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Selecting Appropriate Water–Energy Solutions for Desalination Projects in Coastal Areas

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Abstract: Selecting the appropriate desalination and renewable energy technologies is crucial for the success of desalination projects, as each technology offers distinct advantages and disadvantages tailored to specific project requirements. This research investigates the application of both the analytic hierarchy process and fuzzy logic techniques to develop four decision-making models: two for selecting the optimal desalination technology and two for selecting the optimal renewable energy technology in coastal communities. For desalination technology selection, the analytic hierarchy process model is structured into four hierarchical levels: the main goal, criteria, sub-criteria, and alternatives. The criteria level encompasses four groups, while the sub-criteria level comprises 26 factors. The alternatives considered are reverse osmosis, electrodialysis, and multi-stage flash. In parallel, the analytic hierarchy process model for renewable energy technology selection is similarly structured, with four criteria groups and 24 sub-criteria factors. The alternatives evaluated include photovoltaic, concentrated solar power, and wind energy. Additionally, fuzzy logic models are developed for both desalination and renewable energy technology selection. These models enhance the decision-making framework by incorporating the uncertainty and vagueness that are inherent in real-world scenarios. The integration of analytic hierarchy process and fuzzy logic methodologies provide a robust approach to identifying optimal technologies, thereby supporting sustainable development in Egypt's water–energy nexus. The research outcomes highlight the effectiveness of integrating analytic hierarchy process and fuzzy logic in decision-making processes, offering decision-makers systematic and reliable approaches for selecting the most suitable technologies to achieve sustainability in water–energy nexus projects. The results of the research indicate that the best alternative for desalination was reverse osmosis, and for renewable energy was photovoltaics.

Keywords: AHP; decision-making; multi-criteria; alternatives; desalination technologies; renewable energy technologies; fuzzy logic

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1. Introduction

Access to freshwater is a pressing global concern, with only 1% of freshwater worldwide considered easily accessible. This scarcity, exacerbated by a growing population, underscores the critical need to conserve these vital water resources. Despite various alternative water supply systems, clean drinking water remains elusive on a global scale. According to Savun-Hekimoğlu [1], alternatives such as desalination, irrigation with recycled water, water transfer between regions, and rainwater harvesting were proposed.

The demand for freshwater continues to escalate due to population growth and climate change, driving substantial growth in the seawater desalination sector. This growth is evidenced by the increasing number of reverse osmosis-based desalination plants [2]. Desalination, which harnesses seawater resources, emerges as a pivotal solution among these alternatives. Globally, over 16,000 desalination facilities are operational, predominantly in high-income nations. Notably, Middle Eastern countries with arid climates have significantly contributed to the surge in freshwater production from seawater. Despite its energy-intensive nature, desalination is also considered for the rejuvenation of ancient freshwater sources in these regions [3]. In [3], different water desalination technologies are compared to each other from a project management point of view.

Renewable energy is a vital solution for many loads including desalination, and solar energy-based water desalination is shaped many times for this purpose [4]. Many developing countries with water scarcity problems have very good potential for solar and wind resources to be converted to electricity and other forms of energy through photovoltaics, concentrated solar power and wind turbines [5]. Energy is considered one of the major topics technically and economically in the planning and operating of water desalination units. To integrate the sustainable development goals, especially SDG 6 and SDG 7, renewable energy is used to power water desalination units [6].

There are a lot of water desalination projects in Egypt with advantages and disadvantages, as mentioned in Appendix A. This study will help to overcome the limitations of such projects in the future.

AHP is considered one of the most applied methods in multi-criteria selection. In [7], SWOT analysis of AHP was presented in 2016. In [8], a multi-criteria decision-making process was presented using different methods. It declared that AHP is better than state-of-the-art techniques in terms of pairwise comparison. In [9], different applications of decision making using AHP and state-of-the-art techniques were presented and the results showed that fuzzy AHP are considered base alternatives. In [10], the authors presented judgment on an AHP model using experts to validate the results.

AHP is widely used in various applications for decision making such as post-industrial area management [11], industrial project prioritization [12], a selection of communication technologies for electrical substation [13], and project selection by international conglomerates [14].

The AHP is used in multi-criteria selection in water desalination and renewable energy areas but each one alone. In [15], the authors presented the optimal selection of desalination systems using AHP. The optimal selection of sea water desalination in Oman was studied using AHP in [16], some of the same criteria are used in this research to build up the model. In [17], AHP is used to evaluate renewable energy technologies and also renewable energy technology selection according to criteria that was applied using AHP in [18].

This research compares the AHP with FL, which is widely used in various applications such as control, power systems, sustainability and decision making. In [19], a hybrid fuzzy multi-criteria decision-making approach was used for desalination TOPSIS neglecting the effect of pairwise comparison. In [20], fuzzy logic was applied for selecting the design of a PV-wind–water desalination unit.

From the reviewed literature, several research gaps were identified. Firstly, a comparison between the Analytic Hierarchy Process (AHP) and Fuzzy Logic (FL) in water–energy solutions has not been thoroughly explored. Additionally, there is a lack of consideration for different geographic locations, particularly inland versus coastal areas. Moreover, the simultaneous evaluation of desalination and renewable energy technologies remains under-researched. There is also a need for enhanced decision-making criteria in this field. Furthermore, real-world case studies are not sufficiently applied to validate the findings. Finally, a comprehensive evaluation of technology combinations for water desalination and sustainable energy is missing from the current body of research.

The main contributions of this paper are:

1. Data Collection and Factor Identification:

Data are collected through interviews with water desalination and renewable energy experts, as well as a comprehensive literature review. This process led to the identification of 26 factors related to desalination technologies and 24 factors related to renewable energy technologies. These factors play a vital role in selecting the optimal technology for both desalination and renewable energy applications.

2. Application of AHP for Optimal Technology Selection:

The AHP is applied to select the optimal water desalination technology. The AHP is also utilized to determine the best renewable energy technology. Both technologies are selected to obtain the best solution in terms of geographical locations. The criteria are selected for developing the AHP models in desalination and renewable energy solutions, particularly in relation to marine engineering applications for both offshore and coastal locations.

3. Application of Fuzzy Logic for Optimal Technology Selection:

FL is employed to enhance the decision-making process for selecting the most suitable water desalination technology. FL is similarly applied to optimize the selection of renewable energy technology. The criteria are selected for developing the FL models in desalination and renewable energy solutions, particularly in relation to marine engineering applications for both off-shore and coastal locations.

4. Comparative Analysis of AHP and Fuzzy Logic Results:

The results obtained from both the AHP and FL methodologies are evaluated.
A comparative analysis is conducted to judge the effectiveness of the two approaches.

2. Sample Size

The sample size needed from the population is calculated according to statistical principles tailored for this exploratory investigation, aiming to achieve a confidence level of 95%. This calculation is performed using the following Equation (1) [21].

$$N = \frac{\left(Z_{1-\frac{\alpha}{2}}\right)^2 * \sigma^2}{e^2} \quad (1)$$

where N is the sample size, $(Z_{1-\frac{\alpha}{2}})$ is the target level of confidence, which determines the critical Z value, σ is the standard deviation, and e^2 is the square of acceptable sampling error.

2.1. Sample Size for Desalination Industry

For the desalination industry in this research, a 95%-degree confidence level corresponds to $\alpha = 0.05$. Each of the shaded tails has an area of $(\alpha/2) = 0.025$. The region is $0.5 - 0.025 = 0.475$. Then, from the Table of the standard normal distribution (z), an area of 0.475 corresponds to a z-value of 1.96. Therefore, the critical value = 1.96, the margin of error is assumed as e = 0.25, and from the 20 samples retaken from population, the standard deviation = 0.84. Accordingly, the sampling size is calculated to be 44 questionnaires, and the level of confidence based on this value is 95%.

Thirty-seven responses were received. Choosing 37 questionnaires as the sample size, we substitute this value into (1) with a standard deviation of 0.92 for all 37 respondents. Accordingly, the critical z-value is calculated by using (1), with a z-value of 1.65 for a confidence level exceeding 90%. Consequently, the 37 responses received can be considered highly representative of the population, as the confidence level was calculated through the application of an interpolation method to be 90%.

2.2. Sample Size for Renewable Energy Industry

Similarly, for the renewable energy industry, the 95%-degree confidence level corresponds to $\alpha = 0.05$. Each of the shaded tails has an area of $(\alpha/2) = 0.025$. The region is $0.5 - 0.025 = 0.475$. Then, from the Table of the standard normal distribution (z), an area of 0.475 corresponds to a z-value of 1.96. Therefore, the critical value = 1.96, the margin of error is assumed as e = 0.25, and from the 20 samples retaken from the population, the standard deviation = 0.885. Accordingly, the sampling size is calculated to be 48 questionnaires, and the level of confidence based on this value is 95%.

Thirty-seven responses were received. Choosing 37 questionnaires as the sample size, we substitute this value into (1) with a standard deviation of 0.922 for all 37 respondents. Accordingly, the critical z value is calculated by using the (1), Z value of 1.649 for a confidence level exceeding 90%. Consequently, the 37 responses received can be considered highly representative of the population, as the confidence level was calculated through the application of an interpolation method to be 90%.

3. Statistical Analysis

For the collected questionnaire responses, key statistical measures including mean, mode, standard error (SE), and standard deviation (SD) were calculated for each factor individually affecting the choice of desalination technology. The standard deviation was used to assess variability, while the standard error represented the standard deviation of the sampling distribution of a statistic. Additionally, the standard error of the mean was evaluated to determine the extent of variation in means from different samples relative to the population mean due to chance error in the sampling process.

Abdul Gawad demonstrated that comparing the calculated standard error to 0.2 is significant, as this value indicates a relatively precise point estimate of the results, as suggested by Montgomery et al. If the SE was found to be less than 0.2, it indicated an acceptable agreement among experts on the risk significance for most of the examined factors [22,23].

3.1. Statistical Analysis of Desalination Factors

We conducted a comprehensive statistical analysis encompassing 37 responses related to desalination factors. The results, summarized in Table 1, demonstrate a consensus among experts, with all SE values below 0.2. This suggests a unanimous agreement regarding the significance of the most examined factors in the desalination domain.

Table 1. Statistical results for factors affecting desalination technology choice.

Group	No.	Factor	Total No. of Expert	Sum of Points	Mean	S.D	S.E	Mode
Group 1: Time	1.1	Time needed for the construction of the civil works.	37	128	3.459	0.918	0.151	3
	1.2	Time needed for the installation of electro-mechanical works.	37	136	3.676	0.988	0.162	4
	1.3	Time needed for the installation of the desalination process.	37	132	3.568	0.917	0.151	3
	1.4	Required water production rate.	37	144	3.892	0.980	0.161	4
Group 2: Cost	2.1	Initial costs of desalination process.	37	150	4.054	1.012	0.166	4
	2.2	Construction cost of the while desalination plant.	37	143	3.865	0.704	0.116	4
	2.3	Budget and financial limitations of desalination process.	37	151	4.081	0.712	0.117	4
	2.4	Running cost of the desalination process (excluding energy cost).	37	134	3.622	0.940	0.155	4
	2.5	Regular maintenance cost.	37	123	3.324	0.840	0.138	3
	2.6	Running cost limitations of desalination process.	37	138	3.730	0.643	0.106	4
Group 3: Material and Equipment	3.1	Availability of used material in local market.	37	140	3.784	1.189	0.195	5
	3.2	Durability of used material.	37	142	3.838	0.945	0.155	4
	3.3	Experience of engineers/consultants with used material.	37	129	3.486	0.976	0.160	4
	3.4	Experience of contractors with used material.	37	125	3.378	0.940	0.155	3
	3.5	Experience of workers with used material.	37	126	3.405	0.853	0.140	3
	3.6	Availability of supplier in Egypt.	37	123	3.324	1.116	0.184	3
	3.7	Available storage area for material, equipment, . . . etc.	37	116	3.135	1.070	0.176	3
	3.8	Land availability.	37	144	3.892	1.085	0.178	5
Group 4: Design, Implementation and Operation	4.1	Experience of engineers/consultant in applied desalination method.	37	133	3.595	0.884	0.145	4
	4.2	Experience of contractors in applied desalination method.	37	129	3.486	0.826	0.136	3
	4.3	Experience of operator in applied desalination method.	37	131	3.541	0.918	0.151	3
	4.4	Efficiency level of desalinated water.	37	148	4.000	0.771	0.127	4
	4.5	Unsuitable weather (humidity–temperature).	37	116	3.135	0.935	0.154	3
	4.6	Health and Safety standards.	37	137	3.703	0.866	0.142	4
	4.7	Maintenance requirements.	37	132	3.568	0.790	0.130	4
	4.8	Environmental regulations (brine quantity, brine disposal, etc.).	37	132	3.568	1.104	0.181	4

3.2. Statistical Analysis of Renewable Energy Factors

Similarly, a statistical analysis was performed for the renewable energy factors using the same dataset. The findings, presented in Table 2, exhibit consistent trends, with all SE values being below 0.2. This indicates a shared perspective among experts regarding the significance of the various factors influencing renewable energy technologies.

Table 2. Statistical results for factors affecting renewable energy technology choice.

Group	No.	Factor	Total No. of Expert	Sum of Points	Mean	S.D	S.E	Mode
Group 1: Time	1.1	Time needed for the construction of the civil works of the renewable energy components.	37	121	3.270	0.890	0.146	3
	1.2	Time needed for the installation electro-mechanical works.	37	120	3.243	0.882	0.145	3
	1.3	Time needed for the installation of energy production.	37	119	3.216	0.990	0.163	4
	1.4	Required energy production rate.	37	145	3.919	0.784	0.129	4
Group 2: Cost	2.1	Initial costs of renewable energy provision.	37	161	4.351	0.625	0.103	4
	2.2	Budget and financial limitations of renewable energy.	37	157	4.243	0.633	0.104	4
	2.3	Energy running cost.	37	136	3.676	1.164	0.191	5
	2.4	Regular maintenance cost of renewable energy system.	37	140	3.784	1.118	0.184	5
Group 3: Material and Equipment	3.1	Availability of used material in local market.	37	116	3.135	1.143	0.188	3
	3.2	Durability of used material.	37	145	3.919	0.941	0.155	4
	3.3	Experience of engineers/consultants with used material.	37	138	3.730	0.859	0.141	4
	3.4	Experience of contractors with used material.	37	131	3.541	0.825	0.136	3
	3.5	Experience of workers with used material.	37	125	3.378	0.783	0.129	3
	3.6	Availability of supplier in Egypt.	37	136	3.676	1.041	0.171	4
	3.7	Available storage area for material, equipment, etc.	37	105	2.838	1.103	0.181	2
	3.8	Land availability for renewable energy system.	37	155	4.189	0.833	0.137	5
Group 4: Methods Statement	4.1	Experience of engineers/consultants in applied renewable energy resource.	37	136	3.676	0.807	0.133	4
	4.2	Experience of contractors in applied renewable energy resource.	37	133	3.595	0.821	0.135	4
	4.3	Experience of operator in applied renewable energy resource.	37	136	3.676	0.840	0.138	4
	4.4	Quality and efficiency level of renewable energy resource.	37	140	3.784	0.810	0.133	4
	4.5	Unsuitable weather (humidity–temperature)	37	139	3.757	1.149	0.189	5
	4.6	Health and Safety standards.	37	134	3.622	0.911	0.150	4
	4.7	Maintenance requirements.	37	128	3.459	1.029	0.169	3
	4.8	Environmental regulations.	37	137	3.703	1.136	0.187	4

4. Water Desalination Models Development

The models developed for water desalination were constructed using the Multi-Criteria Decision-Making Model (MCDM) process. The (AHP) method was utilized as one approach, offering a structured framework for decision-making in complex systems. Additionally, the second approach or technique used was (FL), aiding in the selection of the optimal desalination technology. There are several reasons for employing the AHP and FL in the MCDM for desalination projects such as handling subjective and qualitative data, simplified decision-making, integration of expert opinions, and adaptability and flexibility. The main reason for using the AHP over TOPSIS and other state-of-the-art techniques is pairwise comparison [8]. The reason for doing both FL and the AHP is the validation of the results and criteria.

4.1. Analytical Hierarchy Process (AHP) for Desalination Model

For this research, the hierarchy consists of four levels. The first level is the main goal of this research, which is "Choose a best technique of desalination", the second level is that the criteria consists of four groups: time, cost, material and equipment, and design, implementation and operation, the third level is sub-criteria, which are time needed for the construction of the civil works, time needed for the installation of electro-mechanical works, time needed for the installation of the desalination process, required water production rate, initial costs of desalination process, construction cost of the while desalination plant, budget and financial limitations of desalination process, running cost of the desalination process (excluding energy cost), regular maintenance cost, running cost limitations of desalination process, availability of used material in local market, durability of used material, experience of engineers/consultants with used material, experience of contractors with used material, experience of workers with used material availability of supplier in Egypt, available storage area for material, equipment, etc., land availability, experience of engineers/consultant in applied desalination method, experience of contractors in applied desalination method, experience of operator in applied desalination method, efficiency level of desalinated water, unsuitable weather (humidity–temperature), health and safety standards, maintenance requirements, environmental regulations (brine quantity, brine disposal, etc.). The fourth level is the alternatives, these alternatives are reverse osmosis (RO), electrodialysis (ED) and multi-stage flash (MSF), as shown in Figure 1.

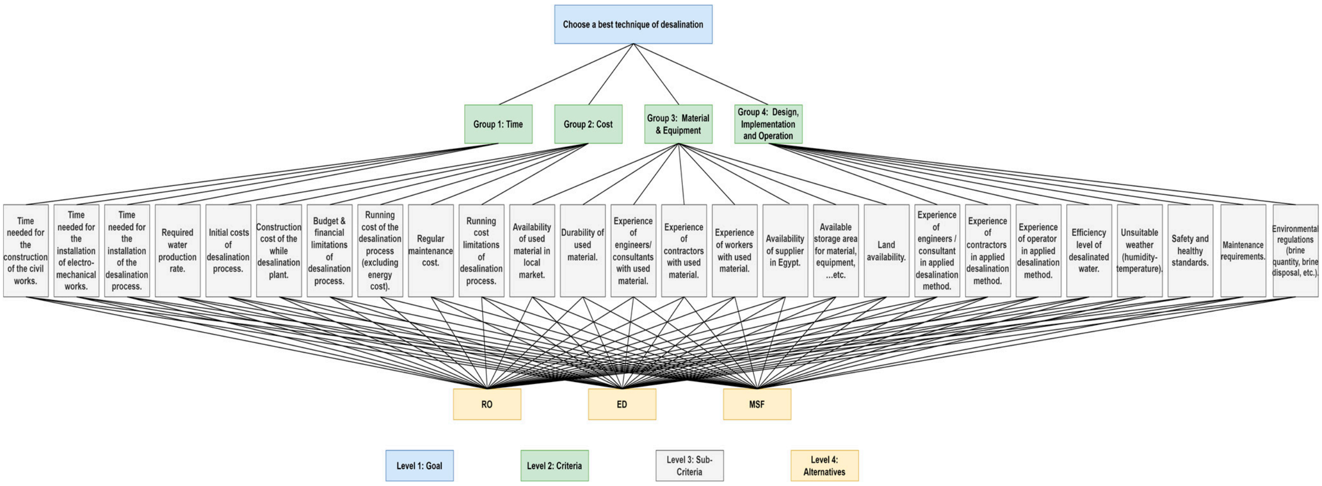

Figure 1. Hierarchy of research problem for desalination model.

4.1.1. Construct Comparison Matrices and Pairwise Comparison for Desalination Model

In this step, the criteria and sub-criteria previously established are organized into comparison matrices. Decision-makers evaluate the relative importance of each element concerning the main goal: "Selection of the Optimal Desalination Technique". Each criterion within its group, and subsequently each sub-criterion, is compared pairwise against others to determine their relative importance.

To facilitate this process, the Analytic Hierarchy Process (AHP) methodology is employed. This involves decision-makers making pairwise comparisons, using a scale from 1 to 9, where a value of 1 indicates that two elements are equally important. A value of 3 indicates a moderate preference for one element over another based on experience and judgment. A value of 5 denotes a strong preference for one element over another. A value of 7 indicates a very strong preference, with significant evidence preferring one element. A value of 9 signifies an extreme preference, with evidence supporting one element over another. Intermediate values of 2, 4, 6, and 8 are used to express preferences between the principal values.

The comparison matrices for the criteria and sub-criteria are developed based on the survey data collected from the decision-makers. These matrices enable the combination of judgments into a clear framework, which reflects the relative weights of each criterion and sub-criterion. This systematic approach ensures that all relevant factors are considered in the decision-making process.

Matrix 1, which shows the comparison between the main groups, is presented in Table 3. Matrix 2, which shows the comparison between the factors in the "Time" group, is presented in Table 4. Matrix 3, which shows the comparison between factors in the "Cost" group, is presented in Table 5. Matrix 4, which shows the comparison between factors in the "Material & Equipment" group, is presented in Table 6. Finally, Matrix 5, which shows the comparison between factors in the Design, Implementation and Operation" group, is presented in Table 7. Table 8 shows the synthesized matrix for the main criteria and the sub-criteria.

Table 3. Water desalination pairwise comparison matrix for criteria groups.

No	Group	Group 1: Time	Group 2: Cost	Group 3: Material and Equipment	Group 4: Design, Implementation and Operation
1	Group 1: Time	1	0.25	3	3
2	Group 2: Cost	4.000	1	4	4
3	Group 3: Material and Equipment	0.333	0.250	1	1
4	Group 4: Design, Implementation and Operation	0.333	0.250	1.000	1

Table 4. Water desalination pairwise comparison matrix for "Time" group.

No	Factor	Time Needed for the Construction of the Civil Works.	Time Needed for the Installation of Electro-Mechanical Works.	Time Needed for the Installation of the Desalination Process.	Required Water Production Rate.
1	Time needed for the construction of the civil works.	1	0.25	0.5	0.125
2	Time needed for the installation of electro-mechanical works.	4.000	1	2	0.25
3	Time needed for the installation of the desalination process.	2.000	0.500	1	0.16666667
4	Required water production rate.	8.000	4.000	6.000	1

Table 5. Water desalination pairwise comparison matrix for "Cost" group.

No	Factor	Initial Costs of Desalination Process.	Construction Cost of the While Desalination Plant.	Budget and Financial Limitations of Desalination Process.	Running Cost of the Desalination Process (Excluding Energy Cost).	Regular Maintenance Cost.	Running Cost Limitations of Desalination Process.
1	Initial costs of desalination process.	1	4	1	7	9	6
2	Construction cost of the while desalination plant.	0.250	1	0.25	5	9	3
3	Budget and financial limitations of desalination process.	1.000	4.000	1	7	9	6
4	Running cost of the desalination process (excluding energy cost).	0.143	0.200	0.143	1	5	0.5
5	Regular maintenance cost.	0.111	0.111	0.111	0.200	1	0.142857
6	Running cost limitations of desalination process.	0.167	0.333	0.167	2.000	7.000	1

Table 6. Water desalination pairwise comparison matrix for "Material & Equipment" group.

No	Factor	Availability of Used Material in Local Market.	Durability of Used Material.	Experience of Engineers/Consultants with Used Material.	Experience of Contractors with Used Material.	Experience of Workers with Used Material.	Availability of Supplier in Egypt.	Available Storage Area for Material, Equipment, . . . etc.	Land Availability.
1	Availability of used material in local market.	1	1	5	7	7	8	9	0.5
2	Durability of used material.	1.000	1	5	7	7	8	9	1
3	Experience of engineers/consultants with used material.	0.200	0.200	1	2	2	3	6	0.14
4	Experience of contractors with used material.	0.143	0.143	0.500	1	1	1	4	0.11
5	Experience of workers with used material.	0.143	0.143	0.500	1.000	1	1	5	0.11
6	Availability of supplier in Egypt.	0.125	0.125	0.333	1.000	1.000	1	0.25	0.11
7	Available storage area for material, equipment, etc.	0.111	0.111	0.167	0.250	0.200	4.000	1	0.11
8	Land availability.	2.000	1.000	7.000	9.000	9.000	9.000	9.000	1

Table 7. Water desalination pairwise comparison matrix for "Design, Implementation and Operation" group.

No	Factor	Experience of Engineers/Consultant in Applied Desalination Method.	Experience of Contractors in Applied Desalination Method.	Experience of Operator in Applied Desalination Method.	Efficiency Level of Desalinated Water.	Unsuitable Weather (Humidity–Temperature).	Health and Safety Standards.	Maintenance Requirements.	Environmental Regulations (Brine Quantity, Brine Disposal, etc.).
1	Experience of engineers/consultant in applied desalination method.	1	2	1	0.14	9	0.5	1	1
2	Experience of contractors in applied desalination method.	0.500	1	1	0.11	6	0.25	1	1
3	Experience of operator in applied desalination method.	1.000	1.000	1	0.11	9	0.33	1	1
4	Efficiency level of desalinated water.	7.000	9.000	9.000	1	9	5	8	8
5	Unsuitable weather (humidity–temperature).	0.111	0.167	0.111	0.111	1	0.11	0.125	0.125
6	Health and Safety standards.	2.000	4.000	3.000	0.200	9.000	1	3	3
7	Maintenance requirements.	1.000	1.000	1.000	0.125	8.000	0.333	1	1
8	Environmental regulations (brine quantity, brine disposal, etc.).	1.000	1.000	1.000	0.125	8.000	0.333	1.000	1

Table 8. Synthesized matrix for main criteria, and sub-criteria for water desalination.

No	Factor	Normalized Value							
1	Group 1: Time	0.1765	0.1429	0.3333	0.3333				
2	Group 2: Cost	0.7059	0.5714	0.4444	0.4444				
3	Group 3: Material and Equipment	0.0588	0.1429	0.1111	0.1111				
4	Group 4: Design, Implementation and Operation	0.0588	0.1429	0.1111	0.1111				
1.1	Time needed for the construction of the civil works.	0.0667	0.0435	0.0526	0.0811				
1.2	Time needed for the installation of electro-mechanical works.	0.2667	0.1739	0.2105	0.1622				
1.3	Time needed for the installation of the desalination process.	0.1333	0.0870	0.1053	0.1081				
1.4	Required water production rate.	0.5333	0.6957	0.6316	0.6486				
2.1	Initial costs of desalination process.	0.3744	0.4147	0.3744	0.3153	0.2250	0.3605		
2.2	Construction cost of the while desalination plant.	0.0936	0.1037	0.0936	0.2252	0.2250	0.1803		
2.3	Budget and financial limitations of desalination process.	0.3744	0.4147	0.3744	0.3153	0.2250	0.3605		
2.4	Running cost of the desalination process (excluding energy cost).	0.0535	0.0207	0.0535	0.0450	0.1250	0.0300		
2.5	Regular maintenance cost.	0.0416	0.0115	0.0416	0.0090	0.0250	0.0086		
2.6	Running cost limitations of desalination process.	0.0624	0.0346	0.0624	0.0901	0.1750	0.0601		
3.1	Availability of used material in local market.	0.2118	0.2687	0.2564	0.2478	0.2482	0.2286	0.2081	0.1620
3.2	Durability of used material.	0.2118	0.2687	0.2564	0.2478	0.2482	0.2286	0.2081	0.3239
3.3	Experience of engineers/consultants with used material.	0.0424	0.0537	0.0513	0.0708	0.0709	0.0857	0.1387	0.0463
3.4	Experience of contractors with used material.	0.0303	0.0384	0.0256	0.0354	0.0355	0.0286	0.0925	0.0360
3.5	Experience of workers with used material.	0.0303	0.0384	0.0256	0.0354	0.0355	0.0286	0.1156	0.0360
3.6	Availability of supplier in Egypt.	0.0265	0.0336	0.0171	0.0354	0.0355	0.0286	0.0058	0.0360
3.7	Available storage area for material, equipment, etc.	0.0235	0.0299	0.0085	0.0088	0.0071	0.1143	0.0231	0.0360
3.8	Land availability.	0.4236	0.2687	0.3590	0.3186	0.3191	0.2571	0.2081	0.3239
4.1	Experience of engineers/consultants in applied desalination method.	0.0735	0.1043	0.0584	0.0742	0.1525	0.0636	0.0620	0.0620
4.2	Experience of contractors in applied desalination method.	0.0367	0.0522	0.0584	0.0577	0.1017	0.0318	0.0620	0.0620
4.3	Experience of operator in applied desalination method.	0.0735	0.0522	0.0584	0.0577	0.1525	0.0424	0.0620	0.0620
4.4	Efficiency level of desalinated water.	0.5143	0.4696	0.5260	0.5192	0.1525	0.6360	0.4961	0.4961
4.5	Unsuitable weather (humidity–temperature).	0.0082	0.0087	0.0065	0.0577	0.0169	0.0141	0.0078	0.0078
4.6	Health and Safety standards.	0.1469	0.2087	0.1753	0.1038	0.1525	0.1272	0.1860	0.1860
4.7	Maintenance requirements.	0.0735	0.0522	0.0584	0.0649	0.1356	0.0424	0.0620	0.0620
4.8	Environmental regulations (brine quantity, brine disposal, etc.).	0.0735	0.0522	0.0584	0.0649	0.1356	0.0424	0.0620	0.0620

The resulting pairwise comparison matrices provide a strong basis for evaluating the alternatives: reverse osmosis (RO), electrodialysis (ED), and multi-stage flash (MSF). The developed matrices, derived from the collective judgments of the decision-makers, facilitate the identification of the most appropriate desalination technique for achieving sustainability in Egypt's water–energy nexus.

4.1.2. Steps for Calculating Consistency in AHP Desalination Model

The following generalized steps are employed to calculate the consistency in the Analytic Hierarchy Process (AHP) for the desalination model:

Step 1: Calculating the priority vector:

The priority vector could be obtained by finding the row averages.

Step 2: Calculating λ_{max}:

To calculate the λ_{max}, the weighted sum matrices have to be calculated by adding the multiplying of the priority vector with each column of the pairwise comparison matrix. After calculating the weighted sum matrix, each element of the weighted sum matrices is divided by their respective priority vector element to obtain values of consistency measure, and then the average of these values is computed to obtain λ_{max}.

Step 3: Calculating the consistency index (CI):

The calculation of CI according to (2) [24]:

$$CI = \frac{\lambda max - n}{(n-1)} \quad (2)$$

where n is the number of alternatives in one hierarchy.

Step 4: Selecting Appropriate Value of the Random Consistency Ratio (RI):

An appropriate value of random consistency ratio RI is selected from Table 9 [25], depending on the matrix size (value of n).

Table 9. RI values.

n	***RI***	***n***	***RI***
3	0.52	11	1.514
4	0.88	12	1.54
5	1.109	13	1.55
6	1.25	14	1.57
7	1.34	15	1.58
8	1.406	16	1.59
9	1.45	17	1.6086
10	1.485		

Step 5: Calculate the Consistency Ratio (CR):

The calculation of CR according to (3) [24]:

$$CR = \frac{CI}{RI} \quad (3)$$

Step 6: Check the Consistency Ratio (CR):

The value of the consistency ratio should be equal to or less than 10%. If it is more than 10%, the judgments may be somewhat random and should perhaps be revised [26].

All of the previous steps, calculations and results are shown in Table 10.

Table 10. Calculation and checking consistency for main criteria, and sub-criteria for water desalination.

No	Factor	Row Avg.	Weighted Sum	Consistency Measure	λ	CI	RI	CR	Consistency Check
1	Group 1: Time	0.246	1.018	4.129	4.15518	0.05173	0.88150	0.05868	Consistency OK
2	Group 2: Cost	0.542	2.375	4.386					
3	Group 3: Material and Equipment	0.106	0.430	4.053					
4	Group 4: Design, Implementation and Operation	0.106	0.430	4.053					5.9%
1.1	Time needed for the construction of the civil works.	0.061	0.244	4.009	4.04597	0.01532	0.88150	0.01739	Consistency OK
1.2	Time needed for the installation of electro-mechanical works.	0.203	0.821	4.037					
1.3	Time needed for the installation of the desalination process.	0.108	0.437	4.027					
1.4	Required water production rate.	0.627	2.579	4.111					1.7%
2.1	Initial costs of desalination process.	0.344	2.375	6.904	6.54657	0.10931	1.21790	0.08976	Consistency OK
2.2	Construction cost of the whole desalination plant.	0.154	1.047	6.818					
2.3	Budget and financial limitations of desalination process.	0.344	2.375	6.904					
2.4	Running cost of the desalination process (excluding energy cost).	0.055	0.338	6.195					
2.5	Regular maintenance cost.	0.023	0.139	6.068					
2.6	Running cost limitations of desalination process.	0.081	0.516	6.391					9.0%
3.1	Availability of used material in local market.	0.229	2.068	9.033	8.96955	0.13851	1.40560	0.09854	Consistency OK
3.2	Durability of used material.	0.249	2.223	8.921					
3.3	Experience of engineers/consultants with used material.	0.070	0.647	9.247					
3.4	Experience of contractors with used material.	0.040	0.374	9.288					
3.5	Experience of workers with used material.	0.043	0.405	9.394					
3.6	Availability of supplier in Egypt.	0.027	0.236	8.650					
3.7	Available storage area for material, equipment, etc.	0.031	0.258	8.230					
3.8	Land availability.	0.310	2.786	8.994					9.9%
4.1	Experience of engineers/consultants in applied desalination method.	0.081	0.697	8.568	8.57765	0.08252	1.40560	0.05871	Consistency OK
4.2	Experience of contractors in applied desalination method.	0.058	0.495	8.564					
4.3	Experience of operator in applied desalination method.	0.070	0.597	8.519					
4.4	Efficiency level of desalinated water.	0.476	4.246	8.917					
4.5	Unsuitable weather (humidity–temperature).	0.016	0.130	8.175					
4.6	Health and safety standards.	0.161	1.417	8.811					
4.7	Maintenance requirements.	0.069	0.588	8.534					
4.8	Environmental regulations (brine quantity, brine disposal, etc.).	0.069	0.588	8.534					5.9%

The final pairwise comparisons among the desalination technology alternatives of reverse osmosis (RO), electrodialysis (ED), and multi-stage flash (MSF) are presented in Table 11. Each alternative is compared against the others across all sub-criteria within the established groups of time, cost, material and equipment, and design, implementation and operation. Decision-makers provided judgments that were used to construct the pairwise comparison matrices for each sub-criterion. The consistency of these judgments was verified using the consistency ratio (CR) to ensure reliability. The calculations involved deriving priority vectors and checking consistency for each factor. The synthesized results combine the weights of all sub-criteria, offering a comprehensive ranking of the desalination technologies. Table 11 summarizes these results, including the consistency ratios to validate the decision-makers' judgments.

Table 11. Final pairwise comparison results and consistency ratios for desalination technologies.

No	Factor	RO	ED	MSF	λ	CI	RI	CR	Consistency Check
1.1	Time needed for the construction of the civil works.	0.500	0.250	0.250	3.000	0.000	0.525	0.000	Consistency OK
1.2	Time needed for the installation of electro-mechanical works.	0.681	0.201	0.118	3.025	0.012	0.525	0.024	Consistency OK
1.3	Time needed for the installation of the desalination process.	0.653	0.251	0.096	3.018	0.009	0.525	0.017	Consistency OK
1.4	Required water production rate.	0.548	0.211	0.241	3.018	0.009	0.525	0.017	Consistency OK
2.1	Initial costs of desalination process.	0.557	0.320	0.123	3.018	0.009	0.525	0.017	Consistency OK
2.2	Construction cost of the whole desalination plant.	0.164	0.297	0.539	3.009	0.005	0.525	0.009	Consistency OK
2.3	Budget and financial limitations of desalination process.	0.200	0.400	0.400	3.000	0.000	0.525	0.000	Consistency OK
2.4	Running cost of the desalination process (excluding energy cost).	0.633	0.260	0.106	3.039	0.019	0.525	0.037	Consistency OK
2.5	Regular maintenance cost.	0.701	0.213	0.085	3.033	0.016	0.525	0.031	Consistency OK
2.6	Running cost limitations of desalination process.	0.701	0.213	0.085	3.033	0.016	0.525	0.031	Consistency OK
3.1	Availability of used material in local market.	0.690	0.161	0.149	3.006	0.003	0.525	0.005	Consistency OK
3.2	Durability of used material.	0.685	0.221	0.093	3.054	0.027	0.525	0.052	Consistency OK
3.3	Experience of engineers/consultants with used material.	0.780	0.083	0.137	3.035	0.018	0.525	0.034	Consistency OK
3.4	Experience of contractors with used material.	0.780	0.083	0.137	3.035	0.018	0.525	0.034	Consistency OK
3.5	Experience of workers with used material.	0.780	0.083	0.137	3.035	0.018	0.525	0.034	Consistency OK
3.6	Availability of supplier in Egypt.	0.750	0.125	0.125	3.000	0.000	0.525	0.000	Consistency OK
3.7	Available storage area for material, equipment, etc.	0.333	0.333	0.333	3.000	0.000	0.525	0.000	Consistency OK
3.8	Land availability.	0.648	0.230	0.122	3.004	0.002	0.525	0.004	Consistency OK
4.1	Experience of engineers/consultants in applied desalination method.	0.780	0.083	0.137	3.035	0.018	0.525	0.034	Consistency OK
4.2	Experience of contractors in applied desalination method.	0.780	0.083	0.137	3.035	0.018	0.525	0.034	Consistency OK
4.3	Experience of operator in applied desalination method.	0.780	0.083	0.137	3.035	0.018	0.525	0.034	Consistency OK
4.4	Efficiency level of desalinated water.	0.648	0.230	0.122	3.004	0.002	0.525	0.004	Consistency OK
4.5	Unsuitable weather (humidity–temperature).	0.556	0.354	0.090	3.054	0.027	0.525	0.051	Consistency OK
4.6	Health and Safety standards.	0.539	0.297	0.164	3.009	0.005	0.525	0.009	Consistency OK
4.7	Maintenance requirements.	0.539	0.297	0.164	3.009	0.005	0.525	0.009	Consistency OK
4.8	Environmental regulations (brine quantity, brine disposal, etc.).	0.539	0.297	0.164	3.009	0.005	0.525	0.009	Consistency OK

The final results of desalination technology priority comparison with overall criteria show that the optimal desalination technology achieving all criteria is reverse osmosis, with a priority of 49.7%, Electrodialysis and multi-stage flash received second and third rank with a percentage of 27.5%, 22.8%, respectively.

In this research, a model for water desalination is developed for applying the AHP in a step-by-step way. This model could calculate all the steps illustrated in the AHP methodology section and also present numerical information.

4.2. Fuzzy Logic (FL) Desalination Model

The developed model in this research is based on MATLAB (R2018a). This software was selected for its ease of installation and operation, its fully tested system with a proven track record, and its flexibility and capacity to handle various types of applications.

4.2.1. Data Organization and Sets for Water Desalination

The first step of the model building is to determine the inputs and the outputs of the model; the next step is to determine the range of all the variables using the membership functions. The selected shape of the membership functions is the trapezoidal membership function. Input variables of the fuzzy logic model are derived to represent the main criteria affecting the selection desalination technique; the criteria are divided into four which are time, cost, material and equipment, and design, implementation and operation. Each group represents an input in the fuzzy model, resulting in four inputs. The membership function model is illustrated in the next figure. As shown in Figure 2, the following points were concluded by industry experts during semi-structured interviews and brainstorming sessions:

- Scores ranging from 0 to 0.5 are considered to have low significance.
- Scores ranging from 0.3 to 0.7 are considered to have moderate significance.
- Scores ranging from 0.5 to 1 are considered to have high significance.

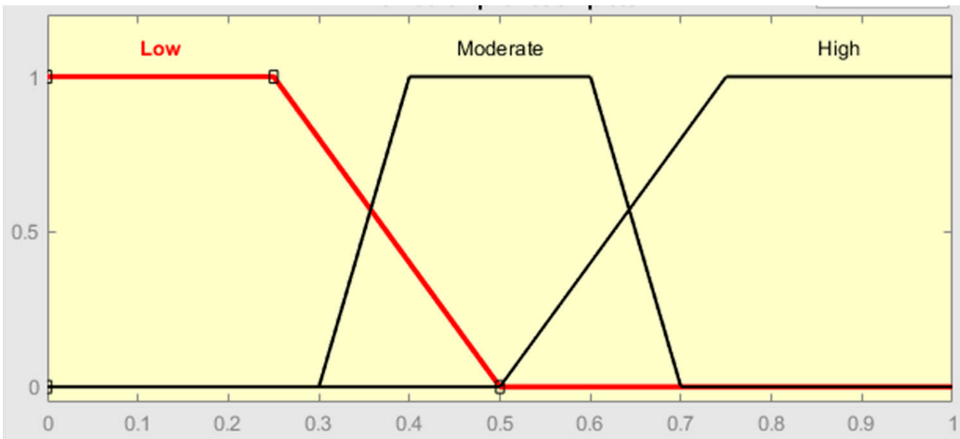

Figure 2. Membership function for input variables of water desalination model.

The output of this model is the optimal desalination technology based on the input factors, represented by membership functions, as illustrated in Figure 3. The following points were concluded by industry experts during semi-structured interviews and brainstorming sessions:

- Scores ranging from 0 to 0.5 are considered RO.
- Scores ranging from 0.3 to 0.7 are considered ED.
- Scores ranging from 0.5 to 1 are considered MSF.

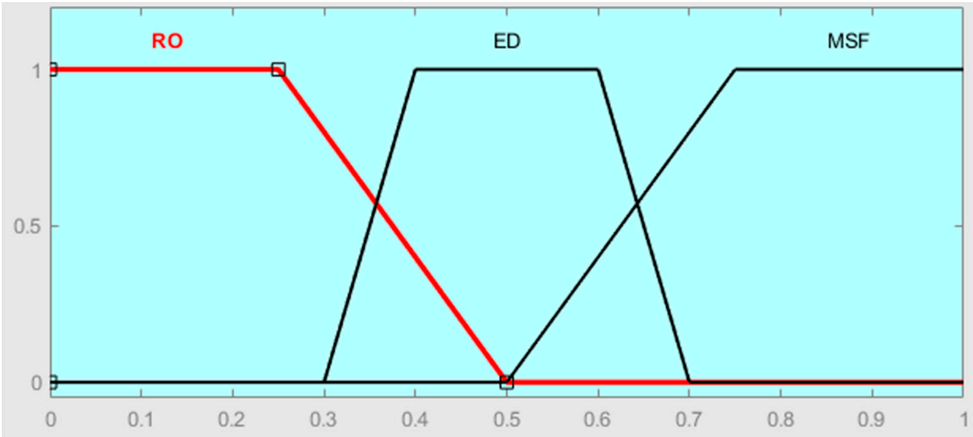

Figure 3. Membership function for output variables of water desalination model.

4.2.2. Rules Adding for Water Desalination Model

After naming the variables and defining the membership functions with appropriate shapes and labels, the next essential step is to formulate the rules. This is the most important phase in building the model. The number of rules required to control a system using fuzzy logic is determined by the following (4) [26,27]:

$$R = m^v \tag{4}$$

where R = number of rules, m = number of membership functions, and v = number of input variables.

For this research, m = 3, and v = 4 then $R = (3)^4 = 81$ rules.

There are 81 different combinations of preconditions that affect the selection of desalination technology. These preconditions have to be stored in the form of if-then rules (called fuzzy rules).

The model includes 81 possible rule combinations, each representing a unique combination of the four main criteria: time (T), cost (C), material and equipment (ME), and design, implementation and operation (DIO). For example, Rule 1 states that if (T), (C), (ME), and (DIO), are all high, then the most suitable desalination technology is (RO). Other rules follow similar structures, adjusting the values of the criteria to determine the best technology. For example, if (T) is medium, (C) is medium, (ME) is high, (DIO) is low then the desalination technology remains (ED). If (T) is medium and (C) is low while other factors are high, then (RO) be the chosen technique, and if (T) is medium (C) is high, (ME) and (DIO) are low, then (MSF) might be the appropriate choice.

These 81 rules, are designed to cover all possible combinations of the input variables, ensuring a thorough and flexible decision-making framework. The fuzzy logic model processes these rules to provide a robust recommendation for the most suitable desalination technology based on the specified criteria, thereby aiding decision-makers in selecting the optimal method tailored to specific conditions. The rules can be added using the rule editor, as shown in the Figure 4.

The rule viewer shows a roadmap of the whole fuzzy inference process; the rule viewer allows for the interpretation of the entire fuzzy inference process at once. It also shows how the shape of certain membership functions influences the overall result. Since it plots every part of every rule, it can become unwieldy for particularly large systems, but for a relatively small number of inputs and outputs, it performs well, the rule viewer of this model is shown in Figure 5.

An Excel model is developed to help the user to determine the required percentage of each group that will be used in the fuzzy model, as shown in Table 12; the user input is an importance scale from 1 to 9, for example, number 9 indicates the highest important factor and number 1 indicates the lowest important factor and so on.

Table 12. Importance scale for input variables in fuzzy desalination model.

Group	No.	Factor	Weights		User Input	Fuzzy Inputs %
Group 1: Time	1.1	Time needed for the construction of the civil works.	15.5%	0.24	4	64.6%
	1.2	Time needed for the installation of electro-mechanical works.		0.25	6	
	1.3	Time needed for the installation of the desalination process.		0.24	5	
	1.4	Required water production rate.		0.27	8	
Group 2: Cost	2.1	Initial costs of desalination process.	24.1%	0.18	9	72.2%
	2.2	Construction cost of the while desalination plant.		0.17	7	
	2.3	Budget and financial limitations of desalination process.		0.18	9	
	2.4	Running cost of the desalination process (excluding energy cost).		0.16	5	
	2.5	Regular maintenance cost.		0.15	2	
	2.6	Running cost limitations of desalination process.		0.16	6	
Group 3: Material and Equipment	3.1	Availability of used material in local market.	30.0%	0.13	7	50.6%
	3.2	Durability of used material.		0.14	7	
	3.3	Experience of engineers/consultants with used material.		0.12	4	
	3.4	Experience of contractors with used material.		0.12	3	
	3.5	Experience of workers with used material.		0.12	3	
	3.6	Availability of supplier in Egypt.		0.12	2	
	3.7	Available storage area for material, equipment, etc.		0.11	1	
	3.8	Land availability.		0.14	8	
Group 4: Design, Implementation and Operation	4.1	Experience of engineers/consultant in applied desalination method.	30.4%	0.13	5	55.6%
	4.2	Experience of contractors in applied desalination method.		0.12	4	
	4.3	Experience of operator in applied desalination method.		0.12	4	
	4.4	Efficiency level of desalinated water.		0.14	9	
	4.5	Unsuitable weather (humidity–temperature).		0.11	1	
	4.6	Health and Safety standards.		0.13	6	
	4.7	Maintenance requirements.		0.12	5	
	4.8	Environmental regulations (brine quantity, brine disposal, etc.).		0.12	5	

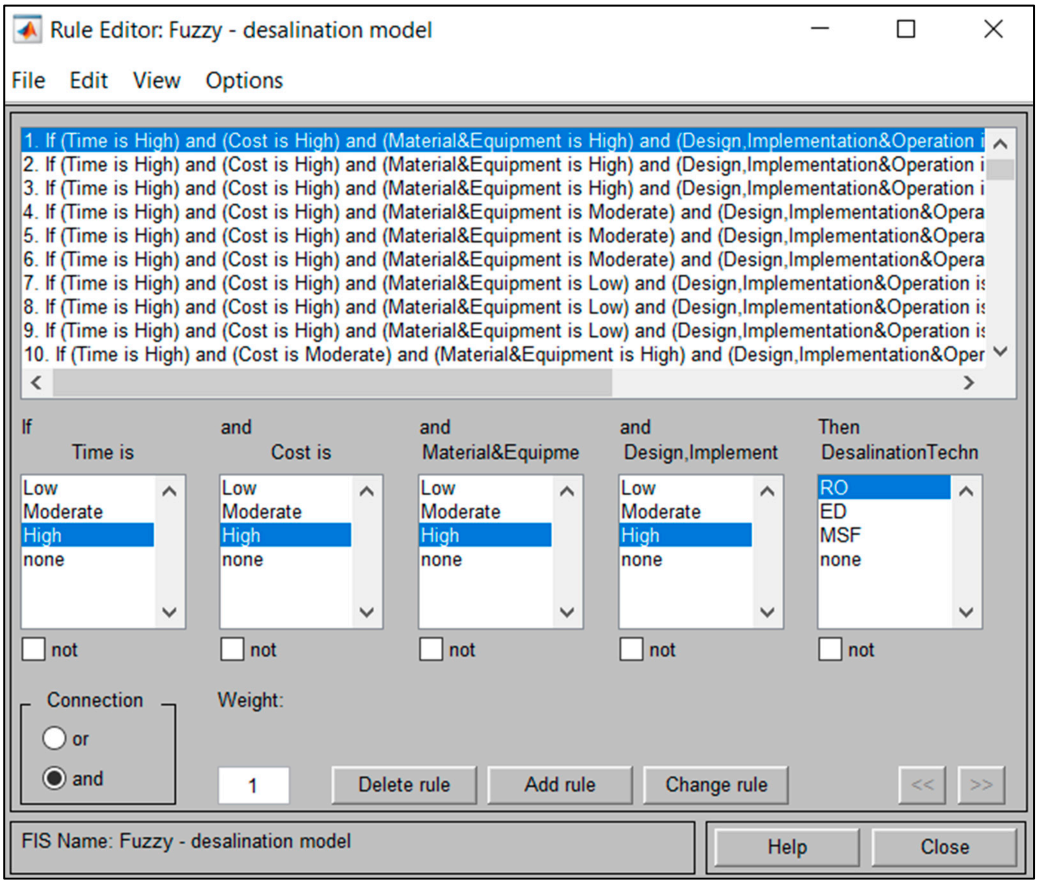

Figure 4. Rules editor for desalination model.

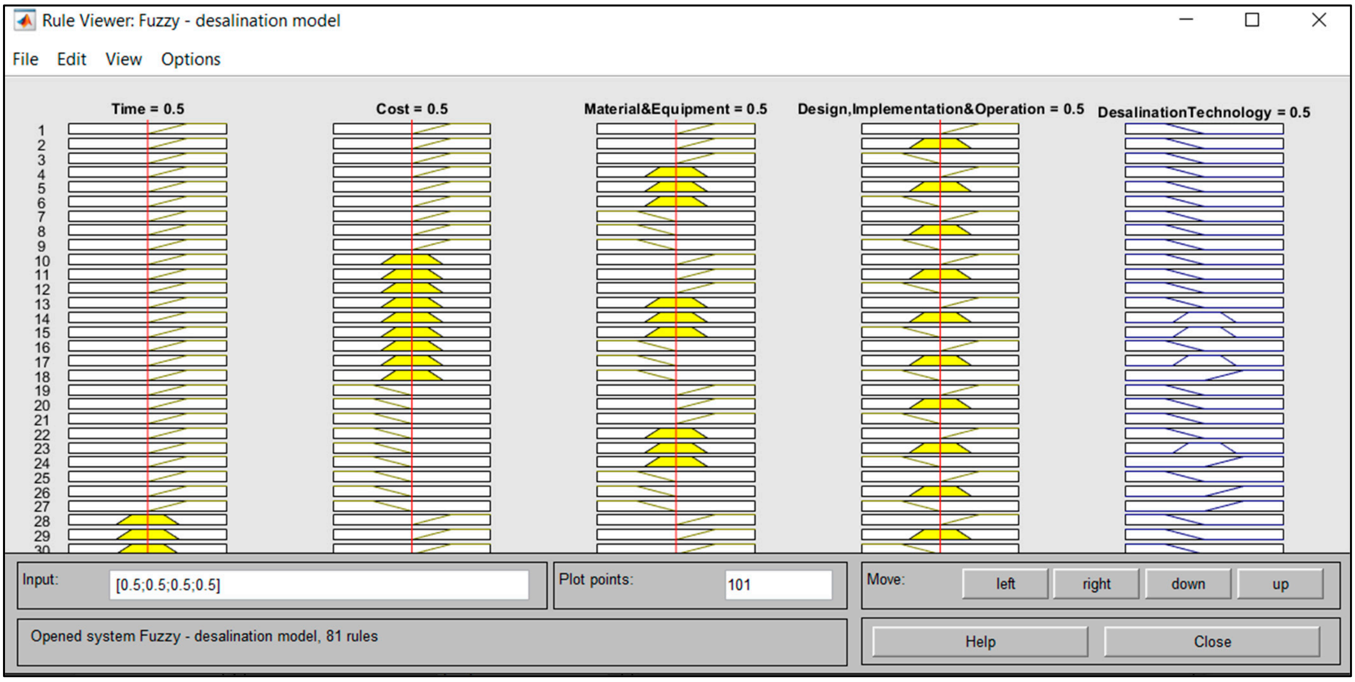

Figure 5. Rule viewer for desalination model.

By entering these values into the model, the output is 0.327, as illustrated in Figure 6. This result showed that RO is the optimal technology with a percentage of 69.3%, followed by ED at 27%, as shown in Figure 7.

The results from both the AHP and fuzzy logic models indicate that reverse osmosis (RO) is the optimal desalination technology. The AHP model determined that RO has the highest score with a result of 49.7%, while the fuzzy logic model showed RO as the most suitable technology with a percentage of 69.3%. This consistency between the two models strengthens the conclusion that RO is the most appropriate choice for desalination technology in the context of this research.

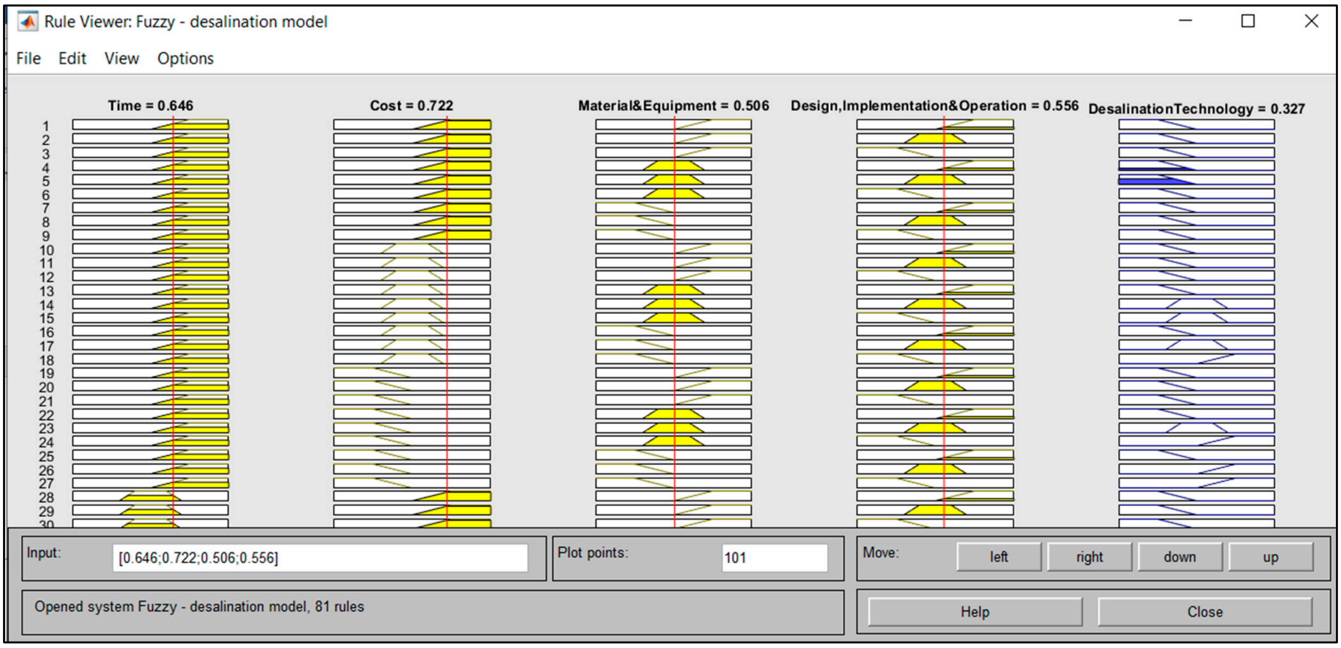

Figure 6. Input and output values for desalination model.

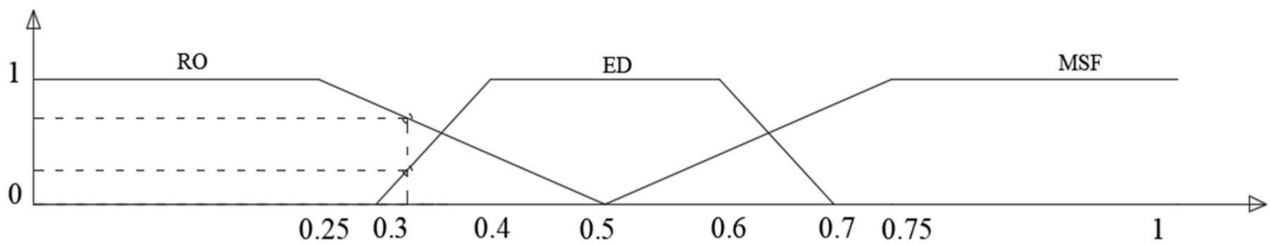

Figure 7. Results of the fuzzy logic model showing optimal desalination technology.

5. Renewable Energy Models Development

Similarly, two models for renewable energy were developed using MCDM techniques. Utilizing the AHP method, a systematic evaluation of criteria and alternatives was conducted to support decision-making in the renewable energy sector. Furthermore, the FL technique was applied to determine the optimal renewable energy technology.

5.1. Analytical Hierarchy Process (AHP) Renewable Energy Model

For this research, the hierarchy consists of four levels. The first level is the main goal of this research, it is "Selection Optimal Renewable Energy Technology"; the second level is the criteria which consists of four groups: time, cost, material and equipment, and methods statement; the third level is sub-criteria, which are time needed for the construction of the civil works of the renewable energy components, time needed for the installation electro-mechanical works, time needed for the installation of energy production, required energy production rate, initial costs of renewable energy provision, budget and financial limitations of renewable energy, energy running cost, regular maintenance cost of renewable energy system, availability of used material in local market, durability of used material, experience of engineers/consultants with used material, experience of contractors with used material, experience of workers with used material, availability of supplier in Egypt, available storage area for material, equipment, etc., land availability for renewable energy system, experience of engineers/consultant in applied renewable energy resource, experience of contractors in applied renewable energy resource, experience of operator in applied renewable energy resource, quality and efficiency level of renewable energy resource, unsuitable weather (humidity–temperature), health and safety standards, maintenance requirements, environmental regulations; and the fourth level is the alternatives, these alternatives are photovoltaic (PV), concentrated solar power (CSP) and wind energy (WE), as shown in Figure 8.

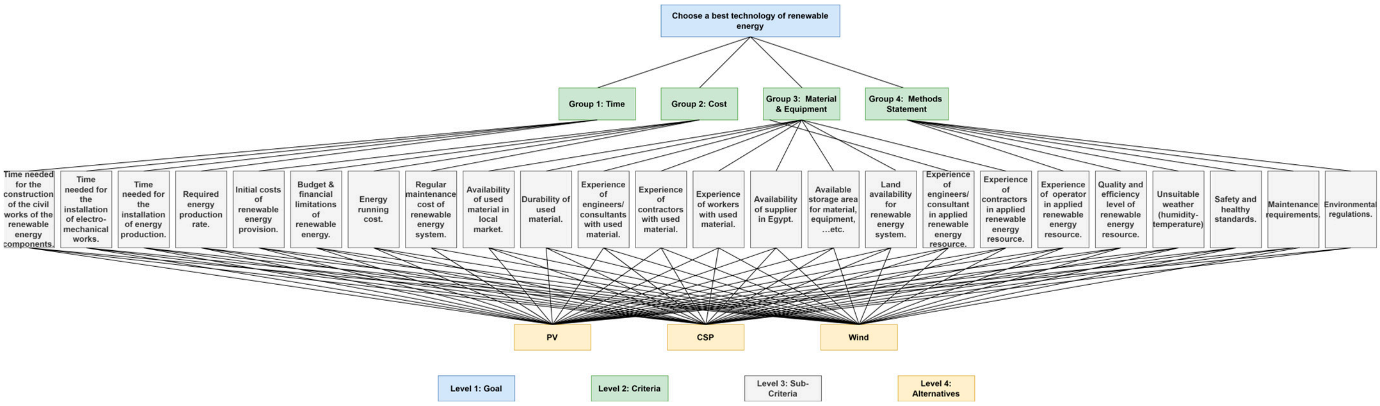

Figure 8. Hierarchy of research problem for renewable energy model.

5.1.1. Construct Comparison Matrices and Pairwise Comparison for Renewable Energy Model

Similarly, the criteria and sub-criteria for the renewable energy model are organized into comparison matrices. Decision-makers evaluate the relative importance of each element concerning the main goal: "Selection of the Optimal Renewable Energy Technique". Each criterion within its group, and subsequently each sub-criterion, is compared pairwise against others to determine their relative importance.

The AHP methodology is employed here as well, using the same scale from 1 to 9 for the pairwise comparisons. The comparison matrices for the criteria and sub-criteria are developed based on the survey data collected from the decision-makers. These matrices enable the combination of judgments into a clear framework, which reflects the relative weights of each criterion and sub-criterion. This systematic approach ensures that all relevant factors are considered in the decision-making process.

Matrix 1, which shows the comparison between the main groups, is presented in Table 13. Matrix 2, which shows the comparison between factors in the "time" group, is presented in Table 14. Matrix 3, which shows the comparison between factors in the "cost" group, is presented in Table 15. Matrix 4, which shows the comparison between factors in the "Material & Equipment" group, is presented in Table 16. Finally, Matrix 5, which shows the comparison between factors in the "methods statement" group is presented in Table 17. Table 18 shows the synthesized matrix for the main criteria and sub-criteria.

Table 13. Renewable energy pairwise comparison matrix for criteria groups.

No	Group	Group 1: Time	Group 2: Cost	Group 3: Material and Equipment	Group 4: Methods Statement
1	Group 1: Time	1	0.25	1	1
2	Group 2: Cost	4.000	1	3	3
3	Group 3: Material and Equipment	1.000	0.333	1	1
4	Group 4: Methods Statement	1.000	0.333	1.000	1

Table 14. Renewable energy pairwise comparison matrix for "Time" group.

No	Factor	Time Needed for the Construction of the Civil Works of the Renewable Energy Components.	Time Needed for the Installation Electro-Mechanical Works.	Time Needed for the Installation of Energy Production.	Required Energy Production Rate.
1	Time needed for the construction of the civil works of the renewable energy components.	1	1	1	0.25
2	Time needed for the installation electro-mechanical works.	1.000	1	1	0.25
3	Time needed for the installation of energy production.	1.000	1.000	1	0.25
4	Required energy production rate.	4.000	4.000	4.000	1

Table 15. Renewable energy pairwise comparison matrix for "Cost" group.

No	Factor	Initial Costs of Renewable Energy Provision.	Budget and Financial Limitations of Renewable Energy.	Energy Running Cost.	Regular Maintenance Cost of Renewable Energy System.
1	Initial costs of renewable energy provision.	1	1	4	3
2	Budget and financial limitations of renewable energy.	1.000	1	4	3
3	Energy running cost.	0.250	0.250	1	1
4	Regular maintenance cost of renewable energy system.	0.333	0.333	1.000	1

Table 16. Renewable energy pairwise comparison matrix for "Material & Equipment" group.

No	Factor	Availability of Used Material in Local Market.	Durability of Used Material.	Experience of Engineers/Consultants with Used Material.	Experience of Contractors with Used Material.	Experience of Workers with Used Material.	Availability of Supplier in Egypt.	Available Storage Area for Material, Equipment, . . . etc.	Land Availability for Renewable Energy System.
1	Availability of used material in local market.	1	0.1667	0.2	0.3333	0.5	0.3333	1	0.125
2	Durability of used material.	6.000	1	1	2	4	2	8	0.5
3	Experience of engineers/ consultants with used material.	5.000	1.000	1	1	3	1	6	0.3333
4	Experience of contractors with used material.	3.000	0.500	1.000	1	1	1	5	0.25
5	Experience of workers with used material.	2.000	0.250	0.333	1.000	1	1	4	0.2
6	Availability of supplier in Egypt.	3.000	0.500	1.000	1.000	1.000	1	5	0.25
7	Available storage area for material, equipment, etc.	1.000	0.125	0.167	0.200	0.250	0.200	1	0.1111
8	Land availability for renewable energy system.	8.000	2.000	3.000	4.000	5.000	4.000	9.000	1

Table 17. Renewable energy pairwise comparison matrix for "Methods Statement" group.

No	Factor	Experience of Engineers/Consultant in Applied Renewable Energy Resource.	Experience of Contractors in Applied Renewable Energy Resource.	Experience of Operator in Applied Renewable Energy Resource.	Quality and Efficiency Level of Renewable Energy Resource.	Unsuitable Weather (Humidity–Temperature)	Health and Safety Standards.	Maintenance Requirements.	Environmental Regulations.
1	Experience of engineers/consultants in applied renewable energy resource.	1	2	1	0.5	0.5	1	3	1
2	Experience of contractors in applied renewable energy resource.	0.500	1	0.5	0.3333	0.3333	0.5	2	1
3	Experience of operator in applied renewable energy resource.	1.000	2.000	1	0.5	0.5	1	3	1
4	Quality and efficiency level of renewable energy resource.	2.000	3.000	2.000	1	1	2	3	2
5	Unsuitable weather (humidity–temperature)	2.000	3.000	2.000	1.000	1	2	3	2
6	Health and Safety standards.	1.000	2.000	1.000	0.500	0.500	1	3	1
7	Maintenance requirements.	0.333	0.500	0.333	0.333	0.333	0.333	1	0.3333
8	Environmental regulations.	1.000	1.000	1.000	0.500	0.500	1.000	3.000	1

Table 18. Synthesized matrix for main criteria and sub-criteria for renewable energy.

No	Factor	Normalized Value							
1	Group 1: Time	0.1429	0.1304	0.1667	0.1667				
2	Group 2: Cost	0.5714	0.5217	0.5000	0.5000				
3	Group 3: Material and Equipment	0.1429	0.1739	0.1667	0.1667				
4	Group 4: Methods Statement	0.1429	0.1739	0.1667	0.1667				
1.1	Time needed for the construction of the civil works of the renewable energy components.	0.1429	0.1429	0.1429	0.1429				
1.2	Time needed for the installation electro-mechanical works.	0.1429	0.1429	0.1429	0.1429				
1.3	Time needed for the installation of energy production.	0.1429	0.1429	0.1429	0.1429				
1.4	Required energy production rate.	0.5714	0.5714	0.5714	0.5714				
2.1	Initial costs of renewable energy provision.	0.3871	0.3871	0.4000	0.3750				
2.2	Budget and financial limitations of renewable energy.	0.3871	0.3871	0.4000	0.3750				
2.3	Energy running cost.	0.0968	0.0968	0.1000	0.1250				
2.4	Regular maintenance cost of renewable energy system.	0.1290	0.1290	0.1000	0.1250				
3.1	Availability of used material in local market.	0.0345	0.0301	0.0260	0.0316	0.0317	0.0316	0.0256	0.0451
3.2	Durability of used material.	0.2069	0.1805	0.1299	0.1899	0.2540	0.1899	0.2051	0.1805
3.3	Experience of engineers/consultants with used material.	0.1724	0.1805	0.1299	0.0949	0.1905	0.0949	0.1538	0.1204
3.4	Experience of contractors with used material.	0.1034	0.0902	0.1299	0.0949	0.0635	0.0949	0.1282	0.0903
3.5	Experience of workers with used material.	0.0690	0.0451	0.0433	0.0949	0.0635	0.0949	0.1026	0.0722
3.6	Availability of supplier in Egypt.	0.1034	0.0902	0.1299	0.0949	0.0635	0.0949	0.1282	0.0903
3.7	Available storage area for material, equipment, etc.	0.0345	0.0226	0.0216	0.0190	0.0159	0.0190	0.0256	0.0401
3.8	Land availability for renewable energy system.	0.2759	0.3609	0.3896	0.3797	0.3175	0.3797	0.2308	0.3611
4.1	Experience of engineers/consultant in applied renewable energy resource.	0.1132	0.1379	0.1132	0.1071	0.1071	0.1132	0.1429	0.1071
4.2	Experience of contractors in applied renewable energy resource.	0.0566	0.0690	0.0566	0.0714	0.0714	0.0566	0.0952	0.1071
4.3	Experience of operator in applied renewable energy resource.	0.1132	0.1379	0.1132	0.1071	0.1071	0.1132	0.1429	0.1071
4.4	Quality and efficiency level of renewable energy resource.	0.2264	0.2069	0.2264	0.2143	0.2143	0.2264	0.1429	0.2143
4.5	Unsuitable weather (humidity–temperature)	0.2264	0.2069	0.2264	0.2143	0.2143	0.2264	0.1429	0.2143
4.6	Health and Safety standards.	0.1132	0.1379	0.1132	0.1071	0.1071	0.1132	0.1429	0.1071
4.7	Maintenance requirements.	0.0377	0.0345	0.0377	0.0714	0.0714	0.0377	0.0476	0.0357
4.8	Environmental regulations.	0.1132	0.0690	0.1132	0.1071	0.1071	0.1132	0.1429	0.1071

The resulting pairwise comparison matrices provide a strong basis for evaluating the alternatives: PV, CSP, and WE. The developed matrices, derived from the collective judgments of the decision-makers, facilitate the identification of the most appropriate renewable energy technique for achieving sustainability in Egypt's energy sector.

5.1.2. Steps for Calculating Consistency in AHP Renewable Energy Model

The same steps outlined in Section 5.1.2 for calculating consistency in the AHP for the desalination model are applied. The priority vector in Table 19 could be obtained by finding the row averages.

Table 19. Calculation and checking consistency for main criteria and sub-criteria for renewable energy.

No	Factor	Row Avg.	Weighted Sum	Consistency Measure	λ	CI	RI	CR	Consistency Check
1	Group 1: Time	0.15166	0.60753	4.00597	4.01036	0.00345	0.8815	0.00391	Consistency OK
2	Group 2: Cost	0.52329	2.10507	4.02275					
3	Group 3: Material and Equipment	0.16253	0.65114	4.00637					
4	Group 4: Methods Statement	0.16253	0.65114	4.00637					0.4%
1.1	Time needed for the construction of the civil works of the renewable energy components.	0.14286	0.57143	4.00000	4	0	0.8815	0	Consistency OK
1.2	Time needed for the installation electro-mechanical works.	0.14286	0.57143	4.00000					
1.3	Time needed for the installation of energy production.	0.14286	0.57143	4.00000					
1.4	Required energy production rate.	0.57143	2.28571	4.00000					0%
2.1	Initial costs of renewable energy provision.	0.38730	1.55544	4.01614	4.01038	0.00346	0.8815	0.00392	Consistency OK
2.2	Budget and financial limitations of renewable energy.	0.38730	1.55544	4.01614					
2.3	Energy running cost.	0.10464	0.41905	4.00482					
2.4	Regular maintenance cost of renewable energy system.	0.12077	0.48360	4.00445					0.4%
3.1	Availability of used material in local market.	0.03204	0.26226	8.18469	8.19875	0.02839	1.4056	0.02020	Consistency OK
3.2	Durability of used material.	0.19208	1.58369	8.24514					
3.3	Experience of engineers/consultants with used material.	0.14216	1.17389	8.25741					
3.4	Experience of contractors with used material.	0.09942	0.81452	8.19248					
3.5	Experience of workers with used material.	0.07319	0.59805	8.17133					
3.6	Availability of supplier in Egypt.	0.09942	0.81452	8.19248					
3.7	Available storage area for material, equipment, etc.	0.02479	0.20003	8.07017					
3.8	Land availability for renewable energy system.	0.33690	2.78829	8.27637					2%
4.1	Experience of engineers/consultants in applied renewable energy resource.	0.11773	0.95749	8.13294	8.11918	0.01702	1.4056	0.01211	Consistency OK
4.2	Experience of contractors in applied renewable energy resource.	0.07300	0.59150	8.10250					
4.3	Experience of operator in applied renewable energy resource.	0.11773	0.95749	8.13294					
4.4	Quality and efficiency level of renewable energy resource.	0.20898	1.70177	8.14315					
4.5	Unsuitable weather (humidity–temperature)	0.20898	1.70177	8.14315					
4.6	Health and Safety standards.	0.11773	0.95749	8.13294					
4.7	Maintenance requirements.	0.04674	0.37666	8.05940					
4.8	Environmental regulations.	0.10911	0.88449	8.10645					1%

The final pairwise comparisons among the renewable energy technology alternatives photovoltaic (PV), concentrated solar power (CSP) and wind energy (WE) are presented in Table 20. Each alternative is compared against the others across all sub-criteria within the established groups of time, cost, material and equipment, and methods statement.

Decision-makers provided judgments that were used to construct the pairwise comparison matrices for each sub-criterion. The consistency of these judgments was verified using the consistency ratio (CR) to ensure reliability. The calculations involved are derived from priority vectors and check the consistency for each factor. The synthesized results combine the weights of all sub-criteria, offering a comprehensive ranking of the desalination technologies. Table 20 summarizes these results, including the consistency ratios to validate the decision-makers' judgments.

Table 20. Final pairwise comparison results and consistency ratios for renewable energy technologies.

No	Factor	PV	CSP	WIND	λ	CI	RI	CR	Consistency Check
1.1	Time needed for the construction of the civil works of the renewable energy components.	0.6333	0.2605	0.1062	3.038715	0.019357	0.5245	0.036906	Consistency OK
1.2	Time needed for the installation electro-mechanical works.	0.6232	0.2395	0.1373	3.018337	0.009169	0.5245	0.017481	Consistency OK
1.3	Time needed for the installation of energy production.	0.6333	0.2605	0.1062	3.038715	0.019357	0.5245	0.036906	Consistency OK
1.4	Required energy production rate.	0.6530	0.2510	0.0960	3.018347	0.009174	0.5245	0.01749	Consistency OK
2.1	Initial costs of renewable energy provision.	0.6025	0.3151	0.0824	3.001982	0.000991	0.5245	0.001889	Consistency OK
2.2	Budget and financial limitations of renewable energy.	0.6555	0.2648	0.0796	3.032534	0.016267	0.5245	0.031015	Consistency OK
2.3	Energy running cost.	0.6555	0.2648	0.0796	3.032534	0.016267	0.5245	0.031015	Consistency OK
2.4	Regular maintenance cost of renewable energy system.	0.7014	0.2132	0.0853	3.032576	0.016288	0.5245	0.031055	Consistency OK
3.1	Availability of used material in local market.	0.6555	0.2648	0.0796	3.032534	0.016267	0.5245	0.031015	Consistency OK
3.2	Durability of used material.	0.5813	0.3092	0.1096	3.003696	0.001848	0.5245	0.003523	Consistency OK
3.3	Experience of engineers/consultants with used material.	0.5813	0.3092	0.1096	3.003696	0.001848	0.5245	0.003523	Consistency OK
3.4	Experience of contractors with used material.	0.5813	0.3092	0.1096	3.003696	0.001848	0.5245	0.003523	Consistency OK
3.5	Experience of workers with used material.	0.5907	0.3338	0.0755	3.014177	0.007088	0.5245	0.013515	Consistency OK
3.6	Availability of supplier in Egypt.	0.6555	0.2648	0.0796	3.032534	0.016267	0.5245	0.031015	Consistency OK
3.7	Available storage area for material, equipment, etc.	0.4720	0.4443	0.0837	3.003696	0.001848	0.5245	0.003523	Consistency OK
3.8	Land availability for renewable energy system.	0.5839	0.3545	0.0616	3.035051	0.017525	0.5245	0.033414	Consistency OK
4.1	Experience of engineers/consultants in applied renewable energy resource.	0.5813	0.3092	0.1096	3.003696	0.001848	0.5245	0.003523	Consistency OK
4.2	Experience of contractors in applied renewable energy resource.	0.5813	0.3092	0.1096	3.003696	0.001848	0.5245	0.003523	Consistency OK
4.3	Experience of operator in applied renewable energy resource.	0.5907	0.3338	0.0755	3.014177	0.007088	0.5245	0.013515	Consistency OK
4.4	Quality and efficiency level of renewable energy resource.	0.7380	0.1676	0.0944	3.014201	0.0071	0.5245	0.013537	Consistency OK
4.5	Unsuitable weather (humidity– temperature)	0.4444	0.4444	0.1111	3	0	0.5245	0	Consistency OK
4.6	Health and Safety standards.	0.4429	0.3873	0.1698	3.018309	0.009155	0.5245	0.017454	Consistency OK
4.7	Maintenance requirements.	0.4429	0.3873	0.1698	3.018309	0.009155	0.5245	0.017454	Consistency OK
4.8	Environmental regulations.	0.4577	0.4160	0.1263	3.009208	0.004604	0.5245	0.008778	Consistency OK

The final results of the renewable energy technology priority comparison with the overall criteria show that the optimal renewable energy technology achieving all criteria is photovoltaic (PV), with a priority of 62%, concentrated solar power (CSP) and wind energy (WE) received second and third rank with a percentage of 29% and 9%, respectively. The results are aligned with the Egyptian strategies for renewable energy future in terms of the availability of materials and equipment, which is really high for PV and then CSP and wind, respectively.

In this research, a model is developed for applying the AHP in a step-by-step way. This model could calculate all the steps illustrated in the AHP methodology section and also present numerical information.

5.2. Fuzzy Logic (FL) Model

The developed model for renewable energy in this research is also based on MATLAB (R2018a). This software was selected for its ease of installation and operation, its fully tested system with a proven track record, and its flexibility and capacity to handle various types of applications.

5.2.1. Data Organization and Sets for Renewable Energy

The first step of the model building is to determine the inputs and the outputs of the model; the next step is to determine the range of all variables by the membership functions, the selected shape of membership functions is the trapezoidal membership function. Input variables of the fuzzy logic model are derived to represent the main criteria affecting the selection of renewable energy technology; the criteria are divided into four sections which are time, cost, material and equipment, and methods statement. Each group represents an input in the fuzzy model, resulting in four inputs. The membership function model for renewable energy is designed as the membership function in water desalination shown in Figure 2.

The output of this model is the optimal renewable energy technology based on the input factors, represented by membership functions, as illustrated in Figure 9. The following points were concluded by industry experts during semi-structured interviews and brainstorming sessions:

- Scores ranging from 0 to 0.5 are considered PV
- Scores ranging from 0.3 to 0.7 are considered CSP.
- Scores ranging from 0.5 to 1 are considered WIND.

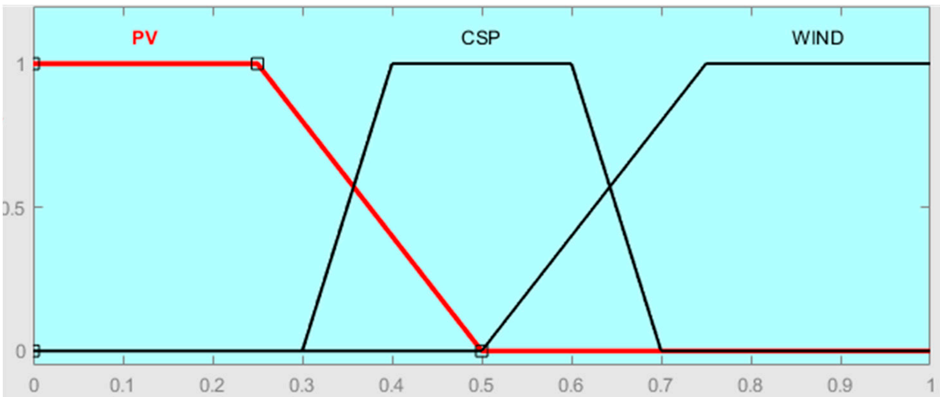

Figure 9. Membership function for output variables of renewable energy model.

5.2.2. Rule Adding for Renewable Energy Model

After naming the variables and defining the membership functions with appropriate shapes and labels, the next essential step is to formulate the rules. This phase is crucial in building the model. The number of rules required to control a system using fuzzy logic is determined by the (4). For this research in renewable energy, $m = 3$, and $v = 4$ then $R = (3)^4 = 81$ rules.

The model includes 81 possible rule combinations, each representing a unique combination of the four main criteria: time (T), cost (C), material and equipment (ME), and methods statement (MS).

For example, rule 1 states that if (T), (C), (ME), and (MS), are all high, then the most suitable renewable energy technology is (PV). Other rules follow similar structures, adjusting the values of the criteria to determine the best technology. For example, if (T) is medium, (C) is medium, (ME) is high, and (MS) is low then the renewable energy technology remains (CSP). If (T) is medium and (C) is low while other factors are high, then (PV) is the chosen technology, and if (T) is medium (C) is high, (ME) and (MS) are low, then (WIND) might be the appropriate choice.

These rules, totalling 81, are designed to cover all possible combinations of the input variables, ensuring a thorough and flexible decision-making framework. The fuzzy logic model processes these rules to provide a robust recommendation for the most suitable renewable energy technology based on the specified criteria, thereby aiding decision-makers in selecting the optimal method tailored to specific conditions. The rules can be added using the rule editor, as shown in Figure 10.

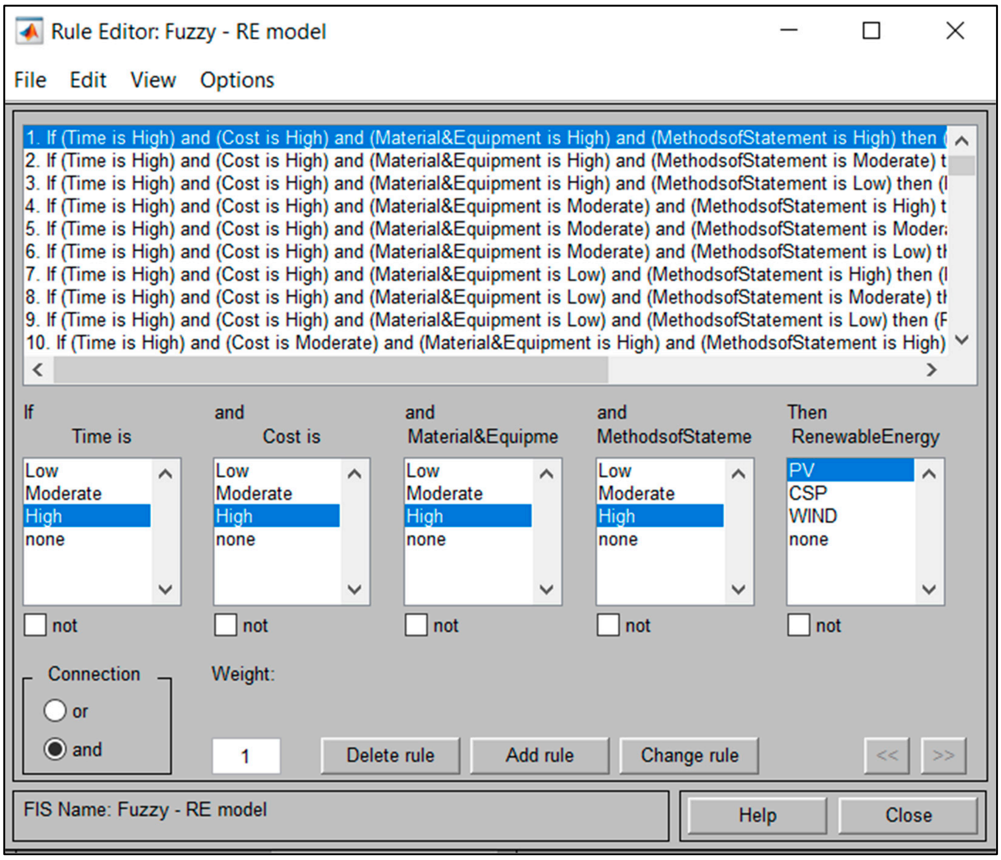

Figure 10. Rules editor for renewable energy model.

The rule viewer shows a roadmap of the whole fuzzy inference process; the rule viewer allows for the interpretation of the entire fuzzy inference process at once. It also shows how the shape of certain membership functions influences the overall result. Since it plots every part of every rule, it can become unwieldy for particularly large systems, but for a relatively small number of input and output, it performs well, the rule viewer of this model is shown in Figure 11.

An Excel model is developed to help the user determine the required percentage of each group that will be used in the fuzzy model, as shown in Table 21; user input is based on an importance scale from 1 to 9, for example, number 9 indicates the highest important factor and number 1 indicates the lowest important factor and so on.

Table 21. Importance scale for input variables in fuzzy renewable energy model.

Group	No.	Factor	Weights		User Input	Fuzzy Inputs %
Group 1: Time	1.1	Time needed for the construction of the civil works of the renewable energy components.	15.4%	0.24	3	42.8%
	1.2	Time needed for the installation electro-mechanical works.		0.24	3	
	1.3	Time needed for the installation of energy production.		0.24	3	
	1.4	Required energy production rate.		0.28	6	
Group 2: Cost	2.1	Initial costs of renewable energy provision.	18.3%	0.27	9	81.9%
	2.2	Budget and financial limitations of renewable energy.		0.26	9	
	2.3	Energy running cost.		0.23	5	
	2.4	Regular maintenance cost of renewable energy system.		0.24	6	
Group 3: Material and Equipment	3.1	Availability of used material in local market.	32.5%	0.11	2	57.1%
	3.2	Durability of used material.		0.14	7	
	3.3	Experience of engineers/consultants with used material.		0.13	6	
	3.4	Experience of contractors with used material.		0.13	5	
	3.5	Experience of workers with used material.		0.12	4	
	3.6	Availability of supplier in Egypt.		0.13	5	
	3.7	Available storage area for material, equipment, etc.		0.10	1	
	3.8	Land availability for renewable energy system.		0.15	9	
Group 4: Methods Statement	4.1	Experience of engineers/consultant in applied renewable energy resource.	33.9%	0.13	6	64.0%
	4.2	Experience of contractors in applied renewable energy resource.		0.12	5	
	4.3	Experience of operator in applied renewable energy resource.		0.13	6	
	4.4	Quality and efficiency level of renewable energy resource.		0.13	6	
	4.5	Unsuitable weather (humidity–temperature)		0.13	6	
	4.6	Health and Safety standards.		0.12	6	
	4.7	Maintenance requirements.		0.12	5	
	4.8	Environmental regulations.		0.12	6	

By entering these values into the model, the output is 0.339, as illustrated in Figure 12. This result showed that PV is the optimal renewable energy technology with a percentage of 64.4%, followed by CSP at 39%, as shown in Figure 13.

Figure 11. Rule viewer renewable energy model.

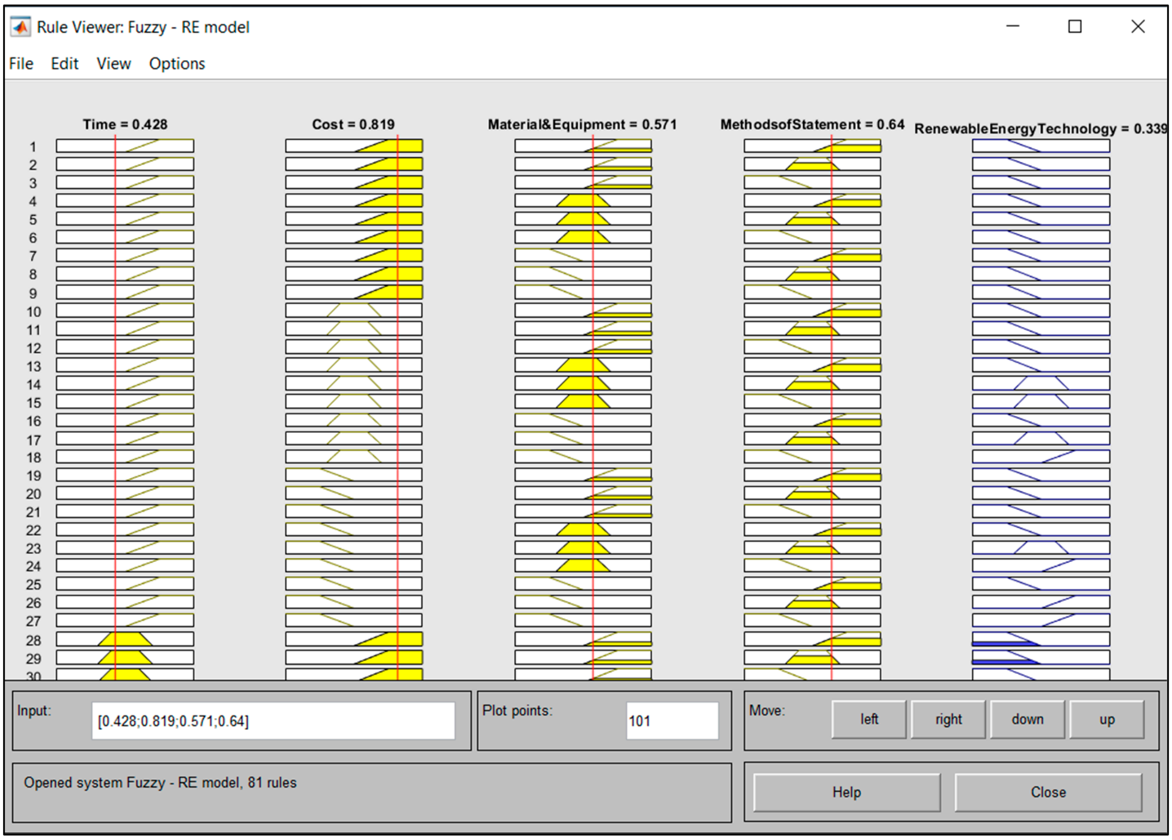

Figure 12. Input and output values for renewable energy model.

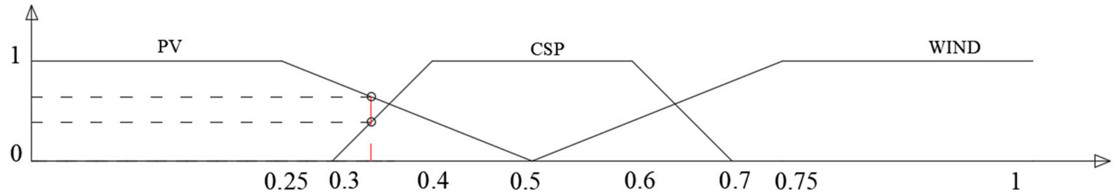

Figure 13. Results of the fuzzy logic model showing optimal renewable energy technology.

The results from both the AHP and fuzzy logic models indicate that photovoltaic (PV) is the optimal renewable energy technology. The AHP model determined that PV has the highest score with a result of 62%, while the fuzzy logic model showed PV as the most suitable technology with a percentage of 64.4%. This consistency between the two models strengthens the conclusion that PV is the most appropriate choice for renewable energy in the context of this research.

6. Discussions and Results

The selection of appropriate desalination and renewable energy technologies is paramount for ensuring the sustainability and efficiency of water–energy nexus projects. The sample size applied to achieve a confidence level above 90% is calculated to be 37 questionnaires, which is sufficient for the type of analysis conducted. While the sample size might appear small, the high level of confidence ensures that the results are statistically significant and reliable for the scope of this study.

This research has successfully applied both the Analytic Hierarchy Process (AHP) and Fuzzy Logic (FL) methodologies to develop robust decision-making models for technology selection in these critical areas.

For desalination technology, the AHP model evaluated 26 sub-criteria across four primary criteria groups, ultimately recommending Reverse Osmosis (RO), Electrodialysis (ED), and Multi-stage Flash (MSF) technologies. Similarly, the AHP model for renewable energy technology assessed 24 sub-criteria to choose between Photovoltaic (PV), Concentrated Solar Power (CSP), and Wind Energy alternatives.

The results from both the AHP and fuzzy logic models indicate that reverse osmosis (RO) is the optimal desalination technology. The AHP model determined that RO has the highest score with a result of 49.7%, while the fuzzy logic model showed RO as the most suitable technology with a percentage of 69.3%. This consistency between the two models strengthens the conclusion that RO is the most appropriate choice for desalination technology in the context of this research.

Similarly, the results from both the AHP and fuzzy logic models indicate that photovoltaic (PV) is the optimal renewable energy technology. The AHP model determined that PV has the highest score with a result of 62%, while the fuzzy logic model showed PV as the most suitable technology with a percentage of 64.4%. This consistency between the two models strengthens the conclusion that PV is the most appropriate choice for renewable energy in the context of this research.

The integration of Fuzzy Logic in parallel with AHP provided a comprehensive approach that accommodates the inherent uncertainty and vagueness in the decision-making process. This dual-method framework enhances the reliability and robustness of the selection process, ensuring that the chosen technologies are well-suited to the specific conditions and requirements of each project.

Our findings highlight the significant potential of combining the AHP and FL methodologies to guide decision-makers in selecting optimal desalination and renewable energy technologies. This integrated approach not only streamlines the decision-making process but also supports sustainable development goals by promoting efficient resource utilization and minimizing environmental impact.

Ultimately, the application of these models offers a systematic, transparent, and adaptable method for addressing the complex challenges associated with technology selection in the water–energy nexus, thereby contributing to the broader objective of sustainable development.

In the future, more artificial techniques will be applied such as neuro-fuzzy, will include other prospectives in the study such as brine disposal, employing nanomaterials in water–energy nexus solutions as in [28], and will employ more indicators such as environmental impact assessment.

7. Conclusions

The selection of suitable desalination and renewable energy technologies is crucial for the sustainability and efficiency of water–energy nexus projects in both marine and inland communities. This research addressed several key gaps in the literature by comparing the performance of the AHP and Fuzzy Logic (FL) in evaluating these technologies. The study applied 26 sub-criteria for desalination and 24 for renewable energy, with Reverse Osmosis (RO) and Photovoltaic (PV) emerging as the optimal technologies. RO achieved scores of 49.7% in the AHP and 69.3% in FL, while PV scored 62% in the AHP and 64.4% in FL, demonstrating consistent results across both methods. By integrating the AHP and FL, this research enhances the decision-making process, offering a comprehensive evaluation of technology options for different locations, including offshore and coastal areas. Additionally, the application of real-world data and models bridges the gap in the literature regarding the simultaneous evaluation of desalination and renewable energy technologies. This integrated approach supports sustainable development by optimizing resource use, reducing environmental impact, and providing a robust framework for decision-making in water–energy nexus projects.

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Nomenclature

AHP	Analytical Hierarchy Process
FL	Fuzzy Logic
MCDM	Multi-Criteria Decision Making Model
MSF	Multi-Stage Flash
RO	Reverse Osmosis
ED	Electrodialysis
PV	Photovoltaics
CSP	Concentrated Solar Power
WE	Wind Energy
CI	Consistency Index
RI	random consistency ratio
CR	Consistency Ratio
SDG	sustainable development goals
SWOT	Strengths, Weaknesses, Opportunities, and Threats
T	Time
C	Cost
ME	material and equipment
DOI	design, implementation and operation
MS	Methods Statement

Appendix A

Table A1. Desalination Projects in Egypt.

Desalination Project	Technology	Advantages	Disadvantages
Al-Arish Desalination Plant	Reverse Osmosis (RO)	- Efficient for small-scale operations - Proven technology worldwide	- High energy consumption - Requires regular maintenance
Al yosr Hurghada Desalination Plant	Reverse Osmosis (RO)	- Provides fresh water - Suitable for coastal areas	- High operational costs - Impact on marine ecosystems
Safaga Desalination Plant	Reverse Osmosis (RO)	- Vital for supporting industrial and mining activities	- Requires a stable energy source - High brine discharge
Sharm El-Sheikh Desalination Plant	Multi-Stage Flash (MSF)	- High capacity - Reliable in extreme environmental conditions	- Very high energy consumption - Requires large infrastructure
Marsa Matrouh Desalination Plant	Reverse Osmosis (RO)	- Critical for supplying drinking water in remote coastal regions	- Susceptible to fouling and scaling - Energy-intensive operation
Ain Sokhna Desalination Plant	Multi-Effect Distillation (MED)	- More energy-efficient compared to MSF - Robust in industrial settings	- Limited scalability - Complex operation and maintenance
Ras Sedr Desalination Plant	Reverse Osmosis (RO)	- Provides fresh water for military and residential use in remote areas	- High cost - Environmental concerns related to brine disposal
Abu Qir Desalination Plant	Multiple Effect Distillation with Thermal Vapor Compression (MED-TVC)	- High energy efficiency - Minimizes brine discharge	- Limited to use in power plant contexts - Requires complex infrastructure

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