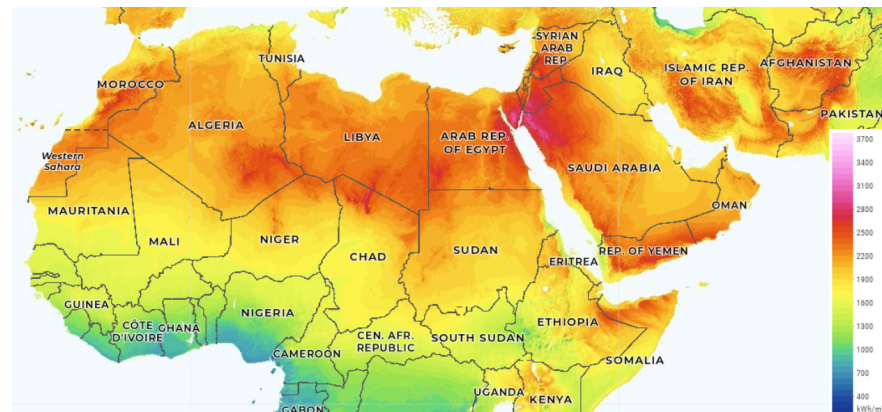


Figure 4. Direct normal irradiation in the MENA region [81].

Furthermore, the region is recognized as the most water-scarce region worldwide, and with continuous population growth, water availability is expected to decrease by 50% by 2050, leading to severe drought conditions in the region [84]. Moreover, ambient temperature in the MENA region has increased by 0.46 °C per decade in the period from 1980 to 2022, which is well above the world average of 0.18 °C [85].

The precipitation rates have significantly decreased, reaching approximately 8.3% per decade for the same period, which made the situation very critical, especially with the existing water scarcity in most MENA countries, and it is projected to decrease further in the future [85]. Consequently, these patterns of decreasing precipitation and increasing temperature are major challenges for PV systems in the region [85]; combined with the temperature rise, the reduction in precipitation has put most MENA countries in the category of arid countries, where the annual precipitation is less than 200 mm/year [86], as illustrated in Figure 5 [87–89].

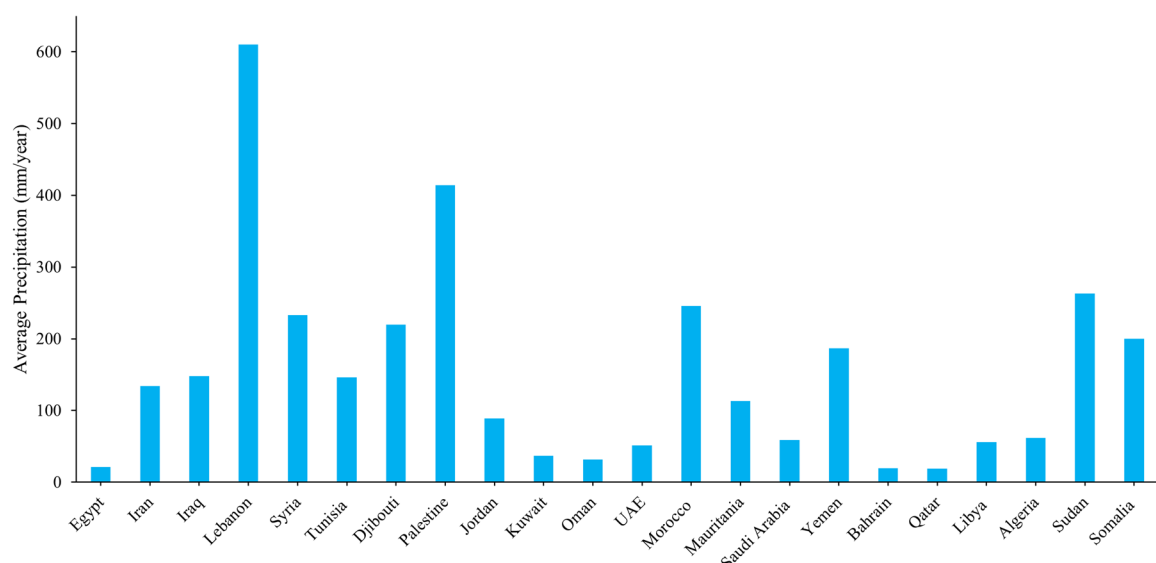


Figure 5. Average precipitation rate in the MENA region. Sources: [87–89].

2.3.3. Associated Costs for PV Cleaning Systems in the MENA Region

The average cost for cleaning a PV module ranges between USD 8 and USD 25 per cleaning visit [90]; this wide range depends on numerous factors, including the type of modules, cleaning methods, labor cost, frequency of cleaning, location, installation settings, etc. For instance, the wet PV cleaning method involves the use of water as a primary element [76], and the MENA region, recognized as the most water-scarce area, faces considerably high costs for water desalination or treatment processes compared to other regions in the world [91]. Therefore, the wet cleaning method emerges as one of the least feasible options for cleaning PV solar modules in the MENA region.

Additionally, electricity prices (USD/MWh) vary notably across the MENA region due to differences in energy sources, costs, governmental subsidies, economic situation, and political status [92]. In the past, electricity prices in the MENA region were lower than the global average prices [93]; however, recently, several countries have been increasing electricity prices and reducing subsidies to foster the efficient use of electricity and promote the transition to renewable energy sources for generating electricity [94]. Consequently, electricity prices in the MENA region have become aligned with global prices [95].

Likewise, the labor cost in the MENA region varies based on several conditions, including each country's demand, economic and political conditions, population, type of industry, level of skills, etc. [96]. Generally, in oil-rich countries like the GCC, the cost of labor is relatively high due to the need for skilled workers in the construction and oil and gas industry [97], while it is lower in less developed countries, particularly in North Africa [98]. Electricity and labor costs in the MENA region are depicted in Figure 6 [99].

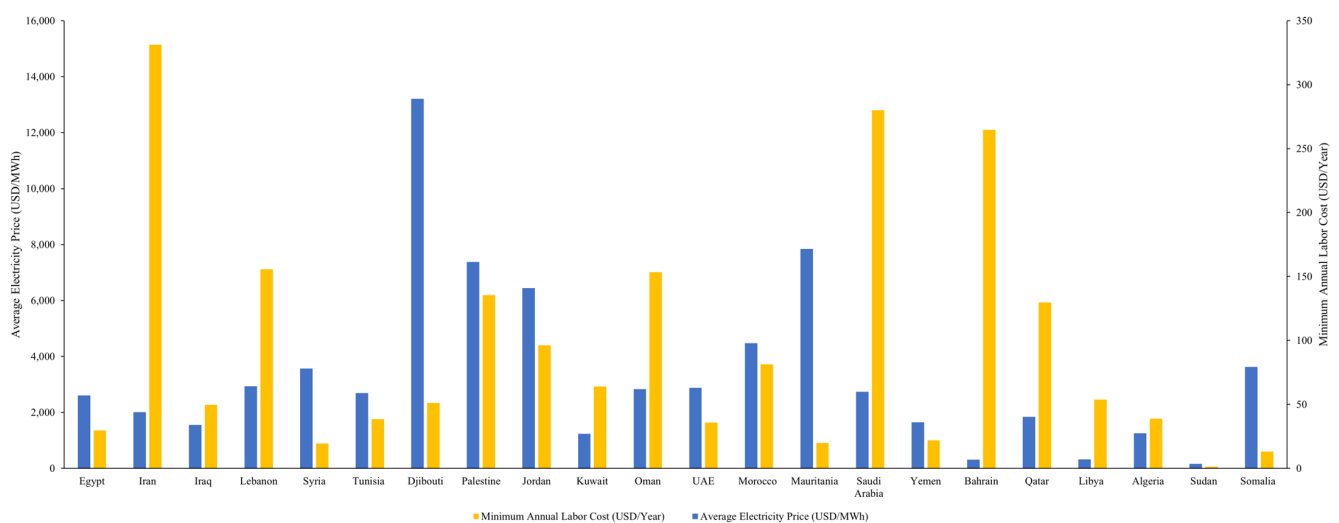


Figure 6. Electricity and labor costs in the MENA region. Sources: [99].

2.4. Sustainability Pillars and PV Cleaning

Regular cleaning of PV modules is a crucial practice that significantly impacts the three pillars of sustainability: environmental, economic, and social [100]. Several studies have emphasized the environmental perspectives, including energy efficiency, water conservation, and reduced emissions [43]. Also, the economic sustainability pillar entails the capital cost of cleaning methods, water cost, electricity cost, labor cost, maintenance, and return on investment [101], while the social perspective involves job creation, health and safety, energy equity, and social value [43]. Therefore, the methods employed for cleaning PV modules play a significant role in overall sustainability by harmonizing the three pillars of sustainability, as illustrated in Figure 7.

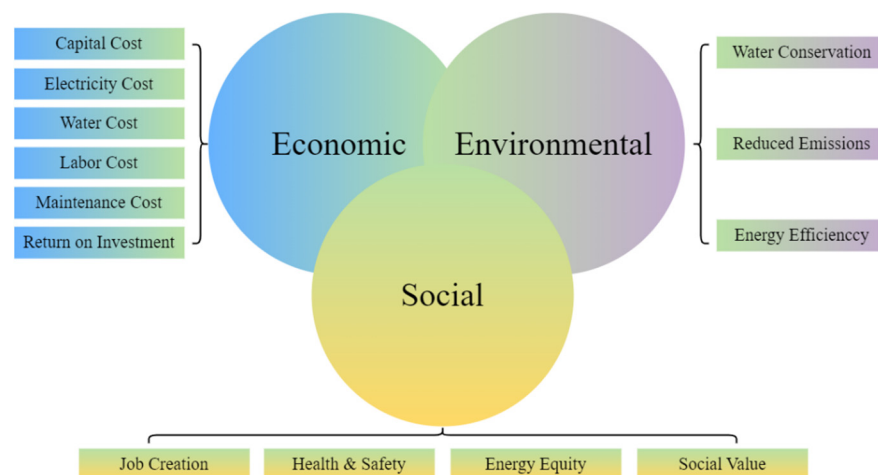


Figure 7. PV cleaning and the sustainability pillars. Source: authors.

In this research, the aforementioned factors that affect dust accumulation and PV cleaning efficiency, as well as relevant sustainability considerations, were employed to prioritize the cleaning methods in the MENA region using the Multi-Criteria Decision-Making (MCDM) approach.

2.5. Multi-Criteria Decision-Making for Ranking PV Cleaning Methods

Multi-Criteria Decision-Making (MCDM) is a well-established research field that solves numerous problems when it comes to ranking or prioritizing several alternatives based on predefined criteria [102]. There are various approaches for MCDM based on the complexity of the problem and the interdependence between the criteria and the alternatives [103]. In the context of PV cleaning methods, a limited number of studies have considered MCDM approaches to resolve the uncertainty associated with prioritizing them.

Aljaghoub et al. proposed a rank for PV cleaning methods concerning relevant Sustainable Development Goals (SDGs) using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), where energy and water goals had the highest priority with respect to PV cleaning, while the manual cleaning method had the highest rank compared to other cleaning methods [104]. Likewise, AlMallahi et al. employed the TOPSIS technique to rank PV cleaning methods in Dubai, UAE, considering the three sustainability pillars as criteria, and the results show that wet robotic cleaning has the highest efficiency [43].

In this research, an MCDM model is presented to prioritize available PV cleaning methods while considering the sustainability pillars and the factors influencing dust accumulation and PV cleaning efficiency in the MENA region. The proposed technique is the Analytic Network Process (ANP), which is a mature technique that is known for its capability of dealing with problems that entail interdependent criteria, as is the case of this research [105,106].

The significance of this research lies in its novelty and comprehensiveness. It starts with an extensive literature review, which identifies and synthesizes all factors influencing the efficiency of PV cleaning, the dust accumulation of PV modules, and the relationship with sustainability pillars, with a particular focus on the MENA region's importance in PV systems' installation and related influential factors.

Also, the involvement of experts from various countries in the MENA region who specialize in the PV industry enriches this research. Their insights, combined with the literature review findings, positively contribute to the ranking of PV cleaning methods. To the best of the authors' knowledge, this research marks the first attempt at such a comprehensive approach, potentially paving the way for future research in this area.

3. Methodology

Figure 8 illustrates the structured methodological approach adopted in this study. We started by conducting multiple interviews with Subject Matter Experts (SMEs) actively working in the field of PV systems, following an initial survey of the existing relevant literature. This initial step assisted in defining the aim of this study, which is to rank PV cleaning methods while considering all influential factors specific to the MENA region. Also, it aided in identifying the research questions that mapped the subsequent steps to achieve this aim.

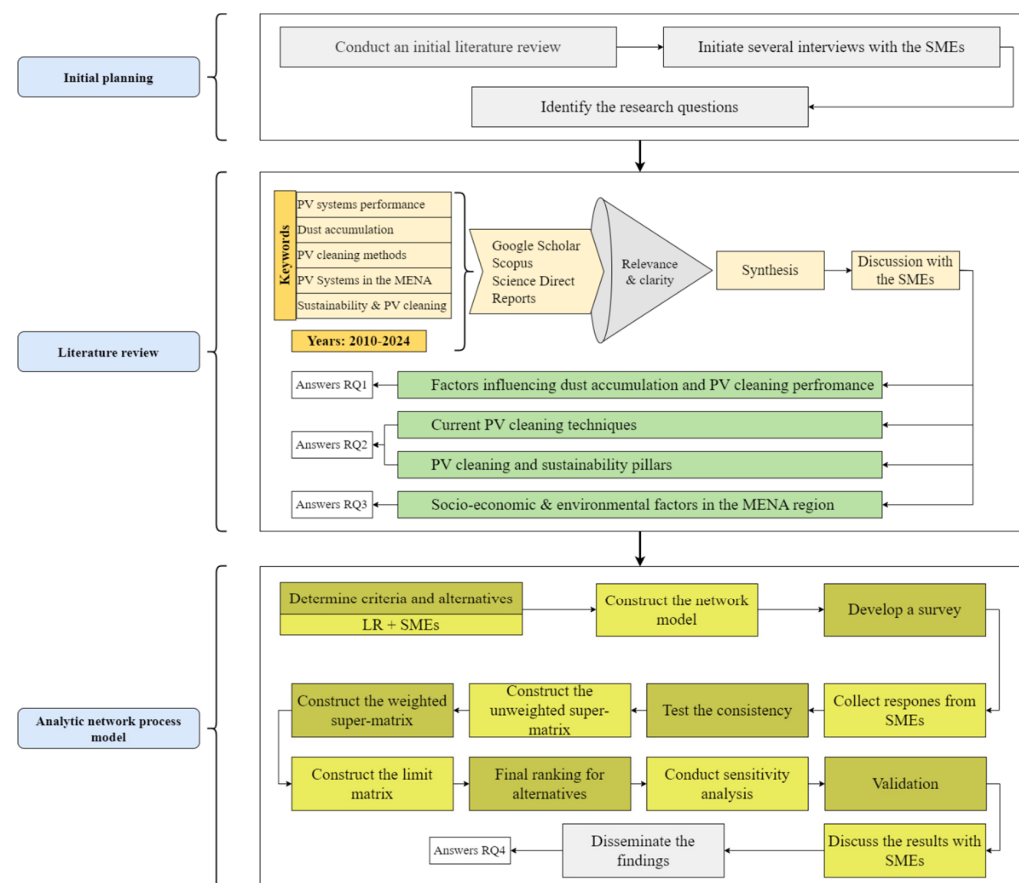


Figure 8. Research methodology.

A thorough literature review of scientific articles published was performed, adhering to the review guidelines outlined by Tranfield et al. [107], covering the period from 2010 to 2024. It was carried out using reputable research engines and journals including Google Scholar, Science Direct, and Scopus. Also, the process involves multiple screening stages to filter the most relevant and recent articles, along with the latest reports issued by international and governmental entities. As a result, the first three research questions were addressed by synthesizing the findings from the literature review.

The MCDM process in this study used the ANP (All equations and matrices are sourced from: [105,106]) technique, originally developed by Saaty, to deal with complex decision-making problems involving interdependencies among criteria. It starts with identifying criteria and alternatives based on the outcomes from the literature review brainstorming sessions with the SMEs, leading to constructing the decision model, as shown in Figure 9. The involved SMEs comprised 18 experts from the field of PV systems including consultants, developers, contractors, decision-making, and maintenance experts from different countries in the MENA region, including Jordan, KSA, Oman, the UAE, Egypt, Bahrain, Qatar, Tunis, Lebanon, and Morocco.

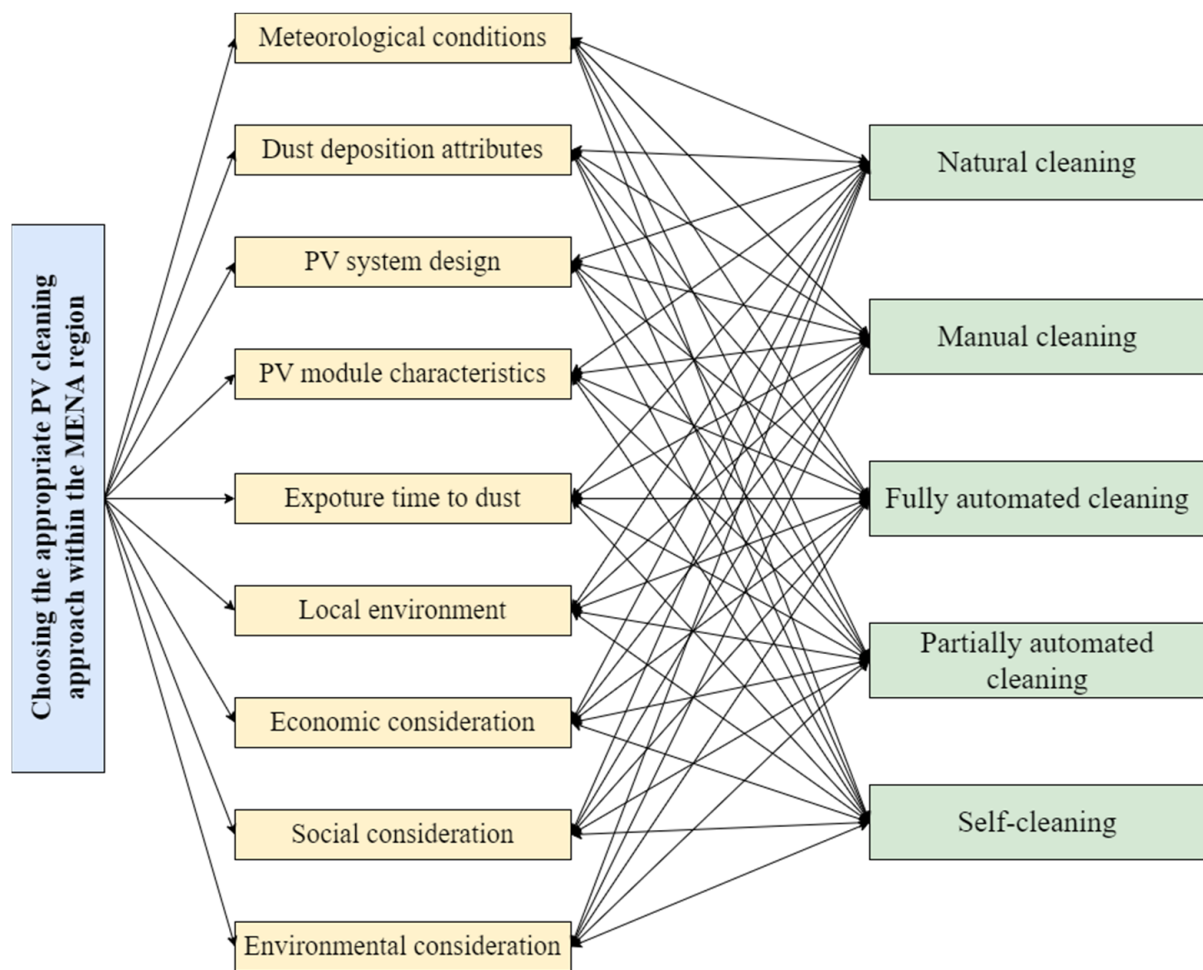


Figure 9. Analytic network process model.

Subsequently, a survey instrument was developed to conduct pairwise comparisons, and responses were collected from the involved SMEs through multiple interviews. This approach was used to simplify the survey procedure while ensuring a thorough understanding of its elements. A scale from 1 to 9 was used, with 1 indicating equal importance/preference and 9 representing extremely high importance/preference. The resulting pairwise comparison matrix for the criteria is expressed as follows:

$$P = \begin{bmatrix} 1 & p_{12} & \cdots & p_{1n} \\ \frac{1}{p_{12}} & 1 & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{p_{1n}} & \frac{1}{p_{2n}} & \cdots & 1 \end{bmatrix}$$

p_{ij} : the pairwise comparison between criteria i and j .

Before the analysis, consistency for the collected responses (pairwise matrix) was examined to ensure reliability, improve the quality of decisions, and enable sensitivity analysis. All the pairwise comparison matrices for the criteria and their related influence matrices are combined to construct the unweighted super-matrix of the network model, which was normalized to construct the weighted super-matrix (S), which is expressed as follows:

		Criteria						Alternatives			
Goal		Goal	C ₁	C ₂	C ₃		C _n	A ₁	A ₂		A _p
Criteria	C ₁	W ₁	0					W ₁₁	W ₁₂	...	W _{1p}
	C ₂	W ₂		0				W ₂₁	W ₂₂	...	W _{2p}
	C ₃	W ₃			0			W ₃₁	W ₃₂	...	W _{3p}
	⋮	⋮				0		⋮	⋮	⋱	⋮
	C _n	W _n					0	W _{n1}	W _{n2}	...	W _{np}
Alternatives	A ₁	0	U ₁₁	U ₁₂	U ₁₃	...	U _{1n}	0			
	A ₂	0	U ₂₁	U ₂₂	U ₂₃	...	U _{2n}		0		
	⋮	⋮	⋮	⋮	⋮	⋱	⋮			0	
	A _p	0	U _{p1}	U _{p2}	U _{p3}	...	U _{pn}				0

Then, the entire network model was synthesized by calculating the limit matrix, resulting from raising the weighted super-matrix (L) to a large power (k) until it converged to a stable value, using the following equation. Afterward, all rows of the limit matrix were normalized to obtain the priority vector representing the relative importance of each element in the network.

$$L = \lim_{k \rightarrow \infty} S^k$$

As a result, the final ranking of alternatives could be calculated by aggregating the resulting priority vectors with respect to the influence matrices for the network model to fulfill, answering the final research question. Then, a sensitivity analysis was conducted to assess the robustness of the results by excluding some of the criteria and testing how sensitive the network model is, where SuperDecision software version 3.2 was used to build and analyze the network model. Subsequently, a number of existing PV systems were surveyed to validate the findings accompanied by ongoing discussion with SMEs involved in each PV system.

This methodology is designed to be adaptable across regions by integrating local expertise from Subject Matter Experts (SMEs) and synthesizing comprehensive insights from a broad literature review. It adapts effectively to diverse regional contexts through its flexible ANP approach, accommodating varying environmental, regulatory, and economic factors. Validation through surveys of existing PV systems and ongoing expert consultations enhances its applicability and credibility, making it suitable for adoption in global research on sustainable energy practices.

4. Results

Assessing the inconsistency of pairwise comparisons made by SMEs is a vital measure to evaluate response reliability. The resulting inconsistency, calculated at 0.0582, indicates a high level of reliability in the responses, leading to more robust results in the ANP analysis. Additionally, Figure 10 represents the weighted super-matrix; it reveals that the meteorological conditions criterion holds the highest weight or importance, followed by economic consideration, PV system design, and PV module characteristics, while the remaining criteria hold comparatively less importance.

Likewise, notable correlations exist between various criteria and the choice of cleaning method, with each criterion carrying different weights based on considerations associated with each cleaning method. Furthermore, the limit matrix for the network model is shown in Figure 11, where it can be noticed that all the columns are identical, providing the ultimate priorities assigned to each criterion and alternative in the model.

		Criteria										Alternatives				
		Goal	Economic consideration	Social consideration	Environmental consideration	PV module characteristics	PV system design	Local environment	Dust deposition attributes	Exposure time to dust	Meteorological conditions	Natural cleaning	Manual cleaning	Fully automated	Partially automated cleaning	Self-cleaning
Criteria	Economic consideration	0.201	0	0	0	0	0	0	0	0	0	0.211	0.185	0.203	0.209	0.180
	Social consideration	0.040	0	0	0	0	0	0	0	0	0	0.027	0.089	0.029	0.048	0.033
	Environmental consideration	0.031	0	0	0	0	0	0	0	0	0	0.032	0.034	0.036	0.029	0.028
	PV module characteristics	0.138	0	0	0	0	0	0	0	0	0	0.057	0.099	0.103	0.092	0.106
	PV system design	0.151	0	0	0	0	0	0	0	0	0	0.109	0.134	0.152	0.142	0.144
	Local environment	0.045	0	0	0	0	0	0	0	0	0	0.071	0.045	0.064	0.042	0.050
	Dust deposition attributes	0.050	0	0	0	0	0	0	0	0	0	0.086	0.058	0.056	0.107	0.095
	Exposure time to dust	0.067	0	0	0	0	0	0	0	0	0	0.093	0.068	0.084	0.056	0.066
	Meteorological conditions	0.277	0	0	0	0	0	0	0	0	0	0.313	0.287	0.272	0.275	0.296
Alternatives	Natural cleaning	0	0.185	0.065	0.436	0.048	0.152	0.084	0.060	0.070	0.062	0	0	0	0	0
	Manual cleaning	0	0.184	0.507	0.252	0.249	0.132	0.294	0.272	0.220	0.269	0	0	0	0	0
	Fully automated	0	0.071	0.115	0.081	0.158	0.359	0.110	0.169	0.166	0.116	0	0	0	0	0
	Partially automated	0	0.365	0.222	0.094	0.439	0.273	0.354	0.393	0.429	0.461	0	0	0	0	0
	Self-cleaning	0	0.196	0.091	0.135	0.106	0.084	0.158	0.105	0.114	0.091	0	0	0	0	0

Figure 10. The unweighted super-matrix for the ANP model.

		Criteria										Alternatives				
Criteria	Goal	Economic consideration	Social consideration	Environmental consideration	PV module characteristics	PV system design	Local environment	Dust deposition attributes	Exposure time to dust	Meteorological conditions	Natural cleaning	Manual cleaning	Fully automated	Partially automated cleaning	Self-cleaning	
	Economic consideration	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	
	Social consideration	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	
	Environmental consideration	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	
	PV module characteristics	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	
	PV system design	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	
	Local environment	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	
	Dust deposition attributes	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	
	Exposure time to dust	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	
	Meteorological conditions	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	
Alternatives	Natural cleaning	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	
	Manual cleaning	0.121	0.121	0.121	0.121	0.121	0.121	0.121	0.121	0.121	0.121	0.121	0.121	0.121	0.121	
	Fully automated	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	
	Partially automated	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	
	Self-cleaning	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	

Figure 11. The limit matrix for the ANP model.

Among the alternatives, the partially automated cleaning method has the highest priority, followed by manual cleaning, and then fully automated cleaning, while the least priorities are for self-cleaning and natural cleaning. Regarding the criteria, meteorological conditions have significant importance, followed by economic consideration, PV system design, PV module characteristics, and, finally, dust deposition attributes.

As a result, the final prioritization or ranking of PV cleaning methods in the MENA region is derived from the limit matrix, as depicted in Figure 12. The results indicate that the partially automated cleaning method is the most suitable method, considering all

influential criteria, followed by the manual cleaning method, and then the fully automated method. Self-cleaning and natural cleaning methods have the least priority.

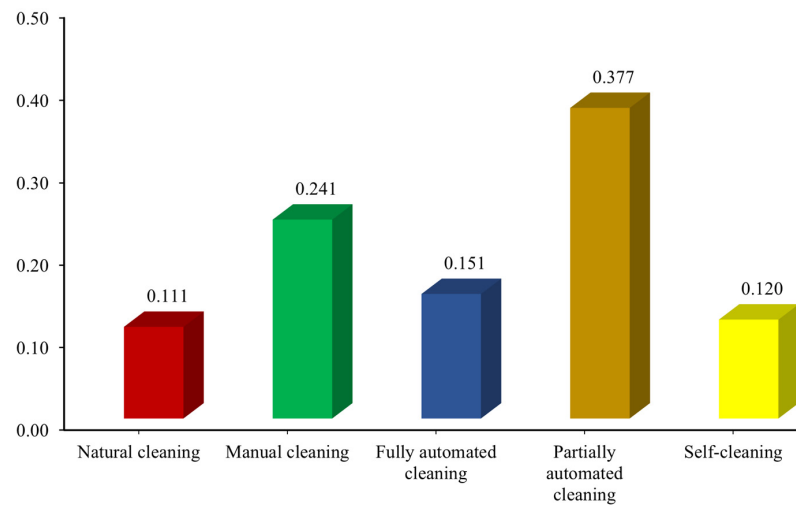


Figure 12. Ranking of PV cleaning methods in the MENA region.

In addition, a sensitivity analysis was conducted to ensure the quality and robustness of the network model and the resulting outcomes. Conducted nine times, each analysis excluded a criterion, with the resulting rankings illustrated in Figure 13. The consistent ranking across all runs underscores the high quality and reliability of the model and its outcomes, thus empowering decision-makers to make reliable selections in the face of uncertainty and variability in the input criteria.

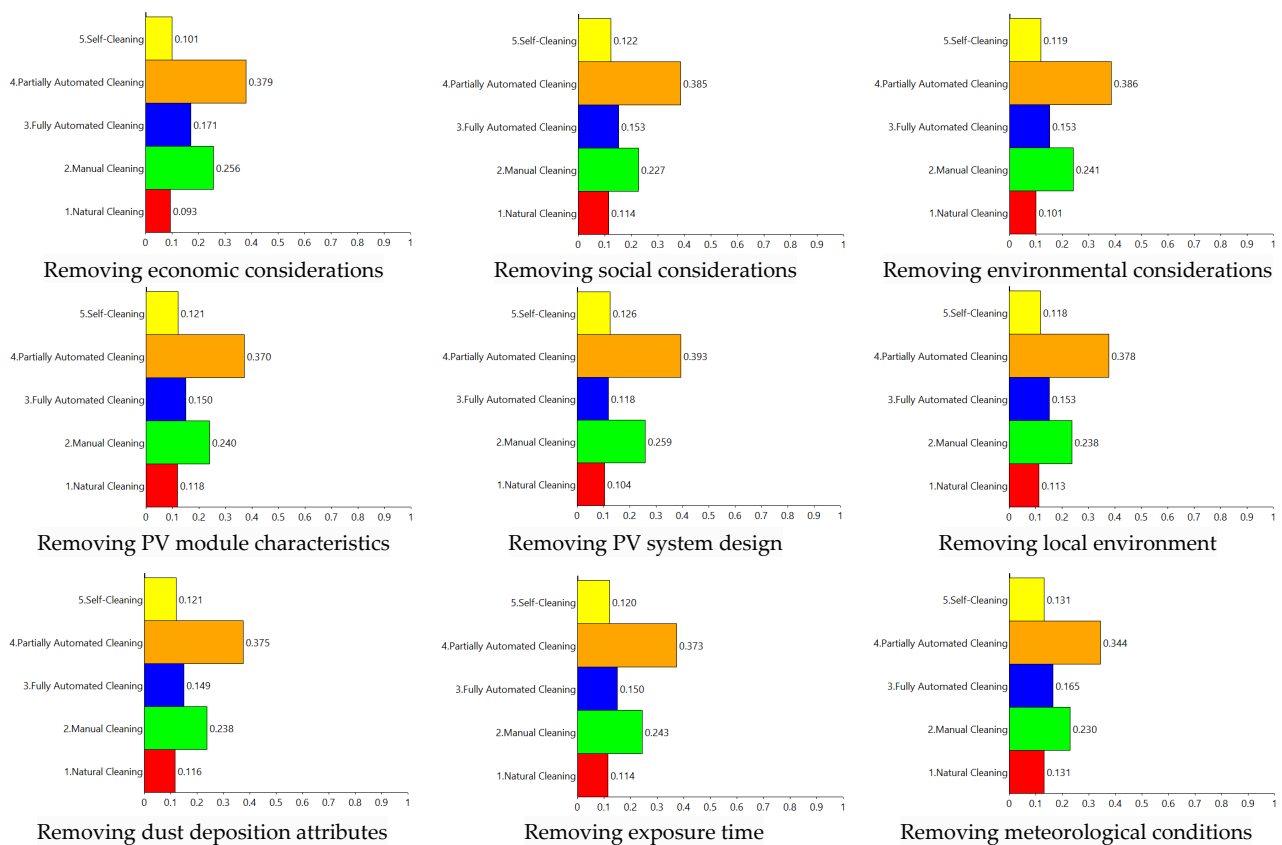


Figure 13. Sensitivity analysis.

Several existing PV systems were visited and surveyed to assess their current cleaning techniques, accompanied by discussion with the operation and maintenance (O&M) teams to investigate the challenges faced and gather feedback and recommendations regarding the entire cleaning process. Table 1 shows these PV systems, with their identities encoded for confidentiality reasons. From the table, it is evident that various cleaning methods are assigned to different types and sizes of PV systems.

Table 1. Surveyed case studies and their cleaning methods.

Case Study	Location	Size	Installation Type	Current Cleaning Technique	Feedback from O&M Team
1	UAE	1.8 MWp	Rooftop	Manual	Effective, reliable, and feasible cleaning.
2	UAE	785 kWp	Car parking	Fully automated	Reliability issues, frequent shutdowns, required human interference. Need to shift to manual cleaning with water management system.
3	Jordan	10 MWp	Ground-mounted	Partially automated	Effective, reliable, and feasible cleaning.
4	Jordan	23 MWp	Ground-mounted, Tracking	Fully automated	Reliability issues, frequent shutdowns, required human interference, accessibility concerns. Need to shift to manual cleaning.
5	Jordan	2.7 MWp	Rooftop	Manual	Effective, reliable, and feasible cleaning.
6	UAE	1.2 GWp	Ground-mounted	Fully automated	Reliability issues, frequent shutdowns, required human interference, frequent need to replace broken PV modules due to vibration problems from cleaning robotics,
7	UAE	2.1 MWp	Rooftop	Manual	Effective, reliable, and feasible cleaning.
8	UAE	870 kWp	Rooftop	Manual	Effective, reliable, and feasible cleaning.
9	Jordan	591 kWp	Car parking	Manual	Effective, reliable, and feasible cleaning.

For large roof-mounted systems in the UAE and Jordan (case study 1, 5, 7, and 8), manual cleaning is preferred due to its accessibility, effectiveness, and feasibility for this specific type of installation. Likewise, manual cleaning is employed for a car park PV system in Jordan (case study 9), with high efficiency and feasibility reported. On the contrary, for a car park PV system in the UAE (case study 2), robotic cleaning is employed, but feedback from the team reports reliability issues and the frequent need for human interference to conduct manual cleaning when the robotics are inefficient.

Moreover, for a ground-mounted large-scale PV systems in Jordan, partially automated cleaning is used and highly recommended (case study 3) since 2017, with feedback indicating efficient and reliable cleaning. Nonetheless, fully automated cleaning is utilized in case studies 4 and 6, in Jordan and the UAE, respectively. Observations from the operation and maintenance teams indicate the ineffectiveness of this technique as well as the necessity for a dedicated team to be onsite to address issue such as sudden machine stoppages, inefficient cleaning after a dust storm, and reliability concerns.

After the results were obtained, a final round of discussions with SMEs confirmed the reliability and practicality of the findings. They recommended generalizing the outcomes within the MENA region based on PV system type and size. Accordingly, self-cleaning techniques are suggested for systems with difficult access, like pole-mounted PV modules. In this regard, Aljdaeh et al. suggested the use of hydrophobic coating layer to prevent dust accumulation for similar installations [108].

While fresh-water-based fully automated systems are recommended for PV floating systems, using sprinkler automated systems, with the use of a special detergent solution to

overcome the contamination of salt dust due to the evaporation of sea water [47], manual cleaning methods are advised for small-scale car parking PV systems. Abdallah et al. recommended this method for PV systems up to 10 kWp [109]. On the other hand, automated techniques are recommended for utility-scale systems.

Partially automated cleaning systems are proposed for utility-scale tracking PV systems. However, for a similar installation in the MENA region, fully automated cleaning is employed, as recommended by Alghamdi et al. in Saudi Arabia [110]; yet, the associated problems, including sudden stoppages, excessive vibration, and high reliability, cost may reduce their efficiency [111]. Thus, partially automated is recommended, while manual cleaning is recommended for small-scale tracking PV systems. Similarly, manual cleaning is also recommended for small-scale rooftop PV systems in residential or commercial settings, and large-scale rooftop systems in industrial or commercial use, with extendable tools for corrugated sheets. Ground-mounted systems are suggested for manual cleaning for small-scale projects and partially automated for utility-scale projects. However, all systems are partially dependent on the natural cleaning method subject to their duration and efficiency. These recommendations are illustrated in Figure 14.

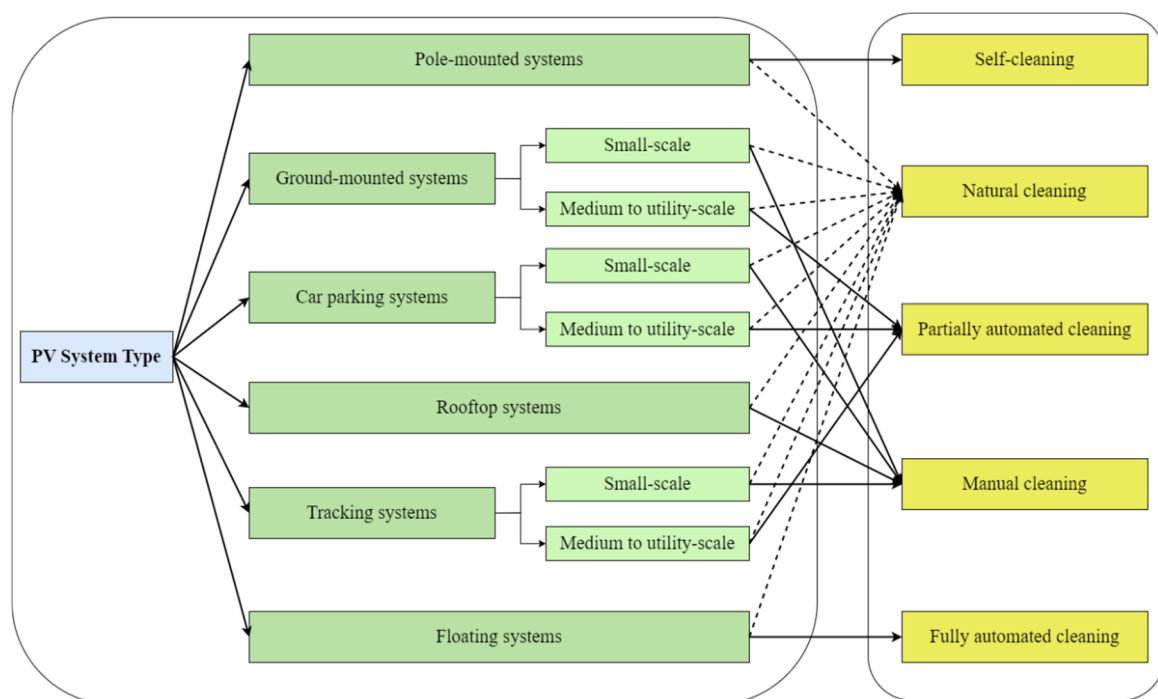


Figure 14. Mapping PV cleaning methods by PV system type.

5. Discussion

The process of ranking suitable PV cleaning methods is complex and involves careful consideration of multifaceted factors, including noncontrollable factors such as meteorological conditions and dust particle characteristics, alongside controllable factors including PV system design and module features, while emphasizing the sustainability of PV cleaning by encompassing economic, social, and environmental factors.

The network model results highlight meteorological factors as the most influential criterion, impacting the level of dust accumulation and PV cleaning. Economic considerations follow closely, balancing cleaning costs with performance benefits. Design settings and module features also significantly influence method selection due to their impact on accessibility, efficiency, and reliability of cleaning.

Partially automated cleaning techniques emerge as the most suitable for the MENA region, addressing the drawbacks of fully automated systems, followed by manual cleaning. Nonetheless, upon comparing the findings of this study with those of previous research on

PV cleaning method selection, it is noticed that manual cleaning, ranked second in preference here, emerged as the most favored option when considering sustainable development goals (SDGs) as the decision criteria, suggesting a strong emphasis on social factors like job creation [104]. In contrast, a study by AlMallahi et al. advocated for PV cleaning in the UAE [43], and indicated that automated cleaning is the most suitable method. However, it overlooked several technical drawbacks and associated losses, particularly for utility-scale PV systems. Therefore, our study offers a comprehensive assessment, considering all influential factors, thereby yielding more reliable outcomes.

This study underscores the complexity of ranking PV cleaning methods, emphasizing both controllable and noncontrollable factors. Specifically, our findings suggest that partially automated cleaning techniques are most suitable for the MENA region, addressing local challenges effectively. This preference aligns with socio-economic factors, including job creation, which are significant in the region's sustainable development context. We acknowledge variations in findings compared to other studies and regions, such as those favoring automated cleaning, and attribute these differences to regional-specific considerations and the comprehensive approach adopted in our study. Thus, our research provides robust insights that can inform PV cleaning practices globally while also recognizing the regional factors influencing method selection.

6. Conclusions

In this study, we conducted a comprehensive literature review and engaged in multiple interviews with experts in the PV system field to identify influential factors affecting dust accumulation and the efficacy of PV cleaning techniques. The identified factors, including meteorological conditions, local environment, PV system design, module characteristics, dust deposition attributes, exposure time, and socio-economic and environmental considerations, formed the criteria for our Multi-Criteria Decision-Making (MCDM) model. Specifically, we employed an Analytic Network Process (ANP) model to address interdependencies among the criteria and determine the most suitable PV cleaning method for utility-scale PV systems in the MENA region. Through expert pairwise comparisons and network analysis, partially automated cleaning emerged as the optimal choice for current utility-scale PV projects in MENA. Additionally, insights from experts informed the development of guidelines for selecting PV cleaning methods based on system type and size, tailored to prevalent factors in the MENA region. These findings provide robust guidance for PV system stakeholders to enhance the sustainability of PV cleaning processes.

Author Contributions: Conceptualization, H.A., M.A. and A.S.; methodology, H.A., M.A. and A.S.; software, H.A.; validation, H.A., M.A. and A.S.; formal analysis, H.A.; investigation, H.A., M.A. and A.S.; resources, H.A.; data curation, H.A.; writing—H.A.; writing—review and editing, H.A., M.A. and A.S.; visualization, H.A.; supervision, M.A. and A.S.; project administration, H.A.; funding acquisition, M.A. All authors have read and agreed to the published version of the manuscript.

Funding: The work in this paper was supported, in part, by the Open Access Program from the American University of Sharjah. This paper represents the opinions of the author(s) and does not mean to represent the position or opinions of the American University of Sharjah.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare that they have no conflicts of interest related to this research.

References

1. REN21. RENEWABLES 2023. *GLOBAL STATUS REPORT*. 2023. Available online: https://www.ren21.net/wp-content/uploads/2019/05/GSR-2023_Energy-Supply-Module.pdf (accessed on 23 November 2023).
2. Kassem, Y.; Gokcekus, H.; Aljatlawe, A. Utilization of Solar Energy for Electric Vehicle Charging and the Energy Consumption of Residential Buildings in Northern Cyprus: A Case Study. *Eng. Technol. Appl. Sci. Res.* **2023**, *13*, 11598–11607. [CrossRef]

3. Gaur, M.; Shrivastava, A.; Pandit, R.K. Performance analysis and sustainability assessment of a building integrated solar PV system. *Int. J. Ambient Energy* **2024**, *45*, 2283762. [CrossRef]
4. Tawalbeh, M.; Al-Othman, A.; Kafiah, F.; Abdelsalam, E.; Almomani, F.; Alkasrawi, M. Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook. *Sci. Total Environ.* **2021**, *759*, 143528. [CrossRef] [PubMed]
5. Mohammad, A.; Mahjabeen, F. Revolutionizing solar energy: The impact of artificial intelligence on photovoltaic systems. *Int. J. Multidiscip. Sci. Arts* **2023**, *2*. [CrossRef]
6. Hess, D.J. Conflict and uneven development in the multidecade distributed solar energy transition in the United States. *Proc. Natl. Acad. Sci. USA* **2023**, *120*, e2206200119. [CrossRef] [PubMed]
7. IEA. Renewable Electricity Capacity Additions by Technology and Segment, 2016–2028. 2024; Renewables 2023. Available online: <https://www.iea.org/data-and-statistics/charts/renewable-electricity-capacity-additions-by-technology-and-segment-2016-2028> (accessed on 19 February 2024).
8. Abuzaid, H.; Awad, M.; Shamayleh, A. Impact of dust accumulation on photovoltaic panels: A review paper. *Int. J. Sustain. Eng.* **2022**, *15*, 264–285. [CrossRef]
9. Salamah, T.; Ramahi, A.; Alamara, K.; Juaidi, A.; Abdallah, R.; Abdelkareem, M.A.; Amer, E.-C.; Olabi, A.G. Effect of dust and methods of cleaning on the performance of solar PV module for different climate regions: Comprehensive review. *Sci. Total Environ.* **2022**, *827*, 154050. [CrossRef]
10. Kazmerski, L.L.; Diniz, A.S.A.; Braga, D.S.; Maia, C.B.; Viana, M.M.; Costa, S.C.; Brito, P.P.; Campos, C.D.; de Moraes Hanriot, S.; de Oliveira Cruz, L.R. Interrelationships among non-uniform soiling distributions and PV module performance parameters, climate conditions, and soiling particle and module surface properties. In Proceedings of the 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC), Washington, DC, USA, 25–30 June 2017; pp. 2307–2311.
11. Jiang, Y.; Lu, L.; Ferro, A.R.; Ahmadi, G. Analyzing wind cleaning process on the accumulated dust on solar photovoltaic (PV) modules on flat surfaces. *Sol. Energy* **2018**, *159*, 1031–1036. [CrossRef]
12. Zereg, K.; Gama, A.; Aksas, M.; Rathore, N.; Yettou, F.; Panwar, N.L. Dust impact on concentrated solar power: A review. *Environ. Eng. Res.* **2022**, *27*, 210345. [CrossRef]
13. Khalid, H.M.; Rafique, Z.; Mueen, S.M.; Raqeeb, A.; Said, Z.; Saidur, R.; Sopian, K. Dust accumulation and aggregation on PV panels: An integrated survey on impacts, mathematical models, cleaning mechanisms, and possible sustainable solution. *Sol. Energy* **2023**, *251*, 261–285. [CrossRef]
14. Chibani, A. Sand and Dust Storms in the MENA Region: A Problem Awaiting Mitigation. Available online: <https://arabcenterdc.org/resource/sand-and-dust-storms-in-the-mena-region-a-problem-awaiting-mitigation/> (accessed on 31 January 2021).
15. NASA. Fine Particulate Maps with and without Dust. NASA: Washington, DC, USA, 2015.
16. Mousavi, S.V.; Karami, K.; Tilmes, S.; Muri, H.; Xia, L.; Rezaei, A. Future dust concentration over the Middle East and North Africa region under global warming and stratospheric aerosol intervention scenarios. *Atmos. Chem. Phys.* **2023**, *23*, 10677–10695. [CrossRef]
17. Univdatos. MENA Solar Photovoltaic Market: Current Analysis and Forecast (2023–2030). 2022. Available online: <https://univdatos.com/report/mena-solar-photovoltaic-market/#:~:text=The%20MENA%20Solar%20Photovoltaic%20Market,roadmap%20for%20solar%20energy%20expansion> (accessed on 31 January 2024).
18. Hernández-Callejo, L.; Gallardo-Saavedra, S.; Alonso-Gómez, V. A review of photovoltaic systems: Design, operation and maintenance. *Sol. Energy* **2019**, *188*, 426–440. [CrossRef]
19. Kazem, H.A.; Chaichan, M.T.; Al-Waeli, A.H.A.; Sopian, K. Effect of dust and cleaning methods on mono and polycrystalline solar photovoltaic performance: An indoor experimental study. *Sol. Energy* **2022**, *236*, 626–643. [CrossRef]
20. Hafner, M.; Raimondi, P.P.; Bonometti, B. Low-carbon energy strategies in mena countries. In *The Energy Sector and Energy Geopolitics in the MENA Region at a Crossroad: Towards a Great Transformation?* Springer: Berlin/Heidelberg, Germany, 2023; pp. 175–261.
21. Santhakumari, M.; Sagar, N. A review of the environmental factors degrading the performance of silicon wafer-based photovoltaic modules: Failure detection methods and essential mitigation techniques. *Renew. Sustain. Energy Rev.* **2019**, *110*, 83–100. [CrossRef]
22. Zarei, T.; Abdolzadeh, M.; Yaghoubi, M. Comparing the impact of climate on dust accumulation and power generation of PV modules: A comprehensive review. *Energy Sustain. Dev.* **2022**, *66*, 238–270. [CrossRef]
23. Nadia, M.; Lassad, H.; Abderrahmen, Z.; Abdelkader, C. Influence of temperature and irradiance on the different solar PV panel technologies. *Int. J. Energy Sect. Manag.* **2021**, *15*, 421–430. [CrossRef]
24. Atsu, D.; Dhaundiyal, A. Effect of ambient parameters on the temperature distribution of photovoltaic (PV) modules. *Resources* **2019**, *8*, 107. [CrossRef]
25. Hadidi, A.; Blal, M.; Saba, D. The study of the arid climate effect on the performance of photovoltaic system. *Energy Syst.* **2021**, *15*, 565–584. [CrossRef]
26. Al Siyabi, I.; Al Mayasi, A.; Al Shukaili, A.; Khanna, S. Effect of Soiling on Solar Photovoltaic Performance under Desert Climatic Conditions. *Energies* **2021**, *14*, 659. [CrossRef]
27. Yao, W.; Kong, X.; Xu, A.; Xu, P.; Wang, Y.; Gao, W. New models for the influence of rainwater on the performance of photovoltaic modules under different rainfall conditions. *Renew. Sustain. Energy Rev.* **2023**, *173*, 113119. [CrossRef]

28. Liu, L.; Qian, H.; Sun, E.; Li, B.; Zhang, Z.; Miao, B.; Li, Z. Power reduction mechanism of dust-deposited photovoltaic modules: An experimental study. *J. Clean. Prod.* **2022**, *378*, 134518. [\[CrossRef\]](#)
29. Dhaouadi, R.; Al-Othman, A.; Aidan, A.A.; Tawalbeh, M.; Zannerni, R. A characterization study for the properties of dust particles collected on photovoltaic (PV) panels in Sharjah, United Arab Emirates. *Renew. Energy* **2021**, *171*, 133–140. [\[CrossRef\]](#)
30. Isaifan, R.J.; Johnson, D.; Ackermann, L.; Figgis, B.; Ayoub, M. Evaluation of the adhesion forces between dust particles and photovoltaic module surfaces. *Sol. Energy Mater. Sol. Cells* **2019**, *191*, 413–421. [\[CrossRef\]](#)
31. Chanchangi, Y.N.; Ghosh, A.; Sundaram, S.; Mallick, T.K. Dust and PV Performance in Nigeria: A review. *Renew. Sustain. Energy Rev.* **2020**, *121*, 109704. [\[CrossRef\]](#)
32. Abderrezek, M.; Fathi, M. Experimental study of the dust effect on photovoltaic panels' energy yield. *Sol. Energy* **2017**, *142*, 308–320. [\[CrossRef\]](#)
33. Zhao, W.; Lv, Y.; Zhou, Q.; Yan, W. Investigation on particle deposition criterion and dust accumulation impact on solar PV module performance. *Energy* **2021**, *233*, 121240. [\[CrossRef\]](#)
34. Lay-Ekuakille, A.; Ciaccioli, A.; Griffo, G.; Visconti, P.; Andria, G. Effects of dust on photovoltaic measurements: A comparative study. *Measurement* **2018**, *113*, 181–188. [\[CrossRef\]](#)
35. Javed, W.; Guo, B.; Figgis, B.; Aïssa, B. Dust potency in the context of solar photovoltaic (PV) soiling loss. *Sol. Energy* **2021**, *220*, 1040–1052. [\[CrossRef\]](#)
36. Wu, Z.; Yan, S.; Ming, T.; Zhao, X.; Zhang, N. Analysis and modeling of dust accumulation-composed spherical and cubic particles on PV module relative transmittance. *Sustain. Energy Technol. Assess.* **2021**, *44*, 101015. [\[CrossRef\]](#)
37. Kazem, H.A.; Chaichan, M.T. The effect of dust accumulation and cleaning methods on PV panels' outcomes based on an experimental study of six locations in Northern Oman. *Sol. Energy* **2019**, *187*, 30–38. [\[CrossRef\]](#)
38. Aghaei, M.; Kumar, N.M.; Eskandari, A.; Ahmed, H.; de Oliveira, A.K.V.; Chopra, S.S. Solar PV systems design and monitoring. In *Photovoltaic Solar Energy Conversion*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 117–145.
39. Aslam, A.; Ahmed, N.; Qureshi, S.A.; Assadi, M.; Ahmed, N. Advances in solar PV systems; A comprehensive review of PV performance, influencing factors, and mitigation techniques. *Energies* **2022**, *15*, 7595. [\[CrossRef\]](#)
40. Hachicha, A.A.; Al-Sawafta, I.; Said, Z. Impact of dust on the performance of solar photovoltaic (PV) systems under United Arab Emirates weather conditions. *Renew. Energy* **2019**, *141*, 287–297. [\[CrossRef\]](#)
41. Semaoui, S.; Arab, A.H.; Boudjelthia, E.K.; Bacha, S.; Zeraia, H. Dust effect on optical transmittance of photovoltaic module glazing in a desert region. *Energy Procedia* **2015**, *74*, 1347–1357. [\[CrossRef\]](#)
42. Aksoy, M.H.; Ispir, M.; YEŞİL, E. Impact of tilt angle on the performance of the photovoltaic systems for different row spacing. *Politek. Derg.* **2023**, *26*, 1573–1585. [\[CrossRef\]](#)
43. AlMallahi, M.N.; El Haj Assad, M.; AlShihabi, S.; Alayi, R. Multi-criteria decision-making approach for the selection of cleaning method of solar PV panels in United Arab Emirates based on sustainability perspective. *Int. J. Low-Carbon Technol.* **2022**, *17*, 380–393. [\[CrossRef\]](#)
44. Younis, A.; Onsa, M. A brief summary of cleaning operations and their effect on the photovoltaic performance in Africa and the Middle East. *Energy Rep.* **2022**, *8*, 2334–2347. [\[CrossRef\]](#)
45. Chiteka, K.; Arora, R.; Sridhara, S.; Enweremadu, C. Cleaning cycle optimisation in non-tracking ground mounted solar PV systems using Particle Swarm Optimisation. *Int. J. Simul. Multidiscip. Des. Optim.* **2020**, *11*, 9. [\[CrossRef\]](#)
46. Amber, K.P.; Hussain, I.; Kousar, A.; Bashir, M.A.; Aslam, M.W.; Akbar, B. A self-cleaning device for pole mounted solar photovoltaic installations. *Therm. Sci.* **2019**, *23*, 739–749.
47. Zahedi, R.; Ranjbaran, P.; Gharehpetian, G.B.; Mohammadi, F.; Ahmadihangar, R. Cleaning of floating photovoltaic systems: A critical review on approaches from technical and economic perspectives. *Energies* **2021**, *14*, 2018. [\[CrossRef\]](#)
48. Chanchangi, Y.N.; Ghosh, A.; Sundaram, S.; Mallick, T.K. An analytical indoor experimental study on the effect of soiling on PV, focusing on dust properties and PV surface material. *Sol. Energy* **2020**, *203*, 46–68. [\[CrossRef\]](#)
49. Wu, Y.; Du, J.; Liu, G.; Ma, D.; Jia, F.; Klemesš, J.J.; Wang, J. A review of self-cleaning technology to reduce dust and ice accumulation in photovoltaic power generation using superhydrophobic coating. *Renew. Energy* **2022**, *185*, 1034–1061. [\[CrossRef\]](#)
50. Younis, A.; Alhorr, Y. Modeling of dust soiling effects on solar photovoltaic performance: A review. *Sol. Energy* **2021**, *220*, 1074–1088. [\[CrossRef\]](#)
51. Khan, R.A.; Farooqui, S.A.; Khan, M.H.; Sarfraz, M.; Luqman, M.; Khan, M.F. Dust deposition on PV module and its characteristics. In *The Effects of Dust and Heat on Photovoltaic Modules: Impacts and Solutions*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 59–95. Available online: https://www.researchgate.net/publication/355856773_Dust_Deposition_on_PV_Module_and_Its_Characteristics (accessed on 31 January 2024).
52. Kayri, İ.; Bayar, M.T. A new approach to determine the long-term effect of efficiency losses due to different dust types accumulation on PV modules with artificial neural networks. *J. Clean. Prod.* **2024**, *434*, 140282. [\[CrossRef\]](#)
53. Alnasser, T.M.A.; Mahdy, A.M.J.; Abass, K.I.; Chaichan, M.T.; Kazem, H.A. Impact of dust ingredient on photovoltaic performance: An experimental study. *Sol. Energy* **2020**, *195*, 651–659. [\[CrossRef\]](#)
54. Said, S.A.; Hassan, G.; Walwil, H.M.; Al-Aqeeli, N. The effect of environmental factors and dust accumulation on photovoltaic modules and dust-accumulation mitigation strategies. *Renew. Sustain. Energy Rev.* **2018**, *82*, 743–760. [\[CrossRef\]](#)
55. Qasem, H.; Betts, T.R.; Müllejans, H.; AlBusairi, H.; Gottschalg, R. Dust-induced shading on photovoltaic modules. *Prog. Photovolt. Res. Appl.* **2014**, *22*, 218–226. [\[CrossRef\]](#)

56. Ali, A. Photovoltaic Module Dust Cleaning Techniques. In *The Effects of Dust and Heat on Photovoltaic Modules: Impacts and Solutions*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 97–112. Available online: https://www.researchgate.net/publication/355856834_Photovoltaic_Module_Dust_Cleaning_Techniques (accessed on 23 November 2023).
57. Smith, M.K.; Wamser, C.C.; James, K.E.; Moody, S.; Sailor, D.J.; Rosenstiel, T.N. Effects of natural and manual cleaning on photovoltaic output. *J. Sol. Energy Eng.* **2013**, *135*, 034505. [CrossRef]
58. Cruz, G.; Vorobiev, P. Dust adhesion physics on photovoltaic surfaces and its application on assisted natural cleaning of solar trackers. *J. Phys. Conf. Ser.* **2022**, *2238*, 012013. [CrossRef]
59. Pawluk, R.E.; Chen, Y.; She, Y. Photovoltaic electricity generation loss due to snow—A literature review on influence factors, estimation, and mitigation. *Renew. Sustain. Energy Rev.* **2019**, *107*, 171–182. [CrossRef]
60. Ghazi, S.; Sayigh, A.; Ip, K. Dust effect on flat surfaces—A review paper. *Renew. Sustain. Energy Rev.* **2014**, *33*, 742–751. [CrossRef]
61. Quan, Z.; Lu, H.; Zhao, W.; Zheng, C.; Zhu, Z.; Qin, J.; Yue, M. A Review of Dust Deposition Mechanism and Self-Cleaning Methods for Solar Photovoltaic Modules. *Coatings* **2022**, *13*, 49. [CrossRef]
62. Jaswal, A.; Sinha, M.K. A review on solar panel cleaning through chemical self-cleaning method. In Proceedings of the International Conference on Advanced Production and Industrial Engineering, Delhi, India, 21–22 December 2019; Springer: Berlin/Heidelberg, Germany, 2021; pp. 835–844.
63. Guo, B.; Javed, W.; Khoo, Y.S.; Figgis, B. Solar PV soiling mitigation by electrodynamic dust shield in field conditions. *Sol. Energy* **2019**, *188*, 271–277. [CrossRef]
64. Kawamoto, H.; Shibata, T. Electrostatic cleaning system for removal of sand from solar panels. *J. Electrostat.* **2015**, *73*, 65–70. [CrossRef]
65. Mazumder, M.; Sharma, R.; Biris, A.; Horenstein, M.; Zhang, J.; Ishihara, H.; Stark, J.; Blumenthal, S.; Sadler, O. Electrostatic removal of particles and its applications to self-cleaning solar panels and solar concentrators. In *Developments in Surface Contamination and Cleaning*; Elsevier: Amsterdam, The Netherlands, 2011; pp. 149–199.
66. Sakhuja, M.; Son, J.; Yang, H.; Bhatia, C.S.; Danner, A.J. Outdoor performance and durability testing of antireflecting and self-cleaning glass for photovoltaic applications. *Sol. Energy* **2014**, *110*, 231–238. [CrossRef]
67. Deb, D.; Brahmabhatt, N.L. Review of yield increase of solar panels through soiling prevention, and a proposed water-free automated cleaning solution. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3306–3313. [CrossRef]
68. Lu, X.; Zhang, Q.; Hu, J. A linear piezoelectric actuator based solar panel cleaning system. *Energy* **2013**, *60*, 401–406. [CrossRef]
69. Ullah, A.; Amin, A.; Haider, T.; Saleem, M.; Butt, N.Z. Investigation of soiling effects, dust chemistry and optimum cleaning schedule for PV modules in Lahore, Pakistan. *Renew. Energy* **2020**, *150*, 456–468. [CrossRef]
70. Zhao, B.; Zhang, S.; Cao, S.; Zhao, Q. Cleaning cycle optimization and cost evaluation of module dust for photovoltaic power plants in China. *Clean Technol. Environ. Policy* **2019**, *21*, 1645–1654. [CrossRef]
71. Alazbe, K.; Roy, H.A.; Alremeithi, A.; Saif, A.; AlHashmi, M.; Daccache, L.; Alnuaimi, A. Insight into dust soiling characteristics and cleaning solutions to investigate impact on PV systems performance across the globe. *Prog. Energy* **2023**, *6*, 012004. [CrossRef]
72. Derakhshandeh, J.F.; AlLuqman, R.; Mohammad, S.; AlHussain, H.; AlHendi, G.; AlEid, D.; Ahmad, Z. A comprehensive review of automatic cleaning systems of solar panels. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101518. [CrossRef]
73. Khadka, N.; Bista, A.; Adhikari, B.; Shrestha, A.; Bista, D. Smart Solar Photovoltaic Panel Cleaning System. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Bangkok, Thailand, 11–14 December 2019; IOP Publishing: Bristol, UK, 2019; p. 012121.
74. Bouaddi, S.; Fernández-García, A.; Sansom, C.; Sarasua, J.A.; Wolfertstetter, F.; Bouzekri, H.; Sutter, F.; Azpitarte, I. A review of conventional and innovative-sustainable methods for cleaning reflectors in concentrating solar power plants. *Sustainability* **2018**, *10*, 3937. [CrossRef]
75. Mohandes, M.; Schulze, F.; Rehman, S.; Suliman, W. Cleaning PhotoVoltaic Solar Panels by Drone Aerodynamic. In Proceedings of the 2021 4th International Symposium on Advanced Electrical and Communication Technologies (ISAECT), Alkhobar, Saudi Arabia, 6–8 December 2021; pp. 1–5.
76. Kazem, H.A.; Chaichan, M.T.; Al-Waeli, A.H.A.; Sopian, K. A review of dust accumulation and cleaning methods for solar photovoltaic systems. *J. Clean. Prod.* **2020**, *276*, 123187. [CrossRef]
77. Al-Housani, M.; Bicer, Y.; Koç, M. Experimental investigations on PV cleaning of large-scale solar power plants in desert climates: Comparison of cleaning techniques for drone retrofitting. *Energy Convers. Manag.* **2019**, *185*, 800–815. [CrossRef]
78. IRENA. Energy Profile. 2024. Available online: <https://www.irena.org/Data/Energy-Profiles> (accessed on 1 August 2024).
79. Santos, B. MENA's Leading Solar PV Markets. 2023. Available online: <https://www.pv-magazine.com/2023/01/17/menas-leading-solar-pv-markets/> (accessed on 31 January 2024).
80. Serrudo, A. The Sun is Brighter in the MENA Region. 2019. Available online: <https://www.ie.edu/school-politics-economics-global-affairs/sun-brighter-mena-region/> (accessed on 31 January 2024).
81. Direct Normal Irradiation Map. Available online: <https://globalsolaratlas.info/map?c=16.701493,37.324229,3&m=site> (accessed on 23 November 2023).
82. WorldBank. MIDDLE EAST & NORTH AFRICA CLIMATE ROADMAP (2021–2025). 2021. Available online: <https://thedocs.worldbank.org/en/doc/6f868d4a875db3ef23ef1dc747fcf2ca-0280012022/original/MENA-Roadmap-Final-01-20.pdf> (accessed on 31 January 2024).

83. WorldBank. Climate and Development in the Middle East and North Africa. 2023. Available online: [https://www.worldbank.org/en/region/mena/brief/climate-and-development-in-the-middle-east-and-north-africa#:~:text=The%20Middle%20East%20and%20North%20Africa%20\(MENA\)%20region%20is%20one,water%20scarcity%20and%20polluted%20air](https://www.worldbank.org/en/region/mena/brief/climate-and-development-in-the-middle-east-and-north-africa#:~:text=The%20Middle%20East%20and%20North%20Africa%20(MENA)%20region%20is%20one,water%20scarcity%20and%20polluted%20air) (accessed on 31 January 2024).
84. de Waal, D.; Khemani, S.; Barone, A.; Borgomeo, E. The Economics of Water Scarcity in the Middle East and North Africa. 2023. Available online: <https://openknowledge.worldbank.org/entities/publication/ab35b03a-23fa-4457-aebd-0f4a89848be1> (accessed on 31 January 2024).
85. IEA. Climate Resilience is Key to Energy Transitions in the Middle East and North Africa. 2023. Available online: <https://www.iea.org/commentaries/climate-resilience-is-key-to-energy-transitions-in-the-middle-east-and-north-africa> (accessed on 31 January 2024).
86. Ezzeldin, K.; Adshead, D.; Smith, P. Adapting to a New Climate in the MENA Region. 2023. Available online: <https://www.unclearn.org/wp-content/uploads/library/Adapting-to-a-new-climate-MENA.pdf> (accessed on 31 January 2024).
87. WorldBank. Average Precipitation by Country. 2021. Available online: <https://tradingeconomics.com/country-list/precipitation> (accessed on 31 January 2024).
88. FAO. *Precipitation—Country Ranking*. 2020. Available online: <https://www.theglobaleconomy.com/rankings/precipitation/MENA/> (accessed on 31 January 2024).
89. WorldBank. *Somalia—Precipitation*. 2020. Available online: <https://climateknowledgeportal.worldbank.org/country/somalia/climate-data-historical#:~:text=The%20average%20annual%20rainfall%20is,rainfall%20on%20an%20annual%20average> (accessed on 31 January 2024).
90. ECOFLOW. How Much Does Solar Panel Cleaning Cost? A Quick Guide. 2023; Volume 2024. Available online: <https://blog.ecoflow.com/us/how-much-does-solar-panel-cleaning-cost/> (accessed on 31 January 2024).
91. Maftouh, A.; El Fatni, O.; Fayiah, M.; Liew, R.; Lam, S.; Bahaj, T.; Butt, M. The application of water-energy nexus in the Middle East and North Africa (MENA) region: A structured review. *Appl. Water Sci.* **2022**, *12*, 83. [CrossRef]
92. Boudekhdekh, K. A Comparative Analysis of Energy Subsidy in the MENA Region. *Econ. Insights Trends Chall.* **2022**, *2022*, 37–56. [CrossRef]
93. Poudineh, R.; Sen, A.; Fattouh, B. An integrated approach to electricity sector reforms in the resource rich economies of the MENA. *Energy Policy* **2020**, *138*, 111236. [CrossRef]
94. Aghahosseini, A.; Bogdanov, D.; Breyer, C. Towards sustainable development in the MENA region: Analysing the feasibility of a 100% renewable electricity system in 2030. *Energy Strategy Rev.* **2020**, *28*, 100466. [CrossRef]
95. Griffiths, S. A review and assessment of energy policy in the Middle East and North Africa region. *Energy Policy* **2017**, *102*, 249–269. [CrossRef]
96. Mertzanis, C.; Said, M. Access to skilled labor, institutions and firm performance in developing countries. *Int. J. Manpow.* **2019**, *40*, 328–355. [CrossRef]
97. Al Abri, I.; Al Hinai, O.; Al Raisi, S.; Al Harrasi, A.; Al Jabri, Z.; Al Maskari, M. Economic growth and the demand for foreign labor in the oil-exporting and labor-importing states of the Arab Gulf: Case of Oman. *Cogent Bus. Manag.* **2023**, *10*, 2256083. [CrossRef]
98. Myovella, G.; Karacuka, M.; Haucap, J. Digitalization and economic growth: A comparative analysis of Sub-Saharan Africa and OECD economies. *Telecommun. Policy* **2020**, *44*, 101856. [CrossRef]
99. BloombergNEF Power Prices and Costs. 2024. Available online: <https://climatescope.github.io/climatescope.org/markets/> (accessed on 31 January 2024).
100. Mallahi, A.; Nooman, M.; Assad, M.E.H.; Rejeb, O.; Delnava, H.; Asaad, S.; Tan, Y.C. A review on cleaning techniques of solar photovoltaic panels. *AIP Conf. Proc.* **2023**, *2847*, 040010.
101. Duran, A.S.; Atasu, A.; Van Wassenhove, L.N. Cleaning after solar panels: Applying a circular outlook to clean energy research. *Int. J. Prod. Res.* **2022**, *60*, 211–230. [CrossRef]
102. Yalcin, A.S.; Kilic, H.S.; Delen, D. The use of multi-criteria decision-making methods in business analytics: A comprehensive literature review. *Technol. Forecast. Soc. Chang.* **2022**, *174*, 121193. [CrossRef]
103. Taherdoost, H.; Madanchian, M. Multi-criteria decision making (MCDM) methods and concepts. *Encyclopedia* **2023**, *3*, 77–87. [CrossRef]
104. Aljaghoub, H.; Abumadi, F.; AlMallahi, M.N.; Obaideen, K.; Alami, A.H. Solar PV cleaning techniques contribute to Sustainable Development Goals (SDGs) using Multi-criteria decision-making (MCDM): Assessment and review. *Int. J. Thermofluids* **2022**, *16*, 100233. [CrossRef]
105. Saaty, T.L.; Vargas, L.G. *The Analytic Network Process*; Springer: Berlin/Heidelberg, Germany, 2013.
106. Saaty, T.L.; Vargas, L.G. *Decision Making with the Analytic Network Process*; Springer: Berlin/Heidelberg, Germany, 2006; Volume 282.
107. Tranfield, D.; Denyer, D.; Smart, P. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *Br. J. Manag.* **2003**, *14*, 207–222. [CrossRef]
108. Aljdaeh, E.; Kamwa, I.; Hammad, W.; Abuashour, M.I.; Sweidan, T.e.O.; Khalid, H.M.; Muyeen, S.M. Performance Enhancement of Self-Cleaning Hydrophobic Nanocoated Photovoltaic Panels in a Dusty Environment. *Energies* **2021**, *14*, 6800. [CrossRef]
109. Abdallah, R.; Juaidi, A.; Abdel-Fattah, S.; Qadi, M.; Shadid, M.; Albatayneh, A.; Çamur, H.; García-Cruz, A.; Manzano-Agugliaro, F. The Effects of Soiling and Frequency of Optimal Cleaning of PV Panels in Palestine. *Energies* **2022**, *15*, 4232. [CrossRef]

110. Alghamdi, A.S.; Bahaj, A.S.; Blunden, L.S.; Wu, Y. Dust Removal from Solar PV Modules by Automated Cleaning Systems. *Energies* **2019**, *12*, 2923. [[CrossRef](#)]
111. Le, N.T.; Nguyen, M.D.; Phan, T.D.; Truong, C.T.; Duong, V.T.; Nguyen, H.H.; Nguyen, T.T. Development of a Multi-Suspension Unit for Solar Cleaning Robots to Mitigate Vibration Impact on Photovoltaic Panels. *Appl. Sci.* **2023**, *13*, 12104. [[CrossRef](#)]

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