Energy production efficiency assessment using network data envelopment analysis

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Abstract

The performance of an energy generation system depends on three sectors of generation, transmission, and distribution. Especially when the power generation system has a decentralized structure in which different companies have different types of power plants, transmission, and distribution architectures. In this study, a network data envelopment analysis (NDEA) model is extended to assess the energy generation system's performance considering all three sectors of the regional electricity companies. There is a gap in the published DEA literature on energy network efficiency in studying the function of individual processes of these subsystems. After identifying the companies' structure, inputs, and outputs for all sectors, the extended NDEA model is implemented to estimate the efficiency of the whole energy generation network including production, transfer, and circulation sectors of the firms. The proposed model's network-based features allow computing the efficiency of individual subsystems and the whole system simultaneously. Iran's energy generation system, including all three sectors during 2015 – 2019, is used to verify the model. The results indicate that while the annual average efficiency score of electricity companies has been increasing by 2018, it was decreased during 2018-2019. The model can be easily applied to energy generation systems in other countries.

Keywords: performance evaluation, regional electricity companies, network data envelopment analysis; energy generation system

1. Introduction

Efficient energy production is a critical driving force for sustainable development. The political and economic structure of countries depends on their energy security, efficiency, and cost-effectiveness. Energy and its related issues influence national development plans, policies, and strategies in different countries with different economic levels, including developing and developed countries. Having enhanced energy efficiency and a diverse energy portfolio are the main two drivers to provide energy security and have a strict energy policy. In this paper, we considered both two drivers.

Regarding promoting energy efficiency, first, a rigorous efficiency assessment scheme is needed. To achieve this scheme, essential challenges in the energy field needs to be considered. First, having information about companies operating in the energy field. Second, protecting the environment in a way that energy consumption causes the least environmental effects. Third, correct pricing mechanisms and proper tariffs for highly efficient and renewable, sustainable, and environmentally friendly energy sources, which is the second driver for creating a secure energy supply.

Electricity is one of the energy kinds mostly at the center of attention due to its characteristics. Information about power consumption, energy voltage, users' composition, load curve, and electricity efficiency can be used to determine the development level of each country. Generating electricity and making it accessible involves three main phases of generation, transfer, and distribution. Therefore, each of these three sections' performance and efficiency influences the electricity industry's economy.

During recent decades, performance assessment of electricity generation companies has been a critical challenge for many scholars and scientists in the energy field. Lack of energy, energy loss, and increased energy demand are only some of the reasons for this growing attention to this challenge. However, most

of the studies carried out in the power generation field have only focused on evaluating power plants or power distribution companies, ignoring the local electricity generation companies; while, the efficiency of the local electricity firms considering all the sectors, including three sectors of production, transition, and dispersion is dealt with in this study as the first research gap. Also, while the conventional DEA formulations refers the decision-making unit (DMU) as a black box and cannot evaluate subsystems and subprocesses due to their complex structure, this paper proposes an interpretable model which evaluates every individual subsystem and subprocess within the regional electricity companies in all of the three sectors (the second research gap is coped with in this study). The subsequent parts of this article are designed as following: first a critical assessment of the published research is provided, followed by a gap analysis. In Part 3, the network data envelopment analysis (NDEA) approach is explained in detail. Then, a test problem is studied to verify the proposed framework and demonstrate the merit of the NDEA formulation, then, the results and discussion of the model implementation on the example in Part 5. Finally, some concluding remarks are provided by discussing what is missing and can be extended followed by recommending some future research directions.

2. Literature review

There are many studies for performance evaluation of energy generation systems concentrating on only the generation sector in the literature. In the following, the seminal studies on the generation sector, particularly on the production side.

Sozen et al. used a DEA model to assess several energy generation types in Turkey (Sözen, et al., 2010). They evaluated gas, coal, and lignite-based power plants. Also, Liu et al. evaluated gas and steam-based power plant performance in Taiwan during 2004-2006. Their studies show that it is better to use combined heat and power plants to achieve higher performance. They also found that energy saving is the best strategy to compensate for the low-performance subsystems (C. Liu, et al., 2010). In another study, Shrivastava et al. evaluate the efficiency by benchmarking Indian gas-based electricity generation units (Shrivastava, et al., 2012). Their findings reveal that the performance of low capacity electricity generation units is lower compared to bigger units. They also found that private units are less efficient than government-based units.

Some other studies are only considered the distribution sector of the electricity generation system. For instance, Mullarkey et al. units the Nonparametric DEA model to evaluate the electricity distribution units (Mullarkey, et al., 2015). They found that considering a goal-based decision maker preference scheme is effective for performance evaluation of the DMUs with uncertain data. Another example is the research conduction by Reyes et al. (Pérez-Reyes, et al., 2009). They assessed the performance of distribution units in Peru from 1996-2006. They found that the performance of the units was much higher in the early stages of their performance. A similar study conducted for Iran's power distribution units (Khodabakhshi, 2010). They also endorsed the previous study's findings while they have converted the stochastic model into the deterministic version. Petridis et al. created an NDEA to assess the performance of dispersal units in Turkey (Petridis, et al., 2019). They found Turkish distribution companies performing almost at an equal level of efficiency. Çelen and Yalçın have proposed a hybrid DEA/ TOPSIS/Fuzzy AHP model and applied it to the power dispersal subsystem in Turkey (Çelen, et al., 2012). More studies on electricity distribution companies performance assessment using DEA in different countries can be developed by Filippini et al. (Slovenia) (Filippini, et al., 2004), Savolainen (Finland) (Kopsakangas-Savolainen, 2004), Nakano and Managi (Japan) (Nakano, et al., 2008), Estache et al. (South African countries) (Estache, et al., 2008), Aghdam (Australia) (Aghdam, 2011), Tovar et al. (Brazil) (Tovar, et al., 2011), Jamasb, L et al. (Brazil) (Jamasb, et al., 2012) and Zhangna (Yuzhi, 2012).

Some studies have also examined the regional electricity companies. For example, Torkmani et al. have evaluated Azerbaijan's regional electricity companies' performance using a balanced scorecard method (Torkamani, et al., 2012). Their study indicated that this company acts in the financial better than other perspectives. Fujii et al. studied 22 local Indonesian power corporations using an hybrid DEA framework in terms of the operative efficiency aspect from 2002 to 2005 (Fujii, et al., 2011). Most companies that are studied in this investigation improved their performance from 2002 to 2004. They determined that the variables of power companies' efficiency improvement are energy loss and company place. Bai-Chen et al. use a two-level DEA formulation to compare the performance of thirty areas in China (Bai-Chen, et al., 2012). There are several studies on efficiency assessment for Iranian energy network (Alizadeh, Beiragh, et al., 2020; Beiragh, et al., 2020; Shafiei Kaleibari, et al., 2016).

Fallahi et al. measured performance level in Iran's electricity firms employing a DEA model (Fallahi, et al., 2011). They studied and estimated the energy performance indicators of 32 power firms over 2005-2016. Rezaee et al. used a combined game theoretic DEA formulation to assess gas-based electricity generation units' performance in Iran (Rezaee, et al., 2012). Atmaca et al. used the Analytic Network Process (ANP) to determine Turkey's best generation unit (Atmaca, et al., 2012). Also, a similar process has been followed for Iran's case (Alizadeh, Lund, et al., 2016; Alizadeh, Soltanisehat, et al., 2020). They compared to wind, coal, gas, hydroelectric, nuclear, lignite, and geothermal-based units.

However, in these studies, the researchers only consider one regional electricity company to evaluate, questioning the results' generality. In this paper, by evaluating 16 electricity generation companies, this problem is addressed. Another gap in the literature is only to consider limited electricity generation sources. For example, Tajbakhsh and Hassini (Tajbakhsh, et al., 2018) studied the performance of only power generation systems, which are only based on fossil-fuels. On the other hand, Liu (G. Liu, 2014) proposed a measure for performance assessment in only renewable-based power plants. Furthermore, many other studies on the impacts of environmental pollution (Abolghasemi, et al., 2014; Alizadeh, Khodaei, et al., 2016; Reza Alizadeh, et al., 2015; Alizadeh & Soltanisehat, 2020; Amirteimoori, et al., 2018; Beynaghi, et al., 2019; Essid, et al., 2018; Sadaghiani, et al., 2014; Soltanisehat, et al., 2019; Zamani Sabzi, et al., 2018), sustainability performance (M.-Q. Wu, et al., 2019), cost-effectiveness (Alizadeh, Majidpour, et al., 2016; R Alizadeh, et al., 2015; Azadi, et al., 2015; Badiezadeh, et al., 2018; Luthra, et al., 2017; X. Zhou, et al., 2016), resource efficiency (Bai, et al., 2019; Cagliano, et al., 2017; Halkos, et al., 2019; Kiani Mavi, et al., 2019; Xiaohong Liu, et al., 2019; Ross, et al., 2010; Soltanisehat, et al., 2020; J. Wu, et al., 2019; Zhang, et al., 2019; Z. Zhou, et al., 2019), and eco-efficiency (Alizadeh, et al., 2014; Bang, et al., 2019; Ezici, et al., 2020; Hu, et al., 2019; Xiuli Liu, et al., 2019; Mavi, et al., 2019; Shao, et al., 2019; Torres-Ruiz, et al., 2019; Wang, et al., 2019; Yu, et al., 2019; Zhu, et al., 2019), which only have focused on a limited set of energy sources in their analysis. However, in this paper, we consider all the possible electricity generation sources.

After assessing the published literature critically, two main gaps in the performance assessment using data envelopment analysis were pinpointed out: (i) Methodological gap: conventional data envelopment models do not consider the individual components of the complex systems in each decision making units during the assessment process. We answer the following question to address this gap: "what is the best DEA model for performance evaluation when there are interconnections among all the system components?" A network data envelopment model is designed to address this question, considering the relations of the complex system's components. Therefore, the performance of both individual components and the whole system can be evaluated by first estimating each component's performance scores and then integrating them to obtain the whole system's performance score. The whole system's initial serial structure should be transformed into a parallel structure by adding some extra connections to accomplish this goal. Based on these two structures, the whole structure's performance is decomposed

into the summation of the performance values of the parallel structures and the multiplication of the serial structure's components' values. This decomposing technique, the component that has the largest inefficiency value, is recognizable for later augmentation. (ii) Empirical gap: The developed NDEA model is studied by evaluating a complex power generation system, where there are all three sectors of generation, transmission, and distribution. We also consider the regional electricity generation firms as the subsystems that can operate in one, two, or three of these sectors. In the published literature on the energy generation system's performance evaluation, two sectors of generation and distribution have been extensively investigated while studying all three sectors that have not been touched yet. NDEA provides the ability to address this gap using its advantage in analyzing the network relations. Thus, the empirical gap of estimating performance scores of generation, transmission, and distribution subsystems can be calculated and integrated using the real data from all the regional electricity companies.

3. Method

DEA was presented by Charnes et al. (Charnes, et al., 1978). Without considering internal sectors and sub-sectors, they considered the organization as a black box and limited their calculations to preliminary in and out variables. In reality, the firms and organizations have a complex construction, and it is necessary to consider their sub-sectors in the performance evaluation. To address this challenge, NDEA models have been developed. Fare and Grasskopf (Fare, et al., 2000) discussed the importance of network DEA models. Castelli et al. (Castelli, et al., 2004) estimated the performance scores of dependent decision making subunits that make up the larger units. Lewis and Sexton presented a two-phase DEA to estimate units' efficiency in two stages (Lewis, et al., 2004). They also proposed a network and related sub-units in which some sub-unites produced sources for other sub-units, and other sub-units consume some of the produced sources. Castelli et al. (Castelli, et al., 2004) presented a novel DEA to evaluate hierarchal organized units' efficiency. Prieto and Zofio (Prieto, et al., 2007) evaluated the performance of different countries with different economies based on their technological growth's indicators in 2007. They implemented the input-output model for OECD countries through NDEA models. These input-output networks are optimized using production efficiency criteria.

3.1. Network data Envelopment analysis (NDEA)

Kao (Kao, 2009) introduced several models for evaluating DMUs using both series and parallel configurations. Performance has been defined based on multiplying units' efficiencies. Basic network structures are series and parallel structures, which are described in the subsequent parts.

3.1.1. Series and parallel configuration

When the subsystems perform in a linear form within a multi-section scheme, the system is considered as a series configuration. In this structure, a linear path from the start point (input variable) to the system's endpoint (output variable) is followed. Figure 1 shows the generic formula for series and parallel DEA structures.

a. Serie configuration

b. Parallel configuration

Figure 1. the general formula for series and parallel structures

In the series configuration, a DMU was supposed to h unites next to each other. Let X_{ij} represents the variables and Y_{rj} represents the out variables. Also, $Z_{pj}^{(t)}$ shows the procedure t for the medium variable and the DMU j . Obviously there is no constant medium variable for all the DMUs. Thus, the network configuration of the linear in/out the relationship for the DEA model shown in Figure 1.b is similar to the following model:

$$\begin{aligned}
 E_k &= \max \sum_{r=1}^s u_r Y_{rk} \\
 \text{s.t.} \\
 \sum_{i=1}^m v_i X_{ik} &= 1 \\
 \sum_{r=1}^s u_r Y_{rj} - \sum_{i=1}^m v_i X_{ij} &\leq 0, \quad j = 1, \dots, n \\
 \sum_{p=1}^q w_p^{(1)} Z_{pj}^{(1)} - \sum_{i=1}^m v_i X_{ij} &\leq 0, \quad j = 1, \dots, n \\
 \sum_{p=1}^q w_p^{(t)} Z_{pj}^{(t)} - \sum_{p=1}^q w_p^{(t-1)} X_{pj}^{(t-1)} &\leq 0, \quad j = 1, \dots, n; t = 2, \dots, h-1 \\
 \sum_{r=1}^s u_r Y_{rj} - \sum_{p=1}^q w_p^{(h-1)} X_{pj}^{(h-1)} &\leq 0, \quad j = 1, \dots, n \\
 u_r, v_i, w_p^{(t)} &\geq \varepsilon, \\
 r &= 1, \dots, s; \quad i = 1, \dots, m; \quad p = 1, \dots, q; \quad t = 1, \dots, h-1
 \end{aligned} \tag{1}$$

The optimal values for the decision variables in the above formulation are as u_r^* , v_i^* and $w_p^{(t)*}$. The function of each DMU is found through the following model:

$$\begin{aligned}
E_k^{(1)} &= \sum_{p=1}^q w_p^{(1)*} Z_{pk}^{(1)} \Big/ \sum_{i=1}^m v_i^* X_{ik} \\
E_k^{(t)} &= \sum_{p=1}^q w_p^{(t)*} Z_{pk}^{(t)} \Big/ \sum_{p=1}^q w_p^{(t-1)*} X_{pk}^{(t-1)} \quad t = 2, \dots, h-1 \\
E_h^{(t)} &= \sum_{r=1}^s u_r^* Y_{rk} \Big/ \sum_{p=1}^q w_p^{(h-1)*} X_{pk}^{(h-1)}
\end{aligned} \tag{2}$$

In model (2), it is clear that a DMU performs well if and only if the corresponding sub-units of them perform well.

3.1.2. Parallel configuration

In this type of configuration, single processes are functioning in a parallel and separate way. Single procedures are subsystems functioning alone and similarly within the subsystem. In a parallel configuration, the DMUs have a multi-level configuration, and sub-DMUs are organized in a parallel configuration. A generic parallel configuration is shown in Figure 1.b. The NDEA formulation for a parallel configuration is presented below:

$$\begin{aligned}
E_k &= \max \sum_{r=1}^s u_r Y_{rk} \\
s.t. \\
\sum_{i=1}^m v_i X_{ik} &= 1 \\
\sum_{r=1}^s u_r Y_{rj} - \sum_{i=1}^m v_i X_{ij} &\leq 0, \quad j = 1, \dots, n \\
\sum_{r=1}^s u_r Y_{rj}^{(t)} - \sum_{i=1}^m v_i X_{ij}^{(t)} &\leq 0, \quad j = 1, \dots, n; \quad t = 1, \dots, h \\
u_r, v_i &\geq \varepsilon; \quad r = 1, \dots, s; \quad i = 1, \dots, m
\end{aligned} \tag{3}$$

In Model (3) (parallel configuration), entries are split between sub-units, and the outcome comes out of the outcome of the whole sub-units. X_{ij} stands for the input variables for the DMU of j . $X_{ij}^{(t)}$ represents the unit of t in DMU of j . This is while u_r^*, v_i^* represents the optimal solutions of the outcome attained by Model (3). In this case, the efficiencies are as the model (4).

$$\begin{aligned}
E_k &= \sum_{r=1}^s u_r^* Y_{rk} \Big/ \sum_{i=1}^m v_i^* X_{ik} = 1 - s_k^* \\
E_k^{(t)} &= \sum_{r=1}^s u_r^* Y_{rj}^{(t)} \Big/ \sum_{i=1}^m v_i^* X_{ij}^{(t)} = 1 - s_k^{(p)*} \Big/ \sum_{i=1}^m v_i^* X_{ij}^{(t)} = 1 - \hat{s}_k^{(p)*} \quad t = 2, \dots, h-1
\end{aligned} \tag{4}$$

Each DMU will perform well when their corresponding sub-DMUs perform well.

3.2. NDEA formulation

Previously used DEA formulations have not fully taken into account the entire system beneath assessment and usually ignore the subsystems and middle procedures. To deal with this gap, an extended NDEA formulation is created taking into account the linkage among the middle procedures together with the efficiency of the entire network. This network-based assessment framework is built by (Färe, et al., 1997), and strengthened by (Kao, 2009) to encompass the whole system and individual units function assessment using a relation-based scheme. Figure 2 shows the performance assessment scheme and the partitioning approach implemented in a network-based configuration.

Figure 2. The network-based configuration for three units.

Xs show the inputs and Ys shows the outputs. First subsystem creates the first result based on what it obtains from the input 1 and 2. On the other hand, there is initial results obtained by the Subsystem 3. The Subsystem 2 generates the result 2 based on both inputs 1 and 2. Similar to the Subsystem 1, output 2 is partially used in the Subsystem 3 to generate the electricity. Also, some parts of the Subsystems 1 and 2 caused some parts of the Results 1 and 2. Finally, some parts of the Subsystems 1 and 2 resulted in some parts of the Results 1 and 2.

$X_{ij}^{(t)}$ shows the Subsystem i for DMU j where three different time periods are shown by t . The input for the whole network is shown by the accumulation of the first $X_{ij}^{(1)}$, second $X_{ij}^{(2)}$ and third $X_{ij}^{(3)}$ subsystems. $Y_1^{(o)}$ and $Y_1^{(I)}$ are the outcome of the Subsystem 1 in which $Y_1^{(o)}$ shows the final outcome, and $Y_1^{(I)}$ represents the portion of the Subsystem 3 in generating the electricity. Equally, $Y_2^{(o)}$ and $Y_2^{(I)}$ are the outcome of the Subsystem 2 in which $Y_2^{(o)}$ shows the final outcome and $Y_2^{(I)}$ represents the portion of the Subsystem 3 in generating the electricity. Besides, u_r shows the multipliers for outcome r while v_i shows the multiplier for input i . To estimate the efficiency score for the DMU k , each condition of each subsystem must be met in a way that we do not go over the threshold of the aggregate values for the inputs when we are estimating the outcomes. Summing up all these conditions we come up with the following formulation:

$$\begin{aligned}
E_k &= \max u_1 Y_{1k}^{(o)} + u_2 Y_{2k}^{(o)} + u_3 Y_{3k} \\
\text{s.t. } & v_1 X_{1k} + v_2 X_{2k} = 1 \\
& (u_1 Y_{1j}^{(o)} + u_2 Y_{2j}^{(o)} + u_3 Y_{3j}) - (v_1 X_{1j} + v_2 X_{2j}) \leq 0, \quad j=1, \dots, n \\
& u_1 Y_{1j} - (v_1 X_{1j}^{(1)} + v_2 X_{2j}^{(1)}) \leq 0, \quad j=1, \dots, n \\
& u_2 Y_{2j} - (v_1 X_{1j}^{(2)} + v_2 X_{2j}^{(2)}) \leq 0, \quad j=1, \dots, n \\
& u_3 Y_{3j} - (v_1 X_{1j}^{(3)} + v_2 X_{2j}^{(3)} + u_1 Y_{1j}^{(I)} + u_2 Y_{2j}^{(I)}) \leq 0, \quad j=1, \dots, n \\
& u_1, u_2, u_3, v_1, v_2 \geq \varepsilon.
\end{aligned} \tag{5}$$

Such that the first line provides the connection with the whole network, and the rest of the constraints bounds the functioning of the subsystem together. All these equations added to NDEA compared to the conventional DEA provides higher differentiating ability. Thus, we estimated the efficiency values based on the created network. Additionally, since the new constraints are framed based on individual subsystems and not the whole system no DMU has the highest efficiency as '1'. Thus, it takes place in the 2nd and 3rd formulations. By calculating u_1^* , u_2^* , u_3^* , v_1^* and v_2^* through model (5), we compute the efficiency values for the network shown in Figure 2:

$$\begin{aligned}
E_k^{(1)} &= u_1^* Y_{1k} / (v_1^* X_{1k}^{(1)} + v_2^* X_{2k}^{(1)}) \\
E_k^{(2)} &= u_2^* Y_{2k} / (v_1^* X_{1k}^{(2)} + v_2^* X_{2k}^{(2)}) \\
E_k^{(3)} &= u_3^* Y_{3k} / (v_1^* X_{1k}^{(3)} + v_2^* X_{2k}^{(3)} + u_1^* Y_{1k}^{(I)} + u_2^* Y_{2k}^{(I)})
\end{aligned} \tag{6}$$

4. Case study: Iranian local electricity firms

The architecture of the electricity sector in Iran is different compared with other countries. In Iran, there are local electricity firms with the production, transmission, and circulation areas. The researchers have evaluated one of the three mentioned sectors, separately and there is no integrated framework to investigate the regional companies with all sectors. This paper presents an integrated network DEA model to estimate the regional electricity companies' efficiency scores, production, transfer networks, and circulation firms, simultaneously.

Iran's local electricity firms work beneath Tavanir which manages production, transfer, and circulation of the electricity throughout the country. Thus, all of the firms have similar goals and regulations and only have some little differences like geographical domain, these companies' general structure.

4.1. The network architecture of Iran's regional power companies

Figure 3 indicates a network architecture designed for Iranian regional electricity companies. As shown, the network structure of system 1 is related to generation and transmission sectors, and system 2 is related to distribution companies. It is notable that the electricity distribution companies in Iran are independent, and therefore, they are considered system 2 in Figure 3. Also, in Figure 3, all in and out variables of subsystems have been recognized. The variables required for the efficiency assessment of local power firms are as follows:

- z_1^0 : Nominal power (kW)
- z_2^0 : Costs of consumed fuel (Rial)

- z_1^1 : produced energy (MWh)
 z_1^2 : Energy delivered to distribution companies (MkWh¹)
 x_1^1 : Total size of transmission unit (MVA)
 x_2^1 : Distance between generation and circulation points (Km)
 x_3^1 : Energy reception from adjacent companies and power imports (GWh)
 y_1^1 : sending energy to adjacent companies and exporting power (GWh)
 z_1^3 : Total sold energy (MkWh)
 z_2^3 : Number of costumers (*1000)
 x_4 : Distribution lines length (Km)
 x_5 : Number of distribution companies' human source (*1000)

Figure 3. the network structure designed for regional electricity companies in Iran.

In this study, data from 2015 to 2019 is retrieved from various public reports of the Ministry of Energy and specifically Tavanir organization. The network DEA model is expressed for the local electricity firms as below:

²million KWh

$$\begin{aligned}
E_k &= \text{Max} \sum_{\substack{l \in I \\ p=3}} w_{lp} z_{lk}^{(p)} + \sum_{\substack{r=1 \\ p=1}}^s u_r y_{rk}^{(p)} \\
s.t \\
\sum_{\substack{l \in I \\ p=0}} w_{lp} z_{lk}^{(p)} + \sum_{i=1}^m v_i x_{ik}^{(p)} &= 1 \\
(\sum_{\substack{l \in I \\ p=3}} w_{lp} z_{lj}^{(p)} + \sum_{\substack{r=1 \\ p=1}}^s u_r y_{rj}^{(p)}) - (\sum_{\substack{l \in I \\ p=0}} w_{lp} z_{lj}^{(p)} + \sum_{i=1}^m v_i x_{ij}^{(p)}) &\leq 0 \\
j &= 1, \dots, 16 \\
\sum_{\substack{l \in I \\ p=3}} w_{lp} z_{lj}^{(p)} - (\sum_{\substack{l \in I \\ p=1}} w_{lp} z_{lj}^{(p)} + \sum_{i=1}^m v_i x_{ij}^{(p)}) &\leq 0 \\
j &= 1, \dots, 16 \\
(\sum_{\substack{l \in I \\ p=2}} w_{lp} z_{lj}^{(p)} + \sum_{\substack{r=1 \\ p=1}}^s u_r y_{rj}^{(p)}) - (\sum_{\substack{l \in I \\ p=1}} w_{lp} z_{lj}^{(p)} + \sum_{i=1}^m v_i x_{ij}^{(p)}) &\leq 0 \\
j &= 1, \dots, 16 \\
\sum_{\substack{l \in I \\ p=1}} w_{lp} z_{lj}^{(p)} - \sum_{\substack{l \in I \\ p=0}} w_{lp} z_{lj}^{(p)} &\leq 0 \\
j &= 1, \dots, 16 \\
u_r, v_i, w_i &\geq 0
\end{aligned} \tag{7}$$

Model (7) shows the efficiency value for local power firm k represented by the model's objective. Also, to estimate the performance of network sub-sectors, the model (4) can be applied.

5. Results and discussion

Table 1 indicates the performance scores for local electricity firms for five years in Iran. The 1st column indicates the local power firms. The 2nd column is the efficiency scores, and the third column shows each regional electricity company's rank for five years. Table 1 shows that the companies Fars, Khorasan, and Semnan have been introduced as superior companies from an efficiency perspective for five years. Moreover, Yazd, Tehran, and Sistan and Baluchestan had the lowest efficiency values among the firms. The mean performance score of the local power firms is 0.842 and indicates that these firms function well.

Table 1. The mean efficiency of local electricity firms between 2015 and 2019

DMUs	Efficiency score	Rank
Azerbaijan	0.858	11
Bakhtar	0.861	10
Esfahan	0.853	12
Fars	0.954	1
Gharb	0.907	5
Ghilan	0.908	4
Hormozghan	0.777	13
Kerman	0.905	6
Khorasan	0.92	2

DMUs	Efficiency score	Rank
Khozestan	0.862	9
Mazandaran	0.886	8
Semnan	0.912	3
Sistan & Baluchestan	0.475	16
Tehran	0.716	15
Yazd	0.771	14
Zanjan	0.891	7

Table 2 displays the efficiency values of local electricity firms over 2015-2019. To better display, Figure 4 also indicates the changes in the efficiency of local electricity firms between 2015 and 2019.

Table 2. The efficiencies of local electricity firms between 2015 and 2019

DMUs	2015	2016	2017	2018	2019
Azerbaijan	0.922	0.889	0.832	0.836	0.815
Bakhtar	0.898	0.896	0.867	0.89	0.75
Esfahan	0.834	0.828	0.973	0.83	0.802
Fars	1	1	0.981	0.847	0.94
Gharb	0.957	0.959	0.953	0.961	0.707
Ghilan	0.941	0.984	0.92	0.855	0.846
Hormozghan	1	0.831	0.823	0.719	0.514
Kerman	0.854	0.93	0.977	0.974	0.788
Khorasan	0.922	1	0.943	0.921	0.814
Khozestan	1	0.966	0.771	0.775	0.795
Mazandaran	0.919	0.917	0.825	0.860	0.912
Semnan	0.793	0.942	0.946	0.885	0.994
Sistan & baluchestan	0.536	0.510	0.528	0.512	0.288
Tehran	0.878	0.787	0.684	0.612	0.616
Yazd	0.804	0.782	0.707	0.99	0.573
Zanjan	0.819	1	0.925	1	0.713
Mean	0.88	0.889	0.853	0.842	0.742

Figure 4 indicates that the regional electricity company Sistan and Baluchestan has the weakest performance from 2015 to 2019. Fars regional company, which was introduced as the best company for five years, also functions better compared to other firms. The efficiency curve of power firms in 2015 is higher than in other years, and it is lower than in other years in 2019. Besides, Iranian regional electricity companies had better performance in 2016, while they had weaker performance in 2019. For better analyses, Figure 5 shows the annual average efficiency score of regional electricity companies between 2015 and 2019. It shows that scores of electricity energy decreases each year since 2016. The company's performance in 2016 could be a reference year for the Energy Department to increase energy efficiency after 2019.

Figure 4. performance scores for regional electricity companies

Figure 5. The annual average performance score of regional electricity companies from 2015 to 2019

The performance values of the generation subsystems are displayed in Table 3.

Table 3. The performance scores of power plants from 2015 to 2019

DMUs	Steam	Gas	Hybrid cycle	Diesel	Hydroelectric and new energy
Azerbaijan	0.3613	0.6918	0.7545	0.6372	0.9781
Bakhtar	0.4479	0.6602	-	-	0.6969
Esfahan	0.529	0.6594	-	0.5948	0.7827
Fars	-	0.6719	0.6296	0.6209	0.6467
Gharb	0.4195	0.7463	0.5467	0.5956	-
Ghilan	0.8109	0.5175	0.8843	-	0.5187
Hormozghan	0.3604	0.7563	-	0.5326	-
Kerman	0.6111	-	0.6981	-	0.6845
Khorasan	0.6978	0.7482	0.7864	0.4867	0.6009
Khozestan	0.6379	0.8663	-	-	0.7021
Mazandaran	0.3949	-	0.8163	-	0.6805
Semnan	-	0.5947	-	-	-
Sistan & baluchestan	0.5876	0.5569	-	0.419	0.6278
Tehran	0.4569	0.7389	0.8099	-	0.6676
Yazd	0.3721	0.7942	0.7268	0.7334	-
Zanjan	-	-	-	-	-
Mean	0.5144	0.6925	0.7392	0.5775	0.6897

Dashes observed in some lines of Table 3 indicate that the considered regional electricity company has no power plants. For example, Isfahan regional electricity company has no combined cycle power plant. Khozestan regional electricity company shows the highest performance with the scores of 0.8663 and 0.8762 among steam and gas power plant subsystems (see Table 3). Moreover, among subsystems of combined cycle power plants, Gilan local electricity firm (efficiency value of 0.884, among diesel power plant subsystems, Fars regional electricity firm (efficiency value of 0.721) and subsystems of hydroelectric plants and new energy, Azerbaijan regional electricity company have the best performance. The mean value of performance scores of the power plants in Table 3 exhibits the hybrid cycle plants have the highest performance in 5 years 2015 to 2019. Also, gas power plants, hydroelectric plants, and new energy, diesel power plants, and steam plants have performed well following hybrid cycle plants. Figure

6 also indicates the variations in the performance of the steam plants subsystem from 2015 to 2019. It shows that Esfahan's efficiency scores in 2017, Khuzestan in 2017, Zanjan in 2015, Sistan & Balochistan in 2015, and Gilan in 2016 are one and these DMUs have the best performance in steam power plants.

Also, Figure 7 indicates the efficiency change of the gas power plants subsystem from 2015 to 2019. It shows that Khuzestan in 2017 has the best performance between gas power plants from 2015 to 2019 in Iran. Zero value for Zanjan, Kerman, and Mazandaran shows that these DMUs (regional electricity companies) do not have gas power plants in their area.

Figure 6. The performance of the steam power plants subsystem between 2015 and 2019.

Figure 7. The performance of gas power plants subsystem between 2015 and 2019

Figure 8 indicates the efficiency change of the combined cycle power plants subsystem from 2015 to 2019. It is evident from Figure 8 that Tehran regional electricity company has the best performance in 2016 with a score of 1. The mean performance score of combined cycle power plants is 0.7392 from 2015 to 2019. Figure 8 indicates that Gilan regional electricity company performed above the average range and has the best performance in this sector (see Table 3). Figure 9 and Figure 10 indicate the efficiency change of Diesel Power Plants and hydroelectric plants and new energy subsystems from 2015 to 2019.

Figure 8. The efficiency of the combined cycle power plants subsystem from 2015 to 2019.

Figure 9. The efficiency of diesel plants and new energy subsystems from 2015 to 2019.

Figure 10. The efficiency of hydroelectric plants and the new energy subsystem from 2015 to 2019.

In Table 4 the efficiency values for the transmission and circulation subsystems (SS) and electricity distribution companies related to each local electricity firms is indicated. Dashes observed in Table 4 show that the related regional electricity company transfers its produced energy to only one electricity distribution company. For example, Isfahan regional electricity companies (Bakhtar) is concerning three power distribution companies, and Sistan and Baluchestan and Semnan regional electricity companies have a relation with just one distribution company. As shown in Table 4, Seman regional electricity company indicates the best performance in the transmission sector subsystem compared with other companies.

Table 4. The efficiency values calculated for the transfer and circulation between 2015 and 2019

DMUs	Transmission sector	Distribution Subsystem (S) 1	Distribution S2	Distribution S3	Distribution S4
Azerbaijan	0.9677	0.7584	0.6627	0.7206	0.8523
Bakhtar	0.9721	0.6591	0.6351	0.747	-
Esfahan	0.8677	0.8107	0.8719	0.7583	-
Fars	0.798	0.601	0.5645	0.7803	-
Gharb	0.8033	0.7784	0.7536	0.7392	-
Ghilan	0.9329	0.7263	-	-	-
Hormozghan	0.6984	0.582	-	-	-
Kerman	0.9446	0.6415	0.6693	-	-
Khorasan	0.8646	0.6782	0.5696	0.5745	0.8365
Khozestan	0.7716	0.7662	0.5666	0.6172	-
Mazandaran	0.875	0.7425	0.7746	0.776	-
Semnan	0.9765	0.5746	-	-	-
Sistan & baluchestan	0.7576	0.5512	-	-	-
Tehran	0.7419	0.728	0.6561	0.6421	-
Yazd	0.9091	0.652	-	-	-
Zanzan	0.8924	0.6471	-	-	-

6. Conclusion

In this paper, considering multi-dimension and complicated structure, a suitable network was designed for Iran's regional electricity companies. The proposed network considered the production, transfer, and electricity circulation segments as subsystems. A network DEA (NDEA) model was then suggested to estimate the performance scores for all sectors in the network. In this study, to evaluate Iranian regional electricity companies' performance, the actual data from 2015 to 2019 were used. To overcome the drawback of conventional DEA formulations in the efficiency measurement of subprocesses within the

complex system, an NDEA formulation taken into account the relationships between the subsystems within the system has been created. Our contribution is to make the simultaneous performance assessment of the whole system and individual subprocesses possible. Also, the proposed methodology enables temporal analysis during the performance evaluation. In other words, considering the linear relationships of the different time periods makes the system components' performance evaluation during multiple periods possible. These contributions become more remarkable as time aspect of the data comes into the picture. In other words, the proposed NDEA performs well for the time series data and predicting the network's performance is crucial. Thus, filling these gaps empowers the decision makers in complex energy production systems assessment to assess the efficiency of the systems more accurately.

Besides these contributions, the practical challenge and the research gap of a thorough assessment of each and individual subsystem in an electricity production network has been tackled utilizing the network-based advantage of the created formulation. To demonstrate the applicability and reliability of the developed NDEA model, a real electricity production network has been built, taking the energy generation system's complexity into account. Afterward, the efficiency values of all three subsystems have been estimated through five-time horizons. According to the obtained values, the mean of local electricity firm efficiency was 0.841 (out of 1) during the studied time span, that exhibits a good efficiency. Moreover, regional electricity companies Fars, Khorasan, Seman, and Gilan have top ranks, respectively.

The created formulation is usable in various types of problem, other countries, diverse time spans under different circumstances. Also, the extended version of the created NDEA can be used for the technologically more advanced or developed countries with private corporations and more competitive energy markets.

The proposed NDEA model addresses two main gaps in performance evaluation using data envelopment analysis, including one methodological gap and one empirical gap. Regarding the methodological gap, there exists a shortcoming of conventional DEA when the units in DMUs are interconnected, and each subsystem's performance affects other components. Our proposed NDEA model enables the system analyzers to evaluate the system's performance considering their different interrelations in these cases. Thus, the entire system's performance can be assessed by estimating the performance scores of each component and integrating them in a network structure.

There is also an empirical gap in the current pool of knowledge in evaluating the efficiency of the electricity production networks in developing countries like Iran, considering all the system components, including all three sectors. The developed NDEA enables the energy system's performance analyzers to address this gap using its network-based feature. Thus, the empirical gap of estimating performance scores of production, transfer, and circulation elements can be calculated and integrated using the real data from all the regional electricity companies.

There are some limits in this research which can be addressed in future research. Particularly there is a challenge in collecting and cleaning the valid and verified data in Iran. Thus, we believe the analysis can be extended if more data is available, specially in case of monthly data availability. Also, uncertainty management can be added to the analysis considering fuzzy sets. Multipliers can be extended using an envelopment scheme instead of merely efficiency value-based scheme. Finally the scale can be dynamic instead of constant scheme used in this study.

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Figures

Figure 1

the general formula for series and parallel structures

Figure 2

The network-based configuration for three units.

Figure 3

the network structure designed for regional electricity companies in Iran.

Figure 4

performance scores for regional electricity companies

Figure 5

The annual average performance score of regional electricity companies from 2015 to 2019

Figure 6

The performance of the steam power plants subsystem between 2015 and 2019.

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