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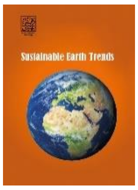

Selection of an optimal alternative for wastewater disposal in combined cycle power plants for semi-arid areas using Analysis Hierarchical Process (AHP)

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ABSTRACT

Living in arid and semi-arid regions is disrupted due to lack of water, and fossil fuel sources of combined cycle thermal power plants play an important role in generating electricity in these areas. The wastewater of these plants often contains various pollutants, including heavy metals, whose discharge to the environment can have a wide range of negative impacts. In this study, a model is presented to select the optimum disposal option of combined cycle power plants in semi-arid areas using the Analysis Hierarchical Process (AHP). The criteria and sub-criteria for determining optimal wastewater disposal in combined cycle power plants were selected based on consultation with experts in three main technical (11 sub-criteria), economical (4 sub-criteria), and environmental (4 sub-criteria). The wastewater disposal option indicated that the environmental and technical criteria score for the evaporation pond is 0.069 and 0.126 and 0.228 and 0.205 for the zero liquid discharge, respectively. The results showed that environmental and then technical and economic criteria are the most important. Also, the most important environmental, technical, and economical sub-criteria are the safety of workers and people, system performance to achieve output standards, and operation and maintenance costs, respectively. To evaluate the model, the proposed method was applied to two combined cycle power plants in Yazd Province with an arid and semi-arid climate in central Iran. The results showed that regarding the characteristics of the power plants and the conditions of the area that is facing water shortage, the best option for disposal of wastewater in both plants is zero liquid discharge.

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1. Introduction

The distinctive climatic and geographical characteristics of arid and semi-arid areas, including limited water resources, significant temperature variations, and susceptibility to drought and flash floods, contribute to their increased vulnerability to natural hazards (El Kenawy, 2024; Masoudi et al., 2025). While arid and semi-arid areas occupy about one-third of the Earth's surface and life is severely affected by the limited access to water resources (Liu et al., 2002), access to great sources of fossil fuel of combined cycle thermal power plants plays a major role in generating electricity in these areas (Wang et al., 2018). Combined cycle power plants are a subset of thermal power plants and are more efficient than steam and gas (Hessari et al., 2018). One of thermal power plants' most important environmental aspects is their impact on water resources (Ahmad, 2017). In addition to high water consumption in these power plants, wastewater from its output is also contaminated with various pollutants during the production process. Monitoring of consumed water and wastewater produced at thermal power plants enables access to qualitative changes and the anticipation of pollution abatement measures (Mousavi et al., 2017). The level and type of pollutants in fossil fuel power plants are dependent on the type of fuel consumed and the method of electricity generation and many pollutants are directly and indirectly from the fuel. The pollutants may also be produced during the main or sub-processes of setting up, producing, and repairing the plant. The power plant wastewater can contain heavy metals, oils, industrial detergents, and other pollutants. For example, high levels of some metals due to the use of alum and lime in the washing process (Saeedi and Amini, 2007), brine of reverse osmosis systems (Saif et al., 2008), operating wastewater and sanitary wastewater can have health and environmental hazards. Also, wastewater treatment plants can be the source of micro-pollutants that are not eliminated during the treatment processes (Saglam, 2016). Disposal of thermal power plants' wastewater into aquatic ecosystems increases water temperature, which, given the many aquatic organisms' sensitivity to water temperature, can have multiple effects on aquatic ecosystems, such as reduced oxygen solubility, increased chemical toxicity, inhibiting biological processes and increasing the vulnerability of aquatic organisms to exposure to chemicals such as ammonia, heavy metals and pesticides, and in some cases even to death of organisms (Madden et al., 2013).

To reduce costs and burden of environmental discharge of pollution (Mudhoo and Sharma, 2011), various methods have been introduced for wastewater disposal in thermal power plants, including condensation and irrigation of high salinity resistant plants (Arnal et al., 2005), injection into wells for disposal of hazardous wastewater (Saripalli et al., 2000), evaporation pond (Glater and Cohen, 2003), deep injection for the disposal of salt wastewater (Gabelich et al., 2011), the use of biosorbents for the removal of toxins (Basso et al., 2002), chemical and electrochemical sequestration for the removal of heavy metals and ion exchange (Bashir et al., 2019; Bergamasco et al., 2024).

The most appropriate waste disposal method is selected based on costs and factors such as the volume of waste and the concentration of pollutants and effluent discharge standards to the environment (Mudhoo and Sharma, 2011), while different criteria should be considered to cover different environmental, technical and economic aspects. Since the relationship between these criteria is complex, a method should be used that simultaneously considers the relationship between different considerations for selecting the optimal option. Meanwhile, the Hierarchical Analysis Process (AHP) has this capability.

The analysis hierarchical process (AHP) is one of the most efficient multi-criteria decision-making (MCDM) techniques first introduced by Saaty (1980) and is based on the human's inherent ability to make correct decisions (Saaty, 1980; Saaty, 1990). This method is a theory of measurement through paired comparisons and relies on expert judgment to extract priorities. These comparisons are made using the Absolute Arbitrage Scale and show how one element overcomes another concerning one particular characteristic (Saaty, 2008). This method has been used for a wide range of problems such as environmental risk evaluation (Topuz and van Gestel, 2016), selection of the appropriate site for wastewater discharge (Li et al., 2017), appropriate wastewater treatment options (Kalbar et al., 2012), industrial wastewater treatment (Dabaghian et al., 2009), and performance evaluation of municipal wastewater treatment plants (Xiaoxin et al., 2018). Various studies have been carried out on the use of decision-making tools in determining the optimal processes of wastewater treatment systems. The application of the analytical hierarchical process (AHP) and the analysis network process (ANP) to evaluate different wastewater treatment systems was investigated (Bottero et al., 2011). Phytoremediation has been selected as the most sustainable wastewater treatment technology. In the other study, the most suitable option for the treatment of heavy polyethylene unit wastewater in the petrochemical center of Arak using the analysis hierarchical process (AHP) was investigated The sequential batch reactor (SBR) method was selected as the most appropriate option for wastewater treatment (Bagheri et al., 2017; Ahmed and Fathy, 2024). Also, investigated the sustainability of textile wastewater management using the fuzzy analytical hierarchy process (FAHP) method. The FAHP method was implemented to identify the best-selected criteria for the sustainability of textile wastewater management (Pattnaik and Dangayach, 2019). Iran is one of the countries in the arid and semi-arid region and in many parts of the country, there are many problems with water supply. Therefore, choosing the method of wastewater disposal and using unconventional water resources is considered essential. Although many studies have been conducted on the use of a variety of decision-making methods in the selection of a wastewater disposal method, a comprehensive study that examines semi-arid regions of Iran based on various criteria and sub-criteria is very rare. Also, in this study, a model is presented for selecting the optimal option of disposal of wastewater in combined cycle power plants in semi-arid areas based on technical, economic, and environmental criteria using the AHP model.

2. Material and methods

2.1. Decision criteria

The criteria and sub-criteria of determining optimal wastewater disposal in combined cycle power plants were selected based on consultation with experts, literature review, and reports on designing, implementing, and utilizing different wastewater disposal processes in power plant projects and grouped into three main technical (11 sub-criteria), economical (4 sub-criteria), and environmental (4 sub-criteria) categories (Fig. 1).

2.2. Wastewater disposal processes

Determining the main criteria for wastewater disposal options in combined cycle power plants is of great importance, and their selection and evaluation are based on studies and summaries of the design, implementation, and operation of these processes in power plants and wastewater treatment plants. The eight common processes were selected for the disposal of thermal power plant wastewater including discharge into surface water, well injection, evaporation pond, chemical precipitation, RO and Evaporation Pond, zero liquid discharge, brine concentrator, and electrode deionization. Fig. 1 shows a hierarchy tree, including its criteria, sub-criteria, and normalized weights, for wastewater treatment options of combined cycle thermal power plants.

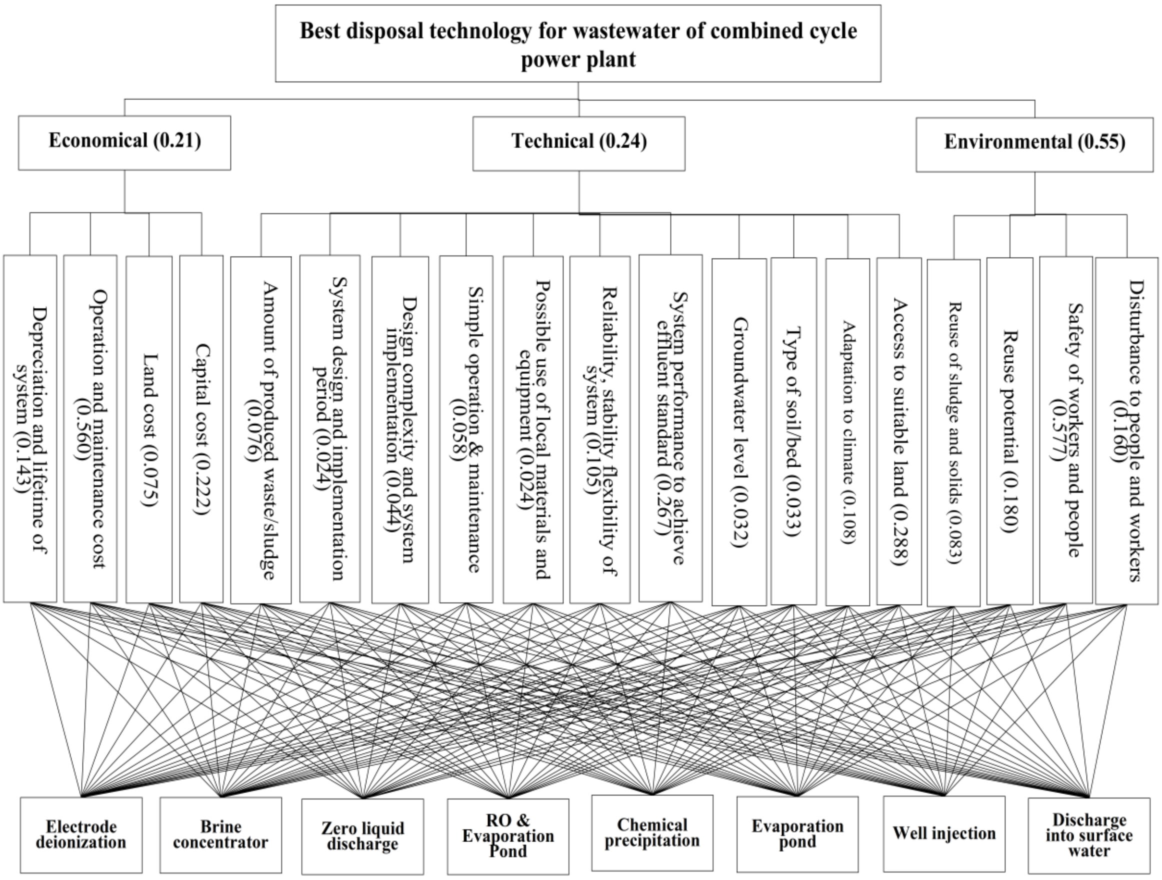

Fig. 1. Hierarchical tree and wastewater disposal options in combined cycle power plants.

2.3. Analytical Hierarchy Process (AHP)

The first step in the AHP process is to break down the problem into a hierarchical structure including goals, criteria, sub-criteria, and options. In this hierarchy, there are no criteria for decision-making, and each of the criteria has its own criteria. Then using this structure, pairwise comparisons between elements were made by the decision-makers. Table 1 shows the hour for judging scores between the two elements on a scale of 1 to 9. At this point, the decision-makers, at each judgment, compare the two elements to their immediately higher-level element and present a score based on Table 1 for the degree of superiority of the first-second option. In the third part of the process, the formulation of concurrent matrices based on the data collected in the previous step is performed as a preliminary to the calculation of weights at this stage. To do this, the elements to be judged are arranged in rows and columns of the agreed matrix. In the next step, to eliminate different measurement scales, the above-normalized matrix and the mean elements of each row will provide the weight of the corresponding option. Choosing the right options using the AHP process was done by pairwise comparisons of criteria against each other and comparing each criterion with the desired options after entering the target, criteria, and options with Expert Choice 11 software. The software also calculated the incompatibility rate and sensitivity analysis. Sensitivity analysis involves recalculating the ranking of options by modifying the weight of each criterion. For this operation, while the weights of the other criteria are constant, the weight of one criterion gradually increases or decreases. After performing a sensitivity analysis, the ranking of options may change. All possible changes can be analyzed by Expert Choice software with a powerful sensitivity analysis model (Aragones-Beltran et al., 2009; Demir et al., 2024). After completing the questionnaires by industry elites and active universities in the field of power plant wastewater management, weights of criteria and sub-criteria were extracted and the mean of expert opinions was identified as the weight of each parameter and these results were used in subsequent hierarchies.

Table 1. 9 hourly rating scale.

Description	Intensity of importance
Absolutely More Important	9
Very Much More Important	7
Much More Important	5
Somewhat More Important	3
Equal Importance	1
Intermediate Values	2, 4, 6, and 8

2.4. Model performance evaluation

To evaluate the model's efficiency, two combined cycle power plants in the central and northwest of Yazd Province were selected (Fig. 2). Yazd Province, with an area of 73765 km², is located in the center of the Iranian plateau on the dry belt of the northern hemisphere and between the deserts of the plateau and has an arid and semi-arid climate. This province is one of the most critical provinces of Iran in terms of access to water resources. The combined cycle power plant in the central part with a capacity of 492 MW (2 gas units of 166 MW gas and one 160 MW steam unit) is located on 100 hectares of land adjacent to a pelletizing plant. The main fuel is natural gas and the support fuel is diesel. The Northwest Power Plant is located 25 kilometers northwest of Yazd, on a 50-h land in Iran with a capacity of 484 MW including two 160 MW gas units and a 160 MW steam unit on a 50-hectare land 25 kilometers northwest of Yazd. At both plants, the chemical wastewater enters the evaporation pond after neutralization and pH adjustment.

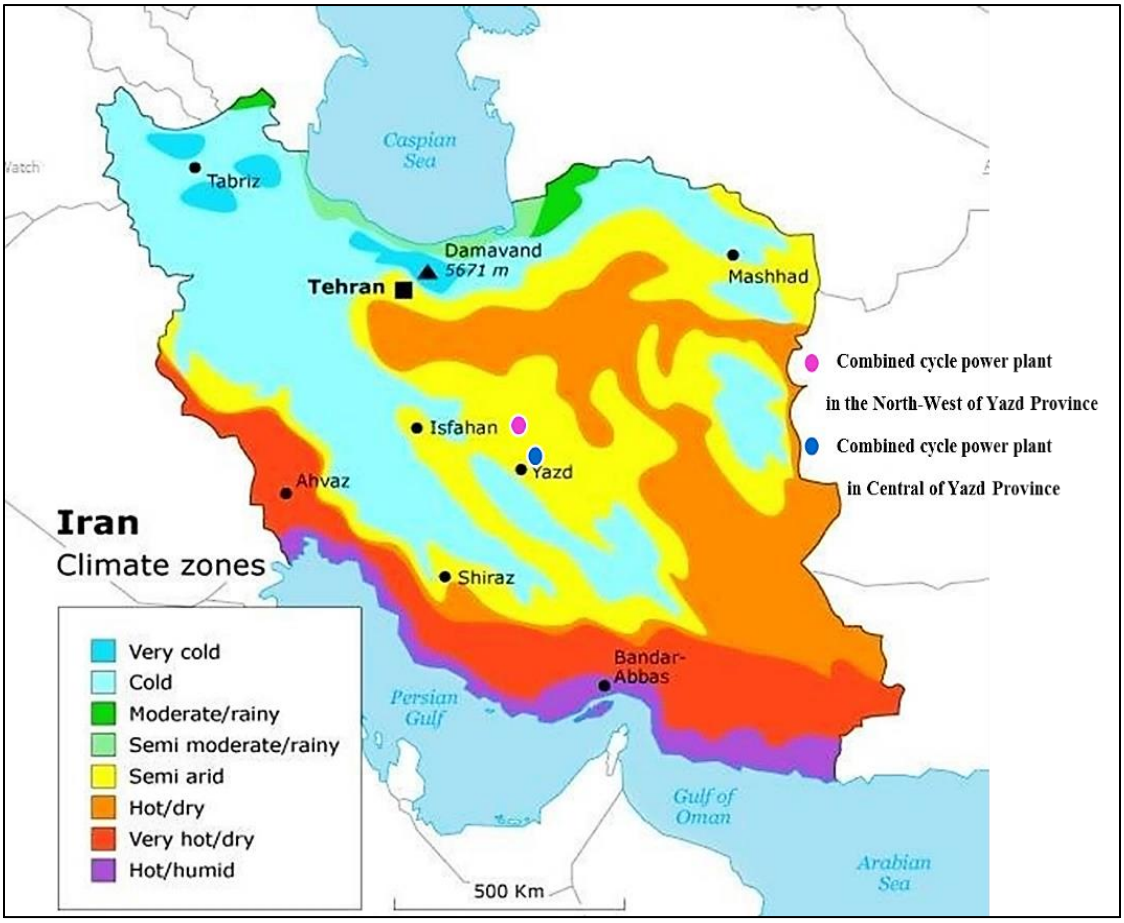

Fig. 2. Location of studied power plants in Yazd province.

3. Results and discussion

3.1. Weight of criteria and sub-criteria

The hierarchical analysis showed that from the expert point of view, environmental criterion (w=0.55) was more important than the technical (w=0.24) and economic (w=0.21) criteria. Also, the environmental safety of workers and people sub-criterion and the economical sub-criterion of cost of operation and maintenance each mattered more than the sum of their sub-criteria. In contrast, since there has been little application to sludge and solids from wastewater disposal processes, this environmental sub-criterion has gained little weight.

In the economic sector, the sub-criterion of cost of land gained little weight, while in the technical sector access to suitable land is very important which indicates that for land-based processes, the availability of suitable land is more than the cost of purchase. In technical sub-criteria, access to suitable land and system performance to achieve output standards are the most important factors affecting decision-making. In contrast, technical constraints, which are removable by payment, often gain little weight. The criteria, sub-criteria, and their normal weight are shown in Fig. 1.

3.2. Suitable option for wastewater disposal

Table 2 shows the relative weight of the options to the criteria and sub-criteria. The study of options shows that simple processes such as discharge into surface water, despite economical superiority, are not often scored high on environmental and technical aspects such as safety of workers and people, system reliability, stability, and flexibility. In contrast, zero liquid discharge processes, chemical precipitation, discharge into surface water, electrode deionization, evaporation pond, RO & evaporation pond, well injection, and brine concentrator obtained the highest weights, respectively.

Table 2. The relative weight of options relative to criteria and sub-criteria.

Criteria and Sub-Criteria	**Discharge into surface water**	**Well injection**	**Evaporation pond**	**Chemical precipitation**	**RO & Evaporation Pond**	**Zero liquid discharge**	**Brine concentrator**	**Electrode deionization**
Environmental	0.088	0.075	0.069	0.186	0.092	0.228	0.100	**0.162**
Disturbance to people and workers	0.275	0.225	0.034	0.089	0.089	0.131	0.055	**0.102**
Safety of workers and people	0.051	0.049	0.076	0.207	0103	0.215	0.120	**0.179**
Reuse potential	0.104	0.066	0.019	0.195	0.031	0.346	0.051	**0.187**
Reuse of sludge and solids	0.020	0.019	0.192	0.153	0.102	0.376	0.093	**0.055**
Economical	0.392	0.182	0.140	0.107	0.058	0.037	0.033	**0.050**
Capital cost	0.500	0.167	0.089	0.092	0.063	0.022	0.028	**0.039**
Land cost	0.332	0.051	0.018	0.145	0.049	0.197	0.073	**0.145**
Operation and maintenance cost	0.386	0.255	0.139	0.096	0.049	0.017	0.025	**0.033**
Depreciation and lifetime of a system	0.331	0.023	0.258	0.140	0.093	0.037	0.045	**0.073**
Technical	0.128	0.048	0.126	0.180	0.099	0.205	0.074	**0.139**
Access to suitable land	0.139	0.006	0.020	0.230	0.041	0.245	0.073	**0.186**
Adaptation to climate	0.052	0.029	0.035	0.228	0.092	0.250	0.085	**0.229**
Type of soil/bed	0.125	0.023	0.053	0.198	0.093	0.189	0.130	**0.189**
Groundwater level	0.153	0.018	0.055	0.207	0.085	0.172	0.107	**0.203**
Performance to achieve effluent standard	0.022	0.021	0.193	0.104	0.166	0.330	0.077	**0.087**
Reliability, stability flexibility of the system	0.035	0.024	0.285	0.247	0.142	0.085	0.077	**0.106**
Possible use of local materials and equipment	0.290	0.186	0.245	0.131	0.063	0.021	0.022	**0.042**
Simple operation & maintenance	0.286	0.064	0.325	0.137	0.089	0.024	0.026	**0.050**
Design complexity and system implementation	0.344	0.033	0.219	0.163	0.106	0.030	0.028	**0.077**
System design and implementation period	0.366	0.092	0.140	0.105	0.105	0.040	0.046	**0.105**
Amount of produced waste/sludge	0.484	0.155	0.058	0.058	0.064	0.058	0.059	**0.063**
Total score	0.143	0.085	0.093	0.172	0.088	0.194	0.084	**0.140**

Figs 3 and 4 show the sensitivity and importance of the criteria for prioritizing wastewater disposal options for combined cycle power plants. Therefore, using these Figures can determine the factors affecting the rating and selection of wastewater disposal options. Fig. 3 shows the sensitivity analysis based on efficiency to the main objective or, in other words, the rating of different wastewater disposal options to the criteria. As it is clear, the process of zero liquid discharge with a score above 0.5 is more sensitive to environmental and technical criteria than other sub-criteria. In contrast, in the economic criteria, the process of discharge into surface waters with a score greater than 0.9 was more sensitive than other sub-criteria. Also, in the sensitivity analysis based on the efficiency of the main objective, zero liquid discharge processes (score of 0.5) and chemical precipitation (score of 0.4) showed the highest sensitivity compared to other processes.

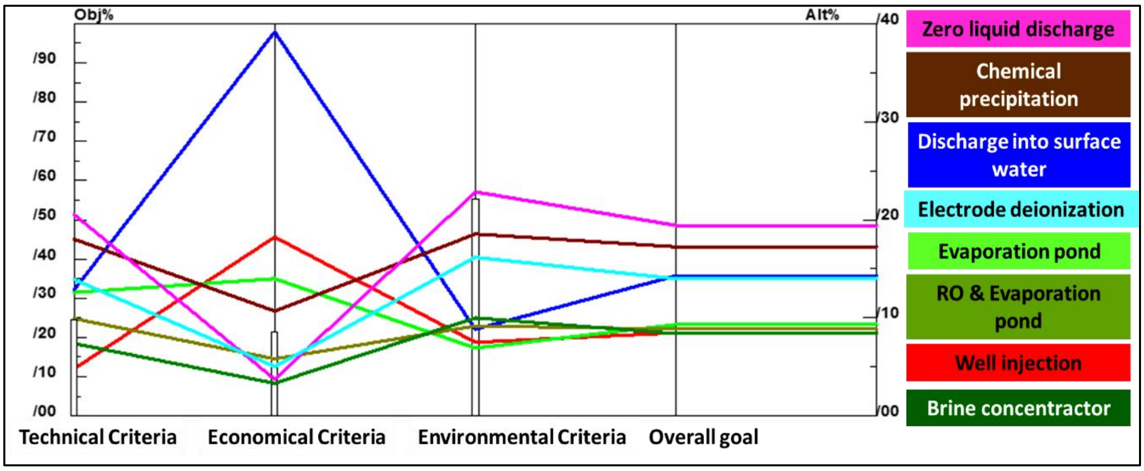

Fig. 3. Sensitivity analysis performance-based relative to overall purpose.

Fig. 4 shows the sensitivity analysis based on the dynamics of the main objective, with the highest sensitivity for environmental (0.55), then technical (0.24) and economical (0.21) criteria, respectively. In other words, the environmental criterion had the most effect on prioritizing processes and choosing the optimal process of wastewater disposal in combined cycle power plants. Also, the prioritization of options shows that the process of zero liquid discharge (19.4%) is the first, followed by chemical precipitation processes (17.2%) and discharge into surface water (14.3%).

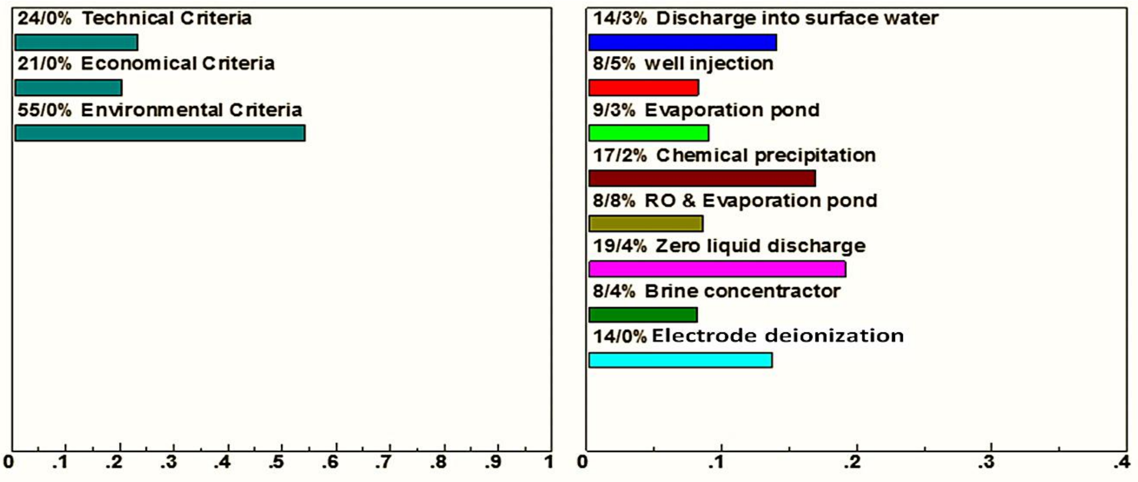

Fig. 4. Sensitivity analysis dynamics-based relative to overall purpose.

In this study, a decision-making model was developed based on AHP and based on technical, economic, and environmental criteria to select the optimal option of wastewater disposal in combined cycle power plants in semi-arid areas and used for two power plants in Yazd with semi-arid climate. The results show that the appropriate wastewater disposal options are zero liquid discharge, chemical precipitation, discharge into surface water, electrode deionization, evaporation pond, RO & evaporation pond, well injection, and brine concentrator. The inconsistency was 0.05 which indicates the compatibility of the comparisons.

Zero liquid discharge is a recycling-based wastewater disposal and reuse system with low wastewater discharge. It also reduces the risk of pollution caused by wastewater discharge and maximizes water use efficiency (Tong and Elimelech, 2016). For this reason, this option could be a suitable method for the disposal of combined cycle power plants in arid and semi-arid areas facing water shortages. The efficiency-based sensitivity analysis to the main objective showed that the zero liquid discharge option is highly sensitive to environmental and technical criteria and less sensitive to economic criteria.

These results are consistent with the results of other studies that stated that the sensitivity of the optimal wastewater disposal option to the technical criterion and low to the process efficiency criterion and that the optimal wastewater disposal process had the highest sensitivity to the environmental criterion (Heidari et al., 2016; Hosseinzadeh Kalkhoran et al., 2017; Renfrew et al., 2024).

In sensitivity analysis based on dynamics to the main objective, the highest sensitivity was related to environmental, technical, and economic criteria, respectively. In the environmental criterion of 0.55, the sub-criteria of the safety of workers and people and the reuse potential of wastewater has the highest score, and in general, this criterion has the highest score in deciding and selecting the optimal option for wastewater disposal. In contrast, the other study that investigated the best option among the five wastewater treatment methods considered the economical criterion with a score of 0.6 as the most important factor affecting the final decision inconsistent with the results of the present study (Ouyang et al., 2015). This could be due to water shortage and importance and the fragility of the environment in arid and semi-arid areas, which makes environmental sub-criteria such as water recycling more important.

Currently, the wastewater discharge method is the evaporation pond in both combined cycle power plants in the central and northwest of Yazd Province. In the combined cycle power plant in the central part of Yazd Province, according to the data analysis, the measured parameters in the wastewater of condensed water treatment plants, main and additional cooling systems, and boiler have been reported as standard. Therefore, separation and disposal of wastewater and non-mixing in evaporative ponds are necessary. Therefore, it is possible to make changes in the design of wastewater to evaporation ponds and to recyclable wastewater, which amounts to 54 m^3/day, to be used to return to the treatment plant for raw water or agricultural uses. Also, according to AHP results, the zero liquid discharge process was selected as the optimal solution considering the quality of plant wastewater in the central part of Yazd Province and to minimize hazardous waste and recycling due to its location in a semi-arid climate compared to the evaporation pond method would be justified. The results of acid wastewater analysis at the start-up stage of Yazd Northwest Power Plant show that the wastewater treatment plant contains high and diverse amounts of heavy metals, petroleum compounds, and total soluble solids. Regarding the quality of the wastewater and given that the northwestern power plant of Yazd is also in a semi-arid climate, the use of a zero liquid discharge system as an optimal option is justified compared to the current evaporation pond method.

A comparison between the current method and the proposed wastewater disposal option shows that the environmental and technical criteria score for the evaporation pond is 0.069 and 0.126 and 0.228 and 0.205 for the zero liquid discharge, respectively. Due to its high safety and efficacy and the ability to recycle water, the option of zero liquid discharge is preferred over the evaporation pond method.

4. Conclusion

Regarding the variety of criteria and sub-criteria that affect the choice of wastewater disposal options in power plants, the use of MCDM techniques is inevitable. In this study, AHP based on technical, economic, and environmental criteria was used to select the appropriate wastewater disposal option in combined cycle power plants in semi-arid areas. Among the evaluated criteria, the environmental criterion and safety of workers and people sub-criteria and reuse potential of wastewater utilization have the most effect. Then, there is the technical criterion with system performance to achieve effluent standard sub-criteria and access to suitable land and the economical criterion with the sub-criteria of operation and maintenance cost and capital cost. Also, the priority of wastewater disposal options for these types of power plants in semi-arid areas is zero liquid discharge processes, chemical precipitation, discharge into surface water, electrode deionization, evaporation ponds, RO & evaporation pond, well injection, and brine concentrator. This shows that water shortage and the fragility of the environment in these areas make the options that have the most water recycling and the least discharge to the environment, despite the higher cost and greater technical complexity.

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