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Performance evaluation with grey relational analysis, two-stage data envelopment analysis, and G-SAW methods: Case study in electricity distribution companies in Iran

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Abstract
Various approaches are used to evaluate the firms' performance. Grey Relational Analysis is one of the multiple-attribute decision-making methods, and Data Envelopment Analysis is used to calculate efficiency. Given the important role of electricity distribution companies in economic development, this study evaluates the performance of 35 electricity distribution companies in Iran using three methodologies: Grey Relational Analysis (GRA), the integrated Grey-Simple Additive Weighting (G-SAW) method, and Data Envelopment Analysis (DEA) with a two-stage model incorporating desirable and undesirable outputs. This research aims to identify the most effective approach for performance evaluation in the electricity sector. To achieve this, the GRA and G-SAW methods were applied to assess companies based on multiple criteria, including cost, productivity, and waste. DEA measured efficiency in two stages, considering both desirable and undesirable outputs. Results indicate that GRA and DEA offer more optimistic evaluations than G-SAW. GRA scores ranged from 0.486 to 0.764, G-SAW scores from 0.428 to 0.648, and DEA scores from 0.288 to 0.957. Sistan et Baluchistan and Qom distribution units demonstrated high efficiency, while Shiraz ranked the lowest in GRA and DEA and the third lowest in G-SAW method.

Keywords: Grey Relational Analysis, Two-stage Data Envelopment Analysis, Electricity Distribution Companies.

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1. Introduction

Electricity is one of the most critical infrastructure components and is necessary for any nation's growth. Due to increasing population and economic growth, developing appropriate electricity infrastructure is crucial for the long-term prosperity of economies [1]. Therefore, evaluating the performance of electricity distribution companies is considered one of the most critical issues among regulators and policy-makers [2]. To assess the performance of an organization, different criteria are used: such as efficiency, effectiveness, profitability, productivity, etc. In many complicated systems, various parameters impact the system simultaneously. Thus, in decision-making process we confront multiple criteria. Multiple-criteria decision-making (MCDM) is designed to investigate different alternatives among diverse criteria and conflicting objectives. It is employed to tackle complex problems through the application of multiple methods. By leveraging technical expertise, these methodologies assist decision-makers in making more logical and sensible decisions [3]. Each technique may generate similar or different outcomes. Consequently, MCDM methods help solve decision problems that typically necessitate considering different aspects [4].

Various methods are used to solve multi-criteria problems, such as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), the Analytic Hierarchy Process (AHP), and the Simple Additive Weighting (SAW) method [5]. However, sometimes the grey relationships between indicators, difficulty in collecting practical data or lack of sufficient information are the problems researchers may face in many systems. Thus, to avoid data aggregation and wasting resources, grey relational analysis is an appropriate methodology in these cases [6]. As is well known, GRA has been used extensively in many research studies in recent years. Therefore, we decided to integrate it with other MCDM methods. G-TOPSIS, G-AHP, G-COPRAS and different methods used to evaluate the performance of companies. But the integration of GRA and SAW has not been used yet in performance measurement.

A relatively new non-parametric method introduced by Charnes, Cooper, and Rhodes in 1978, known as Data Envelopment Analysis (DEA), is utilized in many fields to measure the efficiency of decision-making units (DMUs) [8]. In traditional DEA models, the process treated as a black box, where the inputs and outputs are the focus of investigation and inside the box is typically ignored. In contrast to the black-box approach, a practical system often has a network structure, and it is crucial to provide a consistent analysis tool for both individual and overall efficiencies of the network system. In recent years, many researchers have studied various DEA models for measuring the efficiencies of two-stage systems [9]. Also, in some real occasions, the intermediate or output measures may be undesirable, and we should reduce these products. Modeling such two-stage systems with undesirable outputs is an interesting and important subject in the context of DEA [10].

While GRA, SAW, and DEA have each been used to evaluate performance in various sectors, limited research has employed a structured integration of GRA and SAW (G-SAW) specifically for public utility companies. Furthermore, two-stage DEA models with both desirable and undesirable outputs have rarely been applied in electricity distribution systems, especially in developing countries.

Therefore, this study proposes a novel hybrid framework that combines GRA, a newly designed G-SAW model, and a two-stage DEA approach to evaluate the performance of electricity distribution companies. This combination enables a more comprehensive, comparative, and reliable evaluation system that can support policy-makers in making informed and effective decisions for the electricity sector.

The remainder of this paper is organized as follows. Section 2 provides a brief review of related background information involving DEA and GRA. Section 3 explains the methodologies used in this paper. In Section 4, results, and the conclusions and recommendations presented in the last section.

2. Literature review

2.1.Grey theory

During decision-making, decision makers try to gather as much information as possible through surveys. Since collecting all information is impractical, decisions are often made with incomplete information, referred to as a grey process [11]. Grey system theory, developed by Professor Deng in 1982, addresses cases with partly known and partly unknown information. Systems can be classified into three types: white systems, black systems, and grey systems. Information in white systems is known, black systems have unknown information, and grey systems have partially known information [6]. Grey system theory is a measurement tool in situations with incomplete and uncertain information. It is applied in various fields such as management, supply chain selection, and engineering. Techniques within this theory include grey control, grey relational analysis, grey forecasting, and grey decision-making. The concept of grey systems is illustrated in Figure 1.

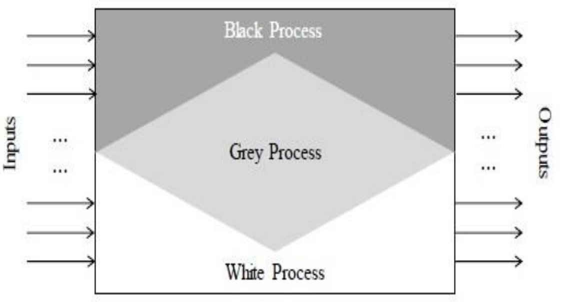

Figure. 1. Grey sys [6]

Grey relational analysis (GRA), introduced by Professor Deng, is the most extensively utilized component of grey system theory. GRA is effective for addressing intricate interconnections among multiple elements and variables. It is also applied in resolving Multiple Attribute Decision Making (MADM) issues. GRA tackles these problems by amalgamating various performance attribute values into a single value [12]. The procedures for grey relational analysis detailed in the following section.

2.1.1. Data normalization

The GRA approach comprises four steps, with data normalization as the initial step. This step is necessary when the units of data sequences differ. Data pre-processing converts the original data sequence into a comparable format. To avoid incorrect results in the final analysis, data must be normalized and become unit-free before proceeding with other steps. This process called grey relational generation [13]. To normalize data for GRA, three formulas are utilized. The choice of formula depends on the characteristics of the data sequences. For example, Equation (1) is used for attributes where higher values are better, and Equation (2) is used for attributes where lower values are better.

$$x^*(k) = \frac{x_i^0 - min\, x_i^0(k)}{max\, x_i^0 - min\, x_i^0(k)} \quad (1)$$

$$x^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{max\, x_i^0 - \min x_i^0(k)} \quad (2)$$

Where,

i= 1… m; k= 1… n.

m is the number of experimental data items

n is the number of parameters

$x_i^0(k)$ is the original sequence

$x_i^*(k)$ is the sequence after data pre-processing $min\ x_i^0(k)$ and $max\ x_i^0(k)$ are the smallest and the largest value of $x_i^0(k)$

2.1.2. Reference sequences

After the data normalization procedure, using Eq. (1) and (2), all values are scaled between zero and one. Thus, an alternative is considered the best choice if all its values are closest to or equal to one [14].

2.1.3. Grey relational coefficient

In the third step, the grey relational coefficient is computed. It indicates the degree of grey relation between the referential sequence and other calculated sequences. Deng (1989) proposed the following Equation for the grey relational coefficient [7]:

$$\xi_i(k) = \frac{\Delta\, min + \rho\Delta max}{\Delta_{0,i}(k) + \rho\Delta max} \qquad (3)$$

Where,

$\Delta_{0,\ i}$= Deviation sequences of the reference sequence and comparability sequence

$$\Delta_{0,j} = \left\| x_0^*(k) - x_i^*(k) \right\| \qquad (4)$$

$$\Delta\ \min = \min\min \left\| x_0^*(k) - x_j^*(k) \right\|\ ;\ \forall j \epsilon i \forall k \qquad (5)$$

$$\Delta\ \max = \max\max \left\| x_0^*(k) - x_j^*(k) \right\|\ ;\ \forall j \epsilon i \forall k \qquad (6)$$

x_0^* is the k the reference sequence, and x_i^* is the k comparative sequence and ρ is distinguished coefficient where ρ∈ [0,1] which can help make better distinction between normalized reference series and normalized comparative series. It could be adjusted by the decision maker exercising judgment, and different distinguishing coefficients usually produce different results in grey analysis. Generally, ρ equals 0.5 because it offers moderate distinguishing effect and stability [15]. Furthermore, based on mathematical proof, the value change of ρ will only change the relational coefficient magnitude, but it will not change grey relational grade ranking [16].

2.1.4. Grey relational grade

Grey relational grade is the numerical measure of similarity between two sequences, such as the reference sequence and the comparability sequence, where n represents the number of process responses. The grey relational grade ranges from zero to one. After averaging the grey coefficients, the grey relational grade is computed using the following formula:

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k) \qquad (7)$$

As mentioned, the reference sequence x_0 (k) indicates the best performance that can be attained among comparability sequences x_i (k). So, if a comparability sequence has highest grey relational grade with reference sequence, it means that comparability sequence is the closest to reference sequence and that alternative has the best performance [17].

2.2.Simple Additive Weighting

Simple Additive Weighting (SAW) is used to solve the problem of multi-attribute decision-making (MADM). In this technique, sum of the weighted performance score for each alternative on all attributes determined. The SAW approach necessitates normalizing the decision matrix (X) to a scale that allows for comparison of the ratings for all current alternatives [18]. There are three steps for ranking options in this method:

2.2.1 Normalization

First, we should determine the utility of attributes. Then all data are normalized to a scale that can be compared with all the ratings of existing alternatives.

For beneficial parameters:

$$r_{rj} = \frac{x_{ij}}{max(x_{ij})} \quad (8)$$

For non-beneficial parameters:

$$r_{rj} = \frac{min(x_{ij})}{x_{ij}} \quad (9)$$

From above formula, decision matrix made. Then relative weights should be calculated by different methods such as AHP, Shannon entropy, etc. in the following step, weights of each parameter multiplied by the normalized value of the alternative in the decision matrix.

$$v_i = \sum_{j=1}^{n} = w_j \, r_{rj} \quad (10)$$

Next is to determine the value of the alternative ranks. A larger value indicates that the alternative is the best.

2.3. Data Envelopment Analysis

DEA is a non-parametric linear programming approach proposed by Charnes et al. in 1978 which used multiple outputs and inputs. This method has been widely used in performance measurement in many fields such as health, education, finance, and insurance. As mentioned, the traditional DEA models regard the production and operation processes as a "black box," Since it only considers the initial input and final output of the system, The calculation results might indicate an unreasonable situation where the overall system demonstrates efficiency. yet, every individual sub-stage does not [19]. It is essential to open the "black box" to explore the inefficiency of DMU and develop more precise and practical improvement strategies. As a result, the network DEA approach has been designed to trace inputs and outputs throughout the entire process, from beginning to final output, and to investigate the underlying causes of the system's overall inefficiency. (Kao and Liu, 2019). A network structure to link the various production stages using intermediate process first developed by [20-25]. Tone and Tsutsui (2009) introduced a non-radial network DEA model, which considered the importance of the subsystems and made it easier to measure two-stage system efficiency [24]. In this paper, we followed Tone and Tsutsui's (2009) two-stage DEA approach by considering undesirable outputs:

$$\rho = min \frac{\sum_{k=1}^{k} \omega^k \left[1 - \frac{1}{m_k}\left(\sum_{i=1}^{m_k} \frac{s_i^{k-}}{x_{i0}^k}\right)\right]}{\sum_{k=1}^{k} \omega^k \left[1 + \frac{1}{r_k + q_k}\left(\sum_{r=1}^{r_k} \frac{s_r^{k+}}{y_{r0}^k} + \sum_{q=1}^{q_k} \frac{s_q^{k-}}{u_{q0}^k}\right)\right]} \quad (11)$$

$$s.t. = \begin{cases} \sum_{j=1, j\neq 0}^{n} \lambda_j^k \, x_j^k = x_0^k - s_x^{k-} (k = 1, \ldots, k) \\ \sum_{j=1, j\neq 0}^{n} \lambda_j^k \, y_j^k = y_0^k - s_y^{k+} (k = 1, \ldots, k) \\ \sum_{j=1, j\neq 0}^{n} \lambda_j^k \, u_j^k = u_0^k - s_u^{k-} (k = 1, \ldots, k) \end{cases}$$

$$z^{(k,h)} = \sum_{j=1, j\neq 0} n_{z_j}^{(k,h)} \lambda_j^k \; (\forall (k,h)) \; (as\ outputs\ from\ k).$$

$$z^{(k,h)} = \sum_{j=1, j\neq 0} n_{z_j}^{(k,h)} \lambda_j^k \; (\forall (k,h)) \; (as\ inputs\ to\ k).$$

Where x_j^k, y_j^k, and u_j^k represent the inputs, desirable outputs, and undesirable outputs in the k_{th} stage of DMU_j, respectively; x_0^k, y_0^k, and u_0^k show the inputs, desirable outputs, and undesirable outputs in the k_{th} stage of estimated DMU or DMU_0. s_x^{k-}, s_y^{k+}, and s_u^{k-} represent the slack in the k_{th} stage of the estimated DMU. λ_j^k is an intensity variable to construct a possible production set. ρ is the overall efficiency of the estimated DMU. ω^k is the weight of the k_{th} stage. The application of the Charnes-Cooper transformation (1978) to Eq. (11) obtains Eq. (12):

$$t = \frac{1}{\sum_{k=1}^{k} \omega^k \left[1 + \frac{1}{r_k + q_k} \left(\sum_{r=1}^{r_k} \frac{s_r^{k+}}{y_{r0}^k} + \sum_{q=1}^{q_k} \frac{s_q^{k-}}{u_{q0}^k} \right) \right]} \quad (12)$$

Equation. (2) is used to rewrite the Equation. (1) as:

$$\rho = min \sum_{k=1}^{k} \omega^k \left[1 - \frac{1}{m_k} \left(\sum_{i=1}^{m_k} \frac{s_i^{k-}}{x_{i0}^k} \right) \right] \times t \quad (13)$$

$$s.t. =$$

$$\begin{cases} \sum_{k=1}^{k} \omega^k \left[1 + \frac{1}{r_k + q_k} \left(\sum_{r=1}^{r_k} \frac{s_r^{k+}}{y_{r0}^k} + \sum_{q=1}^{q_k} \frac{s_q^{k-}}{u_{q0}^k} \right) \right] \times t = 1 \\ \sum_{j=1, j\neq 0}^{n} \lambda_j^k x_j^k = x_0^k - s_x^{k-} (k = 1, \dots, k) \\ \sum_{j=1, j\neq 0}^{n} \lambda_j^k y_j^k = y_0^k - s_y^{k+} (k = 1, \dots, k) \\ \sum_{j=1, j\neq 0}^{n} \lambda_j^k u_j^k = u_0^k - s_u^{k-} (k = 1, \dots, k) \end{cases}$$

$$z^{(k,h)} t = \sum_{j=1, j\neq 0} n_{z_j}^{(k,h)} \lambda_j^k \ t (\forall (k,h)) \ (as\ outputs\ from\ k).$$

$$z^{(k,h)} t = \sum_{j=1, j\neq 0} n_{z_j}^{(k,h)} \lambda_j^k \ t (\forall (k,h)) \ (as\ inputs\ to\ k).$$

Eq. 13 can be simplified as follows:

$$\rho = min \sum_{k=1}^{k} \omega^k t - \sum_{k=1}^{k} \omega^k \frac{1}{m_k} \left(\sum_{i=1}^{m_k} \frac{s_i^{k-}}{x_{i0}^k} \right) \quad (14)$$

$$s.t. =$$

$$\begin{cases} \sum_{k=1}^{k} \omega^k t + \sum_{k=1}^{k} \omega^k \frac{1}{r_k + q_k} \left(\sum_{r=1}^{r_k} \frac{s_r^{k+}}{y_{r0}^k} + \sum_{q=1}^{q_k} \frac{s_q^{k-}}{u_{q0}^k} \right) \times t = 1 \\ \sum_{j=1, j\neq 0}^{n} \lambda_j^k x_j^k = x_0^k - s_x^{k-} (k = 1, \dots, k) \\ \sum_{j=1, j\neq 0}^{n} \lambda_j^k y_j^k = y_0^k - s_y^{k+} (k = 1, \dots, k) \\ \sum_{j=1, j\neq 0}^{n} \lambda_j^k u_j^k = u_0^k - s_u^{k-} (k = 1, \dots, k) \end{cases} \quad (14)$$

$$z^{(k,h)} t = \sum_{j=1, j\neq 0} n_{\Delta_j}^k z_j^{(k,h)} \ (\forall (k,h)) \ (as\ outputs\ from\ k).$$

$$z^{(k,h)} t = \sum_{j=1, j\neq 0} n_{\Delta_j}^k z_j^{(k,h)} \ (\forall (k,h)) \ (as\ inputs\ to\ k).$$

$$S_x^{k-} = s_x^{k-}\ t,\ S_y^{k-} = s_x^{k+}\ t, S_y^{k-} = s_u^{k-}\ t,\ \Delta_j^k = \lambda_j^k t$$

The efficiency of the k_{th} stage can be defined as:

$$\rho^k = \frac{1 - \frac{1}{m_k} (\sum_{i=1}^{m_k} \frac{s_i^{k-}}{x_{i0}^k})}{1 + \frac{1}{r_k + q_k} \left(\sum_{r=1}^{r_k} \frac{s_r^{k+}}{y_{r0}^k} + \sum_{q=1}^{q_k} \frac{s_q^{k-}}{u_{q0}^k} \right)} \quad (15)$$

2.4.Shannon entropy weight

Entropy concept has been extensively employed in physical and social science. The idea of information entropy introduced by Shannon in 1948 in his paper called a mathematical theory of communication. It can be considered a criterion for uncertainty about an event related to a discrete probability distribution. Entropy assesses the expected information contained in a specific message instead of the part of the message that is determined. Entropy idea can be employed in decision making, because it evaluates available contrasts in a range of data and explicates the intrinsic information that convey to decision maker [26]. As an uncertainty measure of information volume in a system or process, Shannon entropy plays a dominant role in information theory. It shows that the volume of each piece of information is directly connected to its uncertainty degree. To measure weight through Shannon entropy, some procedures presented in the following:

- **Step 1** is the normalization of decision matrix arrays (performance indexes) to gain possible outcomes P_{ij}:

$$P_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}};\ \forall \mathrm{i, j} \quad (16)$$

- **Step 2** is the computation of possible outcomes' entropy measurement by using the following equation:

$$E_j = -k \sum_{i=1}^{m} [p_{ij} \ln p_{ij}];\ \forall j \quad (17)$$

In which k = 1/Ln (m) and K is a constant.

$$d_j = 1 - E_j \quad ;\ \forall \mathrm{j} \quad (18)$$

- **Step 3** is defining the objective weight based on the entropy concept:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \quad ;\ \forall \mathrm{j} \quad (19)$$

- **Step 4** is calculating the general form of the entropy weight, if the decision maker allocates subjective weight w_j. By considering w_j, Eq. (19) transforms into the following:

$$w'_j = \frac{\lambda_j w_j}{\sum_{j=1}^{n} \lambda_j w_j} \quad ; \ \forall j \qquad (20)$$

In which subjective and objective weights (λ_j and w_j) are integrated to construct the general form of Shannon entropy weight w_j [27].

2.5. Electricity distribution companies

Tehran Electricity Institute was established in 1936 to convey electricity to the households and streets of Tehran. After the Constitutional Revolution, until 1963 when the Ministry of Water and Electricity was established, there was always a necessity to focus on water and electricity coherently. The primary approved duties of the ministry in the power sector were implementing electricity distribution and transmission projects by establishing regional electricity companies and monitoring the use of electricity.

In 1965, the Ministry of Water and Electricity was obliged to form the "Electricity Organization of Iran" with regional electricity distribution companies to implement power supply projects throughout the country. On 17 February 1975, the Ministry of Energy was established to manage and supply energy for public use. The most important responsibilities of the Ministry of Energy including determining policies, implementing energy programs, supervision and coordination. Additionally, constructing power plants and power supply facilities in all parts of the country is part of its responsibilities [28].

As mentioned, regional electricity companies were established with the aim of supply, produce, transmit, distribute, and sell electricity. At present, there are thirty-nine regional electricity distribution companies in Iran, and data from thirty-five companies were available for this paper.

Data Envelopment Analysis and Grey Relational Analysis techniques have been widely used in the performance evaluation of companies. In the following, we refer to some of this research.

Jukka et al. (2003) employed DEA-model for the efficiency benchmarking of the Finnish electricity distribution companies. The outcomes of efficiency benchmarking showed a crucial role in determining an appropriate return on capital for the distribution sector and shaping the investment strategies for distribution systems. Consequently, efficiency benchmarking significantly affects the growth and development of distribution businesses and networks.

Celen in 2013 measured the efficiency and productivity of 21 Turkish electricity distribution companies from 2002 to 2009. The study employed a two-stage DEA and Tobit regression to account for environmental variables that are beyond the control of the companies. Result showed that customer density and private ownership are key drivers of efficiency in the Turkish electricity distribution sector [29].

Omrani et al. (2015) introduced a novel integrated approach to evaluate the efficiency of electricity distribution companies in Iran. The method combines DEA, Principal Component Analysis (PCA), and game theory to address the limitations of traditional DEA models. They found that the integrated PCA-DEA-Game approach effectively addresses the limitations of conventional DEA by reducing data dimensionality and incorporating competitive dynamics, providing a more robust framework for performance evaluation in the electricity distribution sector [2].

Ebrahimzedeh Shermeh er al. (2018) used a network DEA based on Slacks-Based Measure (SBM) approach to evaluate the efficiency of electricity distributed companies in Iran. In the Blackbox model, efficiency scores tend to be higher than the Network SBM. In Blackbox model, 3 of the 16 companies were inefficient, and 13 companies were efficient. However, in Network SBM, only three companies had been recognized as efficient and 13 companies were inefficient [30].

Nguyen (2020), evaluated the performance of Ho Chi Minh city power companies by DEA and Grey System Theory. Integrating DEA and Grey System Theory offered a comprehensive approach to performance evaluation and forecasting in the electricity sector [31].

Sarraf and Hashemi Nejad (2020), compared grey relational analysis and DEA methods to evaluate the performance of water and wastewater companies in Iran. Results demonstrated that grey relational analysis is a more accurate method to measure the performance of these companies [5].

Dang et al. (2022) presented a comprehensive study on selecting optimal locations for solar photovoltaic (PV) power plants in Vietnam. The study employed a combination of DEA and Grey-Based Multiple Criteria Decision Making (G-MCDM) methodologies to evaluate and rank potential sites for solar PV installations. Results showed that the top five provinces identified for solar PV development.

Susanty et al. (2022), focused on analyzing the efficiency of electricity distribution units within the PLN (Perusahaan Listrik Negara) service area in Semarang, Central Java, Indonesia, using DEA and Soft System Methodology (SSM). The efficiency average was equal to 0.972. Findings suggested that addressing issues like cable length, electricity theft, and transformer capacity utilization can significantly improve the efficiency of distribution units [32].

Karimi and Ahmadian (2024), used the two-stage data envelopment analysis model with grey data to assess the efficiency of bank branches in terms of operations. They used a grey clustering technique to categorize bank branches into three performance tiers (excellent, good, and poor). Subsequently, a comprehensive ranking of all branches generated by integrating two distinct methodologies: the minimax regret-based analysis and whitening value assessment. Results show that after grey clustering based on grey efficiency value obtained from the grey two-stage DEA model, the branches distribute as follows: six demonstrated excellent performance, four show good performance, and twelve had poor performance [33].

3. Research Methodology

3.1.Sample and data collection

The purpose of this research is to provide a quantitative performance evaluation of electricity distribution companies in the public sector in Iran. This evaluation has been done through GRA, DEA and G-SAW methods. Also, the difference in the results can guide managers to choose a better performance evaluation method. This paper is applied in nature and follows a causal-comparative research design. Documentary method used to examine the current situation and descriptive method used in data collection. Statistical population includes thirty-five electricity distribution companies in Iran. Required data and ratios in table 1 collected from Tavanir Power Company in ministry of energy. The period of this research is 2020. The number of indicators is ten. All these criteria are quantitative, and have been selected following consultation with experts and are all strategic criteria.

Table 1: Research indices

Ratios	Formula	Ratios	Formula
Debt to Project Performance	Total Debt to Contractors and Vendors/Project Performance	Voltage Measurement Percentage	The Total Number of Records Transmitted Across Six Voltage Intervals/Reading Periods
Cost of Medium Voltage Distribution Network	Total Cost of Medium Voltage Distribution Network/Network Length	Power Load Per Customer	Peak Power Consumption of Digital Meters/Company's Peak Consumption
Cost of Low Voltage Distribution Network	Total Cost of Low Voltage Distribution Network/Network Length	Percentage of Digital Power Meter	Number of Digital Power Meters/Number of Electricity Subscriptions
The Average Cost of Building a Power Substation	Total Cost of Power Substation Development and Construction/Number of Power Substations	Distribution Transformers Productivity	Total Capacity of Substations/Company's Load Peak
Cost of Building Power Substation to Installed Capacity	Total Cost of Power Substation Development and Construction/Capacity of Substations	Waste	Energy Sold – Energy Delivered/Energy Delivered

3.2.Statistical methods

To calculate the grey relational grade, five steps are required. In the first step, it is necessary to normalize data and then in the next step, by subtracting normalized numbers from one, reference sequence will be achieved. In the third step, grey relational coefficient is calculated and in the fifth one, relational coefficients multiplied by relative weights and numbers summed for each company. Thus, the final grade will be obtained. Fuzzy normalization method used to standardize the data and relative weights of indices calculated by Shannon entropy method. All procedures done by excel spreadsheet. Also, for G-SAW method, data normalized by Eq. 8 and Eq. 9. Then, all numbers subtract from one. In the third step, grey coefficient calculated and in the fourth one, relational coefficients multiplied by relative weights and numbers summed for each company.

For data envelopment analysis, a two-stage DEA model with desirable outputs, and undesirable outputs used to determine companies' efficiency. For the selection of input indices, items such as cost and debts were considered. For desirable output, productivity and for undesirable output, waste were considered. There are also two intermediate indices. Finally, ten indices selected with expert consultation, which Debt to Project Performance, Cost of Medium Voltage Distribution Network, Cost of Low Voltage Distribution Network, The Average Cost of Building Power Substation, Cost of Building Power Substation to Installed Capacity selected as first stage inputs, Power Load Per Customer and Percentage of Digital Power Meter chose as intermediate indices, Voltage Measurement Percentage as second stage input and waste and Distribution Transformers Productivity considered as final outputs. Also, Condition of determining the efficiency (number of inputs + number of outputs) *2≥ the number of DMUs observed. R program used for calculating efficiency of DMUs. Table 2 presents the indices used in this paper. Figure 2 shows the two-stage input-output evaluations in this research. After calculating efficiency, results obtained from three methods compared with each other and better method(s) recommended.

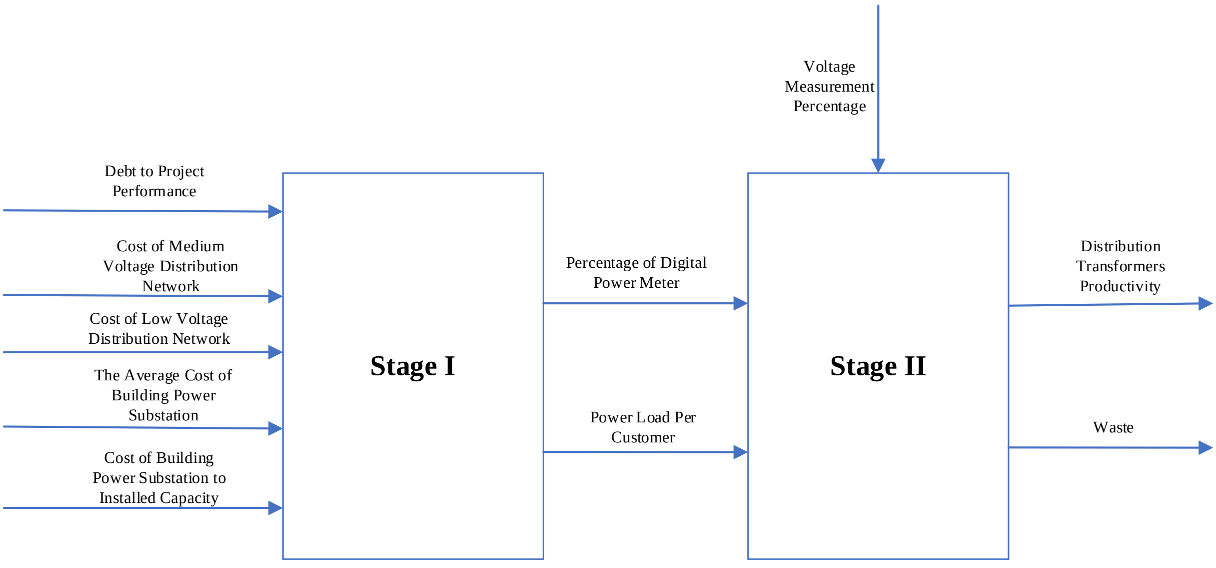

Figure. 2. Two-stage input-output evaluations in this research

4. Results

4.1.statistical method

4.1.1. Data normalization

Initially, data have been normalized and fuzzy method has been used. Then, data placed in spaces between zero and one. Results are shown in Table 2.

4.1.2. Reference sequences

After normalizing, in the second step, the reference sequence is calculated. As stated, it is essential to subtract normalized data from one to obtain the distance between the desired value and each index.

4.1.3. Grey relational coefficient

In the third step, grey relational coefficient obtained. The formula is described in Equation 3. The obtained coefficients are presented in Table 3.

Table. 2: Data normalization

Indices	Debt to Project Performance	Cost of Medium Voltage Distribution Network	Cost of Low Voltage Distribution Network	The Average Cost of Building a Power Substation	Cost of Building Power Substation to Installed Capacity	Voltage Measurement Percentage	Power Load Per Customer	Percentage of Digital Power Meter	Distribution Transformers Productivity	Waste
Zanjan	0.72	0.783	0.842	0.705	0.661	0.5	0	0.821	0.36	0.831
Qom	0.892	0.388	0.929	0.837	0.979	0.664	0.422	0.815	0.105	0.725
Mashhad	0.587	0.044	0.835	0.94	1	0.28	0.037	0.817	0.337	0.559
North Khorasan	0.795	0.477	0.974	1	0.963	0.17	0.593	0.815	0.022	0.798
Isfahan	0.456	0.417	0.566	0.62	0.556	0.542	0.175	0.752	0.33	1
Markazi	0.854	0.724	0.723	0.61	0.841	0.269	0.271	0.739	0.367	0.764
Yazd	0.454	0.719	0.777	0.669	0.503	0.143	0.285	0.778	0.708	1
Sistan et Baluchestan	0.85	1	1	0.866	0.894	0.481	0.959	1	0.551	0.726
Fars	0.326	0.246	0.756	0.816	0.873	0.313	0.626	0.905	0.39	0.874
East Azerbaijan	0.7	0.644	0.7	0.838	0.835	0.242	0.415	0.801	0.255	0.662
Razavi Khorasan	0.729	0.637	0.637	0.939	0.968	0.229	0.404	0.691	0.434	0.655
Golestam	0.687	0.261	0.801	0.823	0.82	0.025	0.633	0.871	0.723	0.578
West Azerbaijan	0.354	0.892	0.835	0.904	0.89	0.358	0.75	0.822	0.487	0.544
Gilan	0.649	0.626	0.765	0.795	0.794	0	0.794	0.723	0.592	0.516
Kurdistan	1	0.732	0.561	0.432	0.593	0.124	0.787	0.876	0.202	0.682
Mazandaran	0.629	0.437	0.719	0.757	0.772	0.941	0.684	0.739	0.573	0.428
Hamedan	0.57	0.36	0.748	0.785	0.767	0.146	0.216	0.797	0.079	0.664
Semnan	0.476	0.644	0.669	0.674	0.825	0.335	0.232	0.875	0.199	0.763
South Khorasan	0.755	0.602	0.723	0.862	0.841	0.063	0.457	0.718	0	0.833
Alborz	0.836	0.171	0.54	0.425	0.778	0.223	0.442	0.871	0.105	0.683
Ilam	0.476	0.288	0.697	0.88	0.974	0.129	0.406	0.976	0.258	0.522
Tehran	0.931	0.679	0.58	0.385	0.741	0.319	0.587	0.897	0.326	0.544
Tabriz	0.607	0.473	0.37	0.232	0.714	0.736	0.547	0.77	0.468	0.734
Shiraz	0.337	0.309	0.56	0	0.508	0.389	0.711	0.867	0.064	0.747
Ardabil	0.636	0.495	0.574	0.562	0.592	0.977	1	0.778	0.416	0.544
Kerman	0.412	0.73	0.743	0.516	0.635	0.431	0.505	0.976	0.401	0.66
Chaharmahal & Bakhtiari	0.83	0.394	0.688	0.7	0	0.233	0.436	0.818	0.296	0.666
Kermanshah	0.925	0.818	0.896	0.71	0.783	0.054	0.849	0.76	0.277	0.361
Luristan	0.285	0.822	0.968	0.87	0.794	0.157	0.656	0.732	0.292	0.742
Qazvin	0.663	0.309	0.685	0.622	0.896	1	0.465	0	0.472	0.909
Ahvaz	0	0.253	0.695	0.771	0.99	0.265	0.79	0.851	1	0.609
Bushehr	0.81	0.413	0	0.675	0.899	0.252	0.959	0.897	0.506	0.478
Kohgiluyeh and Boyer -Ahmad	0.54	0.714	0.896	0.418	0.714	0.085	0.839	0.92	0.045	0
Hormozgan	0.163	0.31	0.431	0.424	0.524	0.049	0.862	0.831	0.783	0.626
Khuzestan	0	0	0.383	0.655	0.883	0.311	0.839	0.877	0.685	0.298

Table 3: Grey relational coefficients

Indices	Debt to Project Performance	Cost of Medium Voltage Distribution Network	Cost of Low Voltage Distribution Network	The Average Cost of Building a Power Substation	Cost of Building Power Substation to Installed Capacity	Voltage Measurement Percentage	Power Load Per Customer	Percentage of Digital Power Meter	Distribution Transformers Productivity	Waste
Zanjan	0.641	0.697	0.76	0.629	0.596	0.5	0.333	0.736	0.439	0.747
Qom	0.822	0.45	0.876	0.754	0.96	0.598	0.464	0.73	0.358	0.645
Mashhad	0.548	0.343	0.752	0.893	1	0.41	0.342	0.732	0.43	0.531
North Khorasan	0.709	0.489	0.951	1	0.931	0.376	0.551	0.73	0.338	0.712
Isfahan	0.479	0.462	0.535	0.568	0.53	0.522	0.377	0.668	0.427	1
Markazi	0.774	0.644	0.644	0.562	0.759	0.406	0.407	0.657	0.441	0.679
Yazd	0.478	0.64	0.692	0.602	0.502	0.368	0.412	0.693	0.631	1
Sistan et Baluchestan	0.769	1	1	0.789	0.825	0.491	0.924	1	0.527	0.646
Fars	0.426	0.399	0.672	0.731	0.797	0.421	0.572	0.84	0.45	0.799
East Azerbaijan	0.625	0.584	0.625	0.755	0.752	0.397	0.461	0.715	0.402	0.597
Razavi Khorasan	0.649	0.579	0.579	0.891	0.94	0.393	0.456	0.618	0.469	0.592
Golestam	0.615	0.404	0.715	0.739	0.735	0.339	0.577	0.795	0.644	0.542
West Azerbaijan	0.436	0.822	0.752	0.839	0.82	0.438	0.667	0.737	0.494	0.523
Gilan	0.588	0.572	0.68	0.709	0.708	0.333	0.708	0.644	0.551	0.508
Kurdistan	1	0.651	0.532	0.468	0.551	0.363	0.701	0.801	0.385	0.611
Mazandaran	0.574	0.47	0.64	0.673	0.687	0.894	0.613	0.657	0.539	0.466
Hamedan	0.538	0.439	0.665	0.699	0.682	0.369	0.389	0.711	0.352	0.598
Semnan	0.488	0.584	0.602	0.605	0.741	0.429	0.394	0.8	0.384	0.678
South Khorasan	0.671	0.557	0.644	0.784	0.759	0.348	0.479	0.639	0.333	0.75
Alborz	0.753	0.376	0.521	0.465	0.693	0.392	0.473	0.795	0.358	0.612
Ilam	0.488	0.413	0.623	0.806	0.951	0.365	0.457	0.954	0.403	0.511
Tehran	0.879	0.609	0.543	0.448	0.659	0.423	0.548	0.829	0.426	0.523
Tabriz	0.56	0.487	0.442	0.394	0.636	0.654	0.525	0.685	0.484	0.653
Shiraz	0.43	0.42	0.532	0.333	0.504	0.45	0.634	0.79	0.348	0.664
Ardabil	0.579	0.498	0.54	0.533	0.551	0.956	1	0.693	0.461	0.523
Kerman	0.46	0.649	0.661	0.508	0.578	0.468	0.503	0.954	0.455	0.595
Chaharmahal & Bakhtiari	0.746	0.452	0.616	0.625	0.333	0.395	0.47	0.733	0.415	0.6
Kermanshah	0.87	0.733	0.828	0.633	0.697	0.346	0.768	0.676	0.409	0.439
Luristan	0.412	0.737	0.94	0.794	0.708	0.372	0.592	0.651	0.414	0.66
Qazvin	0.597	0.42	0.613	0.569	0.828	1	0.483	0.333	0.486	0.846
Ahvaz	0.333	0.401	0.621	0.686	0.98	0.405	0.704	0.77	1	0.561
Bushehr	0.725	0.46	0.333	0.606	0.832	0.401	0.924	0.829	0.503	0.489
Kohgiluyeh and Boyer -Ahmad	0.521	0.636	0.828	0.462	0.636	0.353	0.756	0.862	0.344	0.333
Hormozgan	0.374	0.42	0.468	0.465	0.512	0.345	0.784	0.747	0.697	0.572
Khuzestan	0.333	0.333	0.448	0.592	0.81	0.421	0.756	0.803	0.613	0.416

4.1.4. Relative Weights

As mentioned previously, relative weights have been calculated by using the Shannon entropy method. Table 4 shows the relative weights.

Table 4: Relative weights

Indices	Relative Weight	Indices	Relative Weight
Debt to Project Performance	0.122	Voltage Measurement Percentage	0.234
Cost of Medium Voltage Distribution Network	0.066	Power Load Per Customer	0.14
Cost of Low Voltage Distribution Network	0.059	Percentage of Digital Power Meter	0.031
The Average Cost of Building a Power Substation	0.129	Distribution Transformers Productivity	0.021
Cost of Building Power Substation to Installed Capacity	0.164	Waste	0.034

4.1.5. Grey relational grade

In the final step, by multiply grey relational coefficients in relative weight and sum up numbers, final grey grade will be calculated. Results demonstrated in table 5 and Figure 3.

Table 5: Grey relational grades

No	Company Name	Grey Grade	No	Company Name	Grey Grade
1	Zanjan	0.569	19	South Khorasan	0.583
2	Qom	0.693	20	Alborz	0.532
3	Mashhad	0.607	21	Ilam	0.588
4	North Khorasan	0.676	22	Tehran	0.573
5	Isfahan	0.519	23	Tabriz	0.562
6	Markazi	0.577	24	Shiraz	0.486
7	Yazd	0.514	25	Ardabil	0.707
8	Sistan et Baluchestan	0.764	26	Kerman	0.538
9	Fars	0.584	27	Chaharmahal & Bakhtiari	0.502
10	East Azerbaijan	0.581	28	Kermanshah	0.632
11	Razavi Khorasan	0.626	29	Luristan	0.594
12	Golestam	0.576	30	Qazvin	0.697
13	West Azerbaijan	0.641	31	Ahvaz	0.61
14	Gilan	0.583	32	Bushehr	0.629
15	Kurdistan	0.584	33	Kohgiluyeh and Boyer -Ahmad	0.552
16	Mazandaran	0.681	34	Hormozgan	0.493
17	Hamedan	0.526	35	Khuzestan	0.555
18	Semnan	0.545			

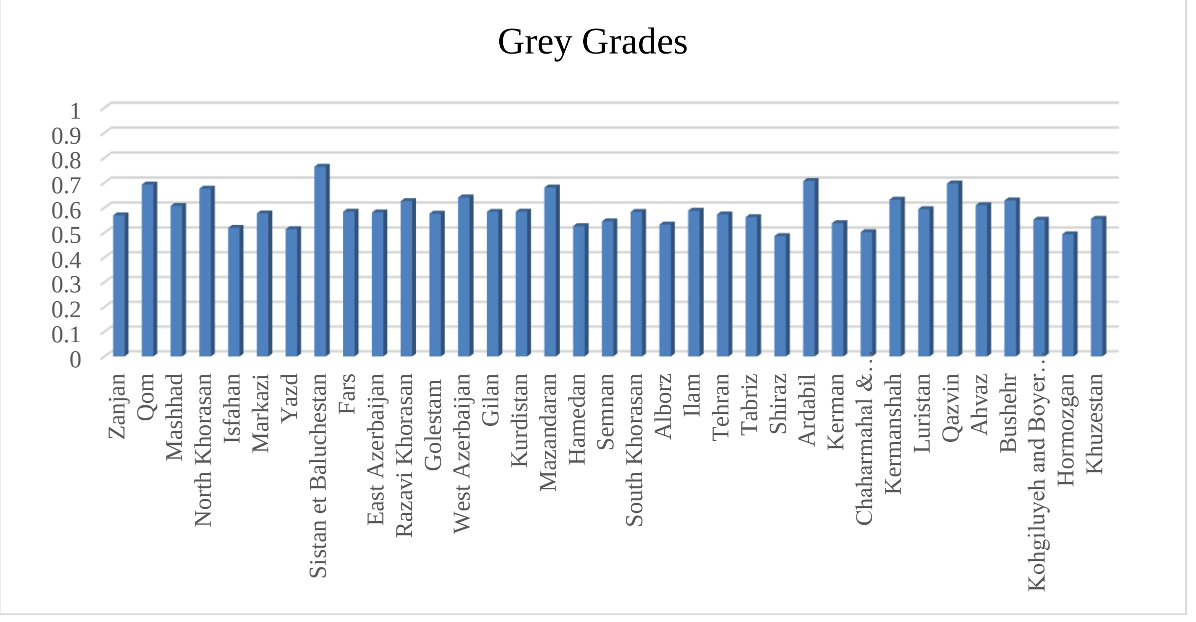

Figure. 3. Grey relational grades

As shown above, Shiraz with a score of 0.486 and Sistan et Baluchestan with a score of 0.764 got the lowest and highest ranks, respectively; Ardabil also has better performance than other companies do. Twenty-one firms ranked between 0.5 and 0.59. Two ranked less than 0.5, which indicates their poor performance in 2020.

4.2. G-SAW grade

The results obtained from applying the G-SAW model are also shown in the table 6 and Figure 4.

Table 6: G-SAW grades

No	Company Name	Grey Grade	No	Company Name	Grey Grade
1	Zanjan	0.488	19	South Khorasan	0.464
2	Qom	0.593	20	Alborz	0.451
3	Mashhad	0.571	21	Ilam	0.507
4	North Khorasan	0.593	22	Tehran	0.481
5	Isfahan	0.474	23	Tabriz	0.498
6	Markazi	0.474	24	Shiraz	0.445
7	Yazd	0.454	25	Ardabil	0.648
8	Sistan et Baluchestan	0.631	26	Kerman	0.468
9	Fars	0.482	27	Chaharmahal & Bakhtiari	0.446
10	East Azerbaijan	0.469	28	Kermanshah	0.495
11	Razavi Khorasan	0.526	29	Luristan	0.486
12	Golestam	0.46	30	Qazvin	0.595
13	West Azerbaijan	0.516	31	Ahvaz	0.538
14	Gilan	0.453	32	Bushehr	0.513
15	Kurdistan	0.514	33	Kohgiluyeh and Boyer-Ahmad	0.456
16	Mazandaran	0.569	34	Hormozgan	0.428
17	Hamedan	0.443	35	Khuzestan	0.469

18	Semnan	0.462			

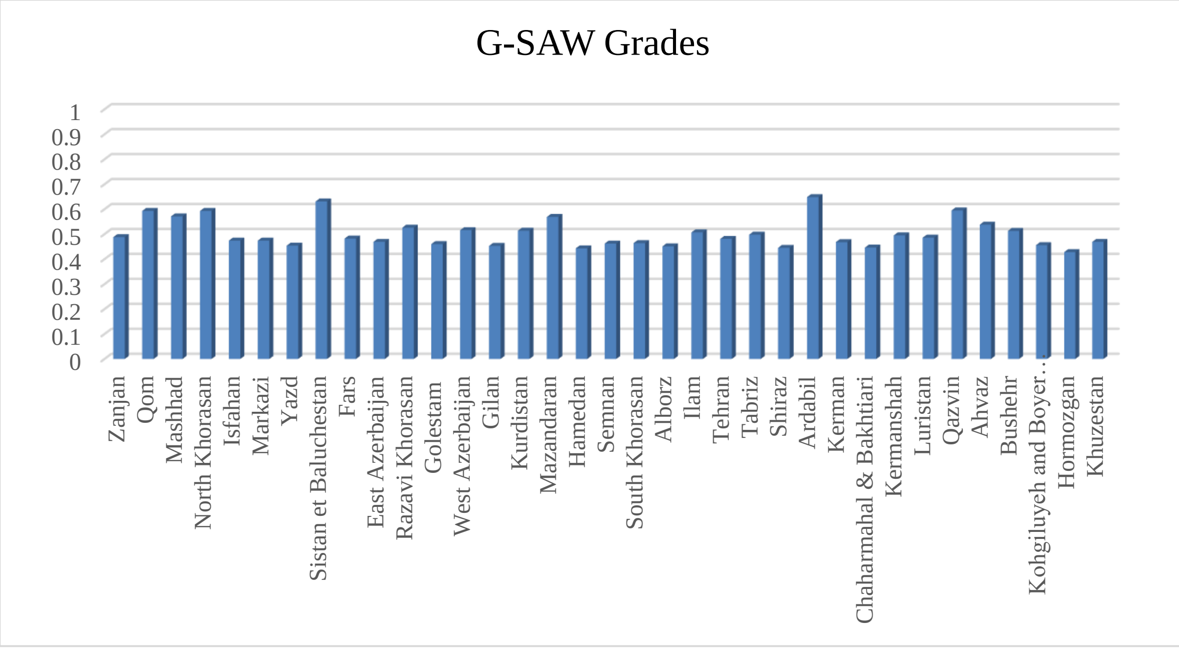

Figure. 4. G-SAW grades

In G-SAW method, Hormozgan with a score of 0.428 and Ardabil with a score of 0.648 got the lowest and highest ranks, respectively; Sistan et Baluchestan score was also higher than 0.6. twenty-two companies had the score of less than 0.5 and eleven countries ranked between 0.5 and 0.59.

4.3. Data envelopment analysis scores

As mentioned, a two-stage DEA model has been used to determine companies' efficiency. Efficiency calculated in two stages and by multiplying two scores, the overall efficiency obtained. Final rates demonstrate in table 8.

Table 7: Efficiency rates

No	Company Name	Efficiency Stage1	Efficiency Stage2	Overall Efficiency	No	Company Name	Efficiency Stage1	Efficiency Stage2	Overall Efficiency
1	Zanjan	1	0.421	0.421	19	South Khorasan	1	0.52	0.52
2	Qom	1	0.957	0.957	20	Alborz	0.835	0.471	0.393
3	Mashhad	1	0.369	0.369	21	Ilam	1	0.433	0.433
4	North Khorasan	1	0.56	0.56	22	Tehran	1	0.54	0.54
5	Isfahan	0.637	0.53	0.338	23	Tabriz	0.501	0.639	0.32
6	Markazi	1	0.503	0.503	24	Shiraz	0.471	0.611	0.288
7	Yazd	1	0.338	0.338	25	Ardabil	0.796	1	0.796
8	Sistan et Baluchestan	1	0.913	0.913	26	Kerman	0.745	0.527	0.393
9	Fars	0.673	0.68	0.458	27	Chaharmahal & Bakhtiari	0.789	0.514	0.406
10	East Azerbaijan	0.938	0.5	0.469	28	Kermanshah	1	0.709	0.709
11	Razavi Khorasan	1	0.55	0.55	29	Luristan	1	0.685	0.685
12	Golestam	1	0.651	0.651	30	Qazvin	0.465	1	0.465

13	West Azerbaijan	1	0.7	0.7	31	Ahvaz	0.776	1	0.776
14	Gilan	1	0.396	0.396	32	Bushehr	0.749	0.855	0.641
15	Kurdistan	1	0.684	0.684	33	Kohgiluyeh and Boyer -Ahmad	1	0.508	0.508
16	Mazandaran	0.657	0.989	0.65	34	Hormozgan	1	0.484	0.484
17	Hamedan	1	0.4	0.4	35	Khuzestan	0.542	0.709	0.384
18	Semnan	1	0.435	0.435					

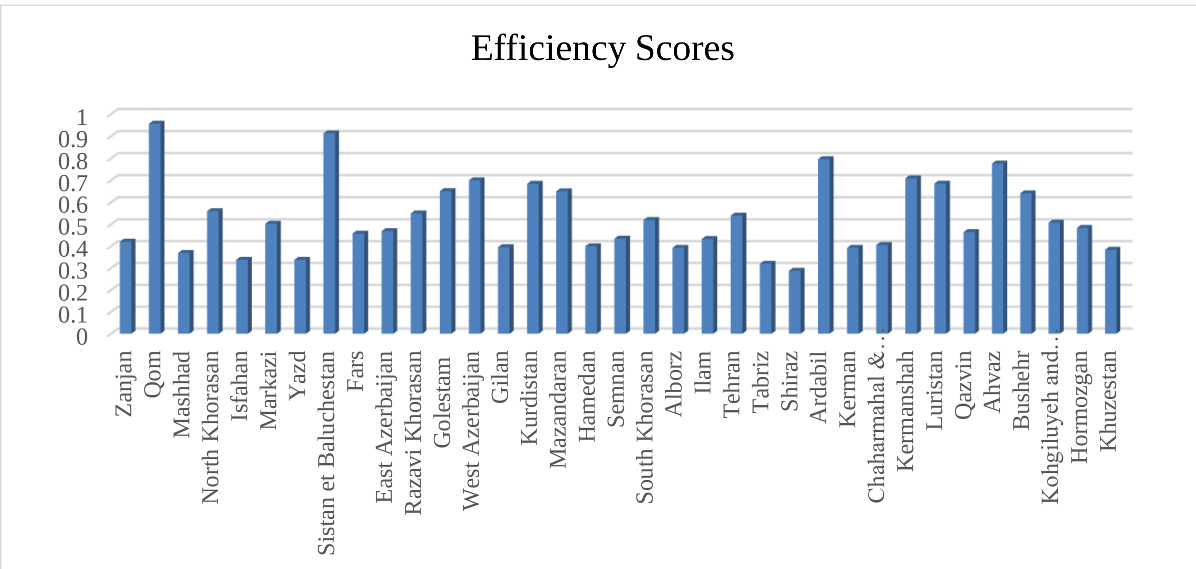

Figure. 5. Efficiency scores

DEA results show that Shiraz with the score of 0.288 had poor performance in 2020. Eight firms ranked between 3 and 3.99. nine companies score was between 4 and 4.99. Qom and Sistan et Baluchestan had the highest efficiency with 0.957 and 0.913 scores respectively. No company achieved an efficiency score of one in both stages.

4.4. Friedman and Nemenyi tests

Also, to examine whether there are statistically significant differences among the applied methods, the Friedman test was employed, followed by a post-hoc test to identify specific pairwise differences. Under the null hypothesis, it is assumed that the average ranks of the methods are equal. The Friedman test statistic, which approximately follows a chi-squared distribution, was calculated, and significance was assessed based on its critical value. The test yielded a chi-squared statistic of 28.417 with 2 degrees of freedom. The essential value of the chi-squared distribution at the 5% significance level and 2 degrees of freedom is 5.991. Since the test statistic exceeds the critical value ($28.417 > 5.991$), the null hypothesis of equal performance among the methods was rejected. This result indicated significant differences between at least two of the methods ($p < 0.001$).

Table 8: Nemenyi Test

Method	GRA	G-SAW
G-SAW	1.1e-06	-
DEA	0.0003	0.4560

Following the Friedman test, the Nemenyi post-hoc test was performed to identify significant pairwise differences. The results indicated that the GRA method significantly outperformed both G-SAW (p = 1.1e-06) and DEA (p = 0.0003). However, the difference between G-SAW and DEA was insignificant (p = 0.4560).

5. Discussion and conclusion

In this study, thirty-five electricity distribution companies selected as statistical population, and grey relational analysis, G-SAW and data envelopment analysis approaches selected as performance measurement tools. In grey analysis, numbers were normalized, then reference sequence and the grey coefficient calculated, and by multiplying relative weight to relational coefficients, the final grey relational grade obtained. In data envelopment analysis method, indices are classified into inputs and outputs. Finally, firms were ranked by three approaches. Results demonstrated that three approaches could be used to evaluate electricity distribution companies. However, GRA produced the most optimistic evaluations (scores: 0.486–0.764) and DEA provided granular insights into operational inefficiencies, particularly through its two-stage model (scores: 0.288–0.957). Including undesirable outputs (e.g., energy waste) allowed for a more nuanced assessment of sustainability trade-offs. G-SAW offered a balanced perspective (scores: 0.428–0.648) by integrating grey relational principles with additive weighting, though its conservative rankings may reflect stricter normalization protocols. Top-performing companies (e.g., Sistan et Baluchestan, Qom) can serve as benchmarks for operational best practices. Underperformers (e.g., Shiraz) require targeted interventions, such as infrastructure upgrades or process optimization, to address inefficiencies identified by DEA. The Friedman test confirmed significant differences in the performance rankings generated by GRA, G-SAW, and DEA. Post-hoc Nemenyi test further revealed that GRA significantly outperformed both G-SAW and DEA, demonstrating its robustness in handling incomplete data and multi-criteria decision-making. Also, no statistically significant difference was observed between G-SAW and DEA, suggesting overlapping utility in specific analytical contexts.

In fact, there are some limitations in DEA. First, the number of DMUs should exceed the number of inputs and outputs by two or three times, but GRA and G-SAW do not make assumptions about the number of indicators. (Kuo et al., 2008). Moreover, some indicators were unavailable for this study such as Return on Assets (ROA), Return on Equity (ROE), solvency or some qualitative data such as customers' satisfaction rate, employees learning and growth or their participation in decision making process. So, it is recommended that for future studies, quantitative or qualitative data might be used by researchers.

Developing effective strategies for sustainable management in the power sector presents a significant challenge. Policy-makers must base their decisions on well-informed insights that promote long-term technical and economic sustainability. The findings of this paper offer valuable guidance for researchers, planners, and decision-makers for several reasons. Firstly, the methodology presented enables the identification of key factors that influence productivity and efficiency changes over time. This insight can support regulators and managers in devising targeted measures to enhance performance. However, the limited selection of indices within Data Envelopment Analysis (DEA) has constrained the inclusion of specific critical indicators, such as revenue, project advancements, and power outages. Secondly, evaluating the performance of companies across different timeframes provides policymakers with a clearer understanding of the consequences of their decisions.

Finally, Policy-makers can leverage these findings to implement targeted interventions for underperforming companies, such as infrastructure upgrades or sustainability initiatives. Future research should expand the indicator set, incorporate dynamic analyses, and explore hybrid methodologies to refine performance evaluation frameworks further.

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