International Journal of Applied Operational Research
Vol. 12, No. 4, pp. 19-53, Autumn 2024

Journal homepage: ijorlu.liau.ac.ir

Greenhouse gases allocation efficiency assessment in the electricity supply chain using the zero-sum gains model: a case study in the power industry

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Received: 16 June 2024; **Accepted:** 20 August 2024

Abstract The energy and power plant sectors of the power industry are among the major greenhouse gas emission sources. Oil and gas fields, refineries, and power plants should control harmful emissions to prevent pollutants from damaging the environment. A practical way of doing this is to monitor the total emissions amount in the electricity supply chain divisions and establish emissions trading rights, assuming that the allocation of the total emissions amount will be determined based on the target total amount. The current paper, applying the input-oriented ZSG-DEA model, computed the allocation efficiency of nitrogen oxides, sulfur oxides, carbon dioxide, and methane emission rights in the energy and power plant sectors of the electricity supply chain. For this to happen, the inefficient divisions had to decrease their emissions and search for partners that enabled them to reduce their emissions to keep the global emissions unchanged. With this in mind, the proposed approach in the present study distinguished effective sectors of an electricity supply chain with a high emission level as a cooperative set that provided a compensatory reduction to achieve the established limit. The results suggested that oil fields had a fundamental need for sulfur monoxide and carbon dioxide reduction in 70% of the supply chains, while the gas field emission efficiency of 50% of the supply chains was approximately close to 1. Although power plants were efficient in at least 70% of the supply chains, some power plants emitted the highest amounts of sulfur oxide because they lacked investment and effective cooperation for pollution abatement.

Keyword: Carbon emission trading, Emission efficiency, Pollutant emissions trading rights, Sustainable supply chain.

1 Introduction

The rapid growth of climate change can alter the balance between species and negative environmental impacts such as heatwaves, droughts, floods, and deforestation. Based on the United Nation Framework Convention on Climate Change (UNECCC) and the last pogranatme carbon project, Iran produced about 780 million tons of greenhouse gases in 2019. This indicates that, contrary to the Paris climate change global agreements, greenhouse gas emissions increased by more than 20% in 2019 compared to 2016. Nitrogen oxides, sulfur oxides, and carbon dioxide (CO_2) are major environmental concerns when it comes to

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[DOI: 10.71885/ijorlu-2024-1-672]

sustainable power production. Nowadays, the acceleration of climate change and the evidence of environmental hazards demonstrate the importance of environmental problems more than ever. The available carbon amount in the earth's atmosphere is a determinative factor of the earth's temperature. In recent decades, industrial growth has increased CO_2 levels in the earth's atmosphere. Climate change will become apparent on a time horizon, and human activities will result in improvements in economic activity. Controlling and managing greenhouse gas emissions plays a key role in minimizing wasted energy in the energy and power plant sectors, as well as in transmission and distribution networks.

Globally, fossil fuels provide a large part of the energy we consume. This results in widespread pollution, which not only endangers human health and other organisms but also reduces the economic return on industrial activities. Power plants are the biggest consumers of fossil fuels among the major energy consumption centers. Pollution caused by power plants is unavoidable for every country since handling greenhouse gases, especially CO_2 gas, is part of the basic requirements of the power industry. Pollutant emissions control and management of greenhouse gases play a fundamental role in wasted energy mitigation in the energy and power plant sectors as well as transmission and distribution networks. Therefore, to overcome such issues, supply chain management should lead to competition and cooperation motivation between divisions of electricity supply chains. One of the ways of reducing pollutant emissions of electricity supply chain divisions is to control the total amount of emissions under the premise that allocation of initial emissions is defined based on the target total amount, as the level of initial emissions determines emission right trading. Therefore, the divisions of the supply chain try to fulfill obligations along with greenhouse gas abatement on a local and global scale.

Carbon Emission Trading allows the supply chain divisions with low emission levels to provide emission rights for the trade-off of the rest of their emission capacity to the divisions with high emission levels. Indeed, the emission rate of pollutant gases, especially monoxide nitration (NO_X), monoxide sulfur (SO_X), CO_2, and methane, should not be increased from the specified limit in the energy and power plant sectors. Decreases in greenhouse gases, particularly CO_2, in the energy and power plant sectors not only reduce environmental harm but also create competition among electricity supply chain divisions for the trade of carbon and other pollutant gases. Indeed, the supply chain divisions will be obliged to reduce their emission rate to the allowable limit as their emission rate should not be more than the determined limit. In this case, those divisions of the electricity supply chain that have the necessary capacities for harmful emissions reduction can invest in projects for greenhouse gases and wasted energy reduction in the energy and power plant sectors of other supply chains as the proven reduction of pollutants concerning projects' performance is applied in financial assets production or carbon and greenhouse gas credits in local and global markets. Such a verification approach can provide information about the allocation of initial emission rights in emission rights trading.

In this study, we will investigate how electricity supply chain divisions with high levels of pollutant emissions can reduce greenhouse gas emissions through collaboration and investment in energy and power plant sectors of other supply chains to achieve emission efficiency. In this case, the energy and power plant divisions of supply chains with low emission levels that achieve emission efficiency relative to the energy and power plant divisions of other supply chains will be obliged to reduce the amount of redundant emissions of inefficient divisions in terms of the initial emission rights. Indeed, the efficient divisions of the energy and power plant sectors can provide capital expenditure by the right of emission reduction, and the inefficient divisions of supply chains or investable sectors can earn

[DOI: 10.71885/ijorlu-2024-1-672]

economic income in addition to the obtainment of new technology and environmental protection.

In other words, the efficient divisions of energy and power plants are persuaded to decrease the greenhouse gases of energy and power plant divisions in inefficient divisions of other supply chains. Divisions whose emissions are less than the allowable limit under carbon emission trading can continue to sell to divisions whose emissions are greater than the determined limit. Carbon finance is one of the financial instruments for greenhouse gas reduction as proven decrement of harmful pollutants provides financial assets or carbon credits at the local and national levels. Therefore, supply chain management identifies an allowable limit of greenhouse gas emissions for different divisions of supply chains. The supply chain divisions that obtain emissions efficiency play a fundamental role in environmental preservation and the harmful effects of greenhouse gases in the energy and power plant sectors.

In this study, undesirable outputs such as greenhouse gases, especially CO_2, are considered inputs in the energy and power plant sectors of the electricity supply chain as the divisions are divided into two categories based on emission efficiency scores. The supply chain divisions that obtained emission efficiency have necessary technologies to support projects' performance, such as fuel consumption decrease and energy productivity increase in energy and power plant sectors; prevention of power losses in transmission and distribution networks; and utilization of renewable energy resources for harmful emissions reduction. As a result, efficient supply chain divisions have the necessary facilities for harmful emissions mitigation because they can reduce pollutant emissions above the allowable limit in inefficient supply chain divisions. In addition, the inefficient parts of the supply chain make them work together and invest in reducing harmful emissions.

In the current paper, first, the emissions efficiency of each supply chain division is calculated as inefficient divisions comprising a single cooperation group, and second, the efficiency is searched for in the original DEA efficient frontier under the zero-sum gains (ZSG) DEA model to reallocate the emissions and create a new frontier. According to this strategy, the inefficient divisions of supply chains searching for efficiency must lose some amount of input (greenhouse gases) and the other efficient divisions must receive that amount of input to keep the total sum of emissions constant.

There are two type of regulations on air pollutants management. One is tax regulation and the other is the emission right trading.

Ruth et al. [1], Malcolm and Zhang [2], Fischer and Newell [3], Rive [4], and Plin and Kesidou [5] have studied the effect of tax regulation on pollutant emission.

Dales [6] formulated the concept of emission right trading for the first time to include the concept of emission right trading for the reallocation of pollutant emissions and the definition of the initial allocation of emission rights. He suggested that emission rights of economic entities can be stipulated in the form of emission permits, and surplus emission rights can also be traded. Burton and Sanjour [7] proposed the method of stipulating emission rights in the form of permits as the initial allocation of emission rights.

Let us now suppose that supply chain divisions apply undesirable outputs as inputs. Thus, greenhouse gas emissions are considered inputs in the energy and power plant sectors, while power losses are inputs in transmission and distribution lines. This study proposed an approach based on the input-oriented zero-sum gains DEA model (ZSG-DEA). In the first phase, the efficiency of a supply chain with the five stages and the fifteen divisions is computed by a non-radial model as the efficiency scores determined for each of the emissions and their weighted average play an efficiency role in the objective function. Then, in the next

[DOI: 10.71885/ijorlu-2024-1-672]

phase, the ZSG-DEA BCC input-oriented model was applied to 10 supply chains for the emissions reallocation.

The remainder of this paper is organized as follows: In Section next, we present an appropriate literature review on how DEA has been used for research on harmful emissions reduction and wasted energy inhibition in energy and power plants' networks and transmission and distribution lines. The following section is devoted to introducing the approach for calculating proportional reallocation of emissions for supply chain divisions in the presence of inputs (pollutant emissions), desirable output, and the two sets of intermediate measures. The next section presents a case study to demonstrate the applicability of the proposed method to the Iranian power industry. Finally, the last section presents conclusions.

2 Literature review

The following subsections briefly summarize various studies on the ZSG-DEA input-oriented model, environmental and operational assessment, and green supply chain management (GSCM).

2.1 The emissions trading rights and ZSG-DEA models

In the early twenty-first century, many scholars, such as MacKenzie et al. [8, 9], Chávez et al. [10], and Pickl et al. [11], have paid attention to the allocation and trading of air pollutant emission rights. Chinese scholars such as Chen et al. [12] and Ma et al. [13] applied the linear programming method to the study of air pollutant allocation, but they did not evaluate the interprovincial allocative efficiency of pollutant emission rights since air pollutant emission belongs to undesirable outputs. Lozano and Villa [14] and Avellar et al. [15] proposed a method for dealing with issues of interdependence input (or output) among decision-making units (DMUs) when looking for targets. Avellar et al. applied functional form to the efficient frontier, which is valid for the CCR model. Also, Lozano and Villa [14] calculated the efficiency maximization of each DMU simultaneously to the minimization of total resources or maximization of total production based on the BCC model.
According to the framework of the Kyoto protocol, Gomes and Lins [16] proposed the ZSG-DEA model to reallocate the CO_2 emission rights of each country. They asserted that the independence of DMUs does not exist in cases of competition and cooperation since DEA models treat the DMUs as independent DMUs. They proposed strategies for DEA target searching, with emphasis on the proportional reduction strategy. Guo et al. [17], based on the ZSG-DEA model, regarded $PM_{2.5}$ as an undesirable output and assessed the discharge efficiency of $PM_{2.5}$ in different provinces under the condition of constant total $PM_{2.5}$ emissions while taking the atmospheric environmental capacities of provinces into account. Wu et al. [18] proposed a model DEA for the allocative efficiency of $PM_{2.5}$ emission rights based on a ZSG-DEA model. With the input and output data of 29 provinces, the factor allocation level was calculated through the ZSG-DEA model, assuming that the overall $PM_{2.5}$ emission efficiency was maximized. Wu et al. [19] achieved input optimization to reduce the undesirable outputs of environmental hazards. They proposed a DEA model in which haze emissions can be controlled by cutting down on input indicators with data on $PM_{2.5}$ in China.

[DOI: 10.71885/ijorlu-2024-1-672]

2.2 Environmental and operational assessment

Shephard [20] defined weak disposability and proposed basic production axioms based on it. Seiford and Zhu [21] proposed a DEA model in the presence of undesirable outputs. Färe et al. [22] and Fare and Grosskopf [23] proposed a new property for modeling undesirable outputs as the weak disposability hypothesis. They built a production possibility set, satisfying the standards available in Banker et al. [24]. Hu and Wang [25] evaluated operational and environmental efficiency in China’s thermal power industry using a global fractional model, taking an effectiveness measure as a complement to an efficiency measure. Zhang et al. [26] proposed a three-stage model based on data envelopment analysis (DEA). They calculated the industrial eco-efficiency of 30 provinces in China. Also, Zhang et al. [27] calculated industrial eco-efficiency in China as a provincial quantification using a three-stage data envelopment analysis. Wang et al. [28] calculated operational and environmental performance in China’s thermal power industry as considered an effective measure as a complement to an efficiency measure. Sueyoshi and Goto [29] proposed returns to scale and damages to scale for U.S. fossil fuel power plants based on radial and non-radial approaches for DEA environmental assessment. Sueyoshi and Goto [30] introduced the slack-adjusted DEA model for time series analysis by performance measurement of the Japanese electric power generation industry from 1984 to 1993. Sueyoshi and Goto [31] presented an environmental assessment for corporate sustainability by resource utilization and technology innovation and conducted a DEA radial measurement for Japanese industrial sectors. They proposed a one-stage DEA model for the operational and environmental assessment of Japanese industrial sectors. They calculated a unified efficiency score under natural and managerial disposability of the decision-making unit by resource utilization and technology innovation.

Zhang et al. [32] proposed a new intermediate network DEA model by combining the intermediate approach with network DEA. Their new model had several methodological advantages. In addition, sustainability involves a three-stage system (i.e., economic growth, environmental protection, and health promotion). Towards the holistic system, quite a few studies have evaluated its performance.

2.3 Green supply chain management (GSCM)

Pouralizadeh [33] presented a radial model to study the investment regions of supply chain divisions. Also, she investigated whether the investment in the electricity supply chain division could effectively decrease the number of undesirable outputs or whether increasing the inputs under managerial disposability would have a limited effect on decreasing the number of undesirable outputs. Pouralizadeh [34] proposed two models for sustainability assessment of the electricity supply chain via reduction of wasted resources and pollution emissions management. She suggested that supply chains are generally evaluated under natural and management disposability based on unified operational and environmental efficiency. Also, the supply chain divisions with the necessary facilities and new technology to confront undesirable outputs can utilize more inputs (under managerial disposability) for more output production without increasing undesirable outputs. Those supply chain divisions that lack the adequate ability to reduce undesirable outputs should prevent the increase of undesirable outputs by using available capacities under natural disposability. Pouralizadeh [35] presented a model to estimate the marginal profit maximization of desirable output. The

[DOI: 10.71885/ijorlu-2024-1-672]

proposed model is introduced for estimating the directional marginal profit maximization of supply chain divisions based on wasted energy and power losses.

Pouralizadeh et al. [36] proposed a new DEA-based model for the sustainability evaluation of an electricity supply chain in the presence of undesirable outputs. They planned a supply chain with five stages and fifteen divisions from different districts in Iran. Also, the weak disposability assumption was adopted for activity level control in the production activity. The proposed approach estimates the directional marginal productivity in the supply chains, which find the optimal direction of efficient divisions on the frontier. Wang et al. [37] proposed the additive decomposition method, in which the overall efficiency was a weighted average of the two-stage efficiencies in a feedback system. They found that the weight of the first stage was never less than that of the second stage. This suggested that the first stage was favored, which caused a biased efficiency evaluation. Also, they built an improved feedback two-stage DEA model with constant weights and developed a heuristic method to solve it.

Wang et al. [38] explored whether nuclear energy can promote economic growth without increasing carbon emissions. They discussed the impact of coal, oil, natural gas, and renewable energy on economic growth and carbon emissions. Also, it was indicated that there was a positive relationship between increased oil, increased natural gas, and economic growth. However, there was a negative relationship between the increase in coal and economic growth. Meanwhile, there was a positive relationship between increased oil, increased coal, and increased carbon emissions. On the contrary, the positive relationship between increased natural gas and increased carbon emissions was not significant, and nuclear energy reduced carbon emissions more significantly than renewable energy.

The proposed model could determine the type and size of inputs to control the undesirable outputs. They proposed a radial model for the performance assessment of the electricity supply chain. By scaling down the production levels, Pouralizadeh et al.'s model dramatically decreased harmful emissions in the energy and power plant sectors and harnessed power losses in transmission and distribution networks.

2.4 Emission efficiency evaluation

In this section, we report approaches for the assessment of the emission efficiency of decision-making units under natural disposability.

2.4.1 The Non-radial DEA model for environmental efficiency evaluation

Let us suppose $X_j=(x_{1j},x_{2j},...,x_{mj})^T>0$, $Y_j=(y_{1j},y_{2j},...,y_{sj})^T>0$ presents the column vectors of inputs, desirable outputs in the jth DMU, respectively. Charnes et al. [39] proposed the first DEA model to measure the efficiency of a kth DMU, which is known as the CCR model.

[DOI: 10.71885/ijorlu-2024-1-672]

$$
\begin{aligned}
& Min \quad \left[\theta - \varepsilon\left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+\right)\right] \\
& \sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = \theta x_{ik} \qquad i = 1,\dots,m \\
& \sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = y_{rk} \qquad r = 1,\dots,s \\
& \lambda_k \geq 0, \quad s_i^- \geq 0,\ s_r^+ \geq 0,\ k = 1,\dots,n,
\end{aligned} \tag{1}
$$

where θ is an efficiency score that measures the distance between the efficiency frontier and one observed vector of the input and s_i^-, s_i^+ are slack variables that belong to input and desirable output. In addition, ε is a small amount and is considered 0.0001 in model (1).

Xu and Sun [40] proposed that the undesirable output model can be classified into radial and non-radial DEA models for the evaluation of environmental efficiency. They supposed that there are n DMUs and each DMU has m inputs, q desirable outputs, and p undesirable outputs. Then, the inputs X_j, the desirable outputs Y_j, and the undesirable outputs Z_j of DMU_k can be defined as follows:

$$X_k = (x_{1k}, x_{2k}, \dots, x_{mk})^T > 0,\ Y_k = (y_{1k}, y_{2k}, \dots, y_{qk})^T > 0,\ Z_k = (z_{1k}, z_{2k}, \dots, z_{pk})^T > 0$$

where x_{mk} refers to the m[th] inputs of DMU_k, y_{qk} refers to the q[th] desirable outputs of DMU_k, z_{pk} refers to the z[th] undesirable outputs of DMU_k $(k = 1,\dots,n)$. Also, the undesirable output is modeled as an input, as the CCR DEA model can be used. The production possibility set, which contains the undesirable outputs, is as follows:

$$T_c = \left\{(X, Y, Z) : X \geq \sum_{k=1}^{n} X_k \lambda_k, Y \leq \sum_{k=1}^{n} Y_k \lambda_k,\ Z \geq \sum_{k=1}^{n} Z_k \lambda_k,\ \lambda_k \geq 0,\ k = 1,\dots,n\right\} \tag{2}$$

Wu et al. [41] proposed a method based on the DEA model in which haze emissions could be controlled by decreasing the input indicators. SO2 emissions, NOX emissions, soot emissions, coal consumption, car ownership, capital, and labor force were used as inputs. The input-output efficiency of provinces was calculated with $PM_{2.5}$ as an undesirable output indicator and GDP as a desirable output indicator.

The input-output efficiency of the non-radial DEA model for the k[th] DMU can be expressed as follows:

$$
\begin{aligned}
& Min \quad \left[\frac{\sum_{i=1}^{m} \rho_i \theta_i}{\sum_{i=1}^{m} \rho_i} - \varepsilon\left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+\right)\right] \\
& s.t. \sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = \theta_i x_{ij} \qquad i = 1,\dots,m \\
& \sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = y_{rj} \qquad r = 1,\dots,q \\
& \lambda_k \geq 0,\ s_i^- \geq 0,\ s_r^+ \geq 0,\ k = 1,\dots,n
\end{aligned} \tag{3}
$$

[DOI: 10.71885/ijorlu-2024-1-672]

θ in Model (1) is replaced by $\frac{\sum_{i=1}^{m}\rho_i\theta_i}{\sum_{i-1}^{m}\rho}$ where ρ_i refers to the preference of decision-makers for the i[th] input variable in DMU $(\rho_i \in [0,1])$.

2.4.2 The DEA model with input-oriented, zero-sum gains

In original DEA models (CCR and BCC), the inputs and outputs are independent as the input and output of the under-considered DMU do not affect the input or output of the other DMUs. This independence, however, cannot exist in some exceptional circumstances. The ZSG-DEA model represents a situation similar to a zero-sum gain. According to the ZSG-DEA model, the cooperation policy implies that the inefficient DMUs comprise a single cooperation group and search for efficiency in the original efficient frontier. In this case, the “cooperation group” should share part of its inputs or surplus emissions with other DMUs that are efficient but do not reside in this group. Also, the input-oriented ZSG-DEA model will promote the total reallocation of the input with a constant sum. After this reallocation, all the DMUs will belong to the efficient frontier, and they will be 100% efficient. This new DEA frontier, called the uniform DEA frontier, will be located at a lower level in relation to the original one, as the efficient DMUs must gain units of input to compensate for the loss of the inefficient DMUs so that the sum is kept constant.

Lins et al. [42] demonstrated how a DMU can reach its target on an efficient frontier and proposed the proportional reduction strategy for finding an efficient new frontier. Gomes and Lins [16] proposed the formulations for the case where a DMU searches for a new efficient frontier without changing the total sum of inputs. In this case, the inefficient DMUs searching for efficiency must lose a certain amount of input, and the other DMUs must receive the amount of input in proportion to their original values of that input.

The input-oriented ZSG-DEA BCC model used in evaluating the relative efficiency of DMU_0 can be expressed as follows:

$$
\begin{aligned}
&Min \quad h_{Rk} \\
&h_{Rk}x_{ik} \geq \sum_{j=1}^{n} x_{ij}\lambda_j \left[1+\frac{x_{ik}\left(1-h_{Rk}\right)}{\sum_{j\neq k} x_{ij}}\right] && i=1,\ldots,m \\
&\sum_{j=1}^{n} y_{rj}\lambda_j \geq y_{rk} && r=1,\ldots,s \\
&\sum_{j=1}^{n} \lambda_j = 1 \\
&\lambda_j \geq 0, \quad j=1,\ldots,n
\end{aligned}
\tag{4}
$$

[DOI: 10.71885/ijorlu-2024-1-672]

In this model h_{Rk} is the efficiency of the DMU_k under the constraint that the total input sum of DMUs must be constant. x_{ij} , y_{rj} are the i[th] input and r[th] desirable output of DMU_j. Moreover, the ZSG-DEA model is a nonlinear programming problem as Gomes and Lins [16] proved a theorem based on the proportional reduction strategy, which states that DMUs act in cooperation to achieve their goals on the efficient frontier using the proportional strategy.

Lins et al. [42] showed the efficiency of DMUs in the ZSG-DEA model is directly proportional to their efficiency in the corresponding classical DEA model. Also, Lins et al. [42] and Gomes and Lins [16] indicated that there is a linear relationship between the efficiency-based original DEA model of the i[th] DMU h_i and the efficiency under the condition of the ZSG model h_{Ri} as follows:

$$h_{Ri} = h_i \left(1 - \frac{\sum_{j \in C} \left[x_j \left(q_{ij} h_{Ri} - 1 \right) \right]}{\sum_{j \in C} x_j} \right) \tag{5}$$

where C refers to a cooperative set formed by DMUs whose efficiency is not equal to one, $q_{ij} = \frac{h_i}{h_j}$ is the proportionality factor in which h_i and h_j are the classical DEA efficiency, and h_{Ri} is considered as ZSG-DEA model efficiency.

3 Methodology

3.1 Noun-redial model for efficiency score calculation in the electricity supply chain

Let us consider x_{ip}^h, y_{jp}^h, c_{bp}^h indicate the i[th] input (i=1,…,s) and the j[th] desirable output and b[th] (b=1,…r) undesirable output of h[th] division (h=1,...,H) in the p[th] (p=1,…,n) supply chain, respectively. Furthermore, $v_{mp}^{(h,h')}$ represents the intermediate measures between the h th division to the h' th division of the p[th] supply chain. The subscript (m, p) indicates the m[th] intermediate measure (m=1,…M_h) in the p[th] supply chain (p=1,…,n), and $z_{ap}^{(h',h)}$ represents the intermediate measures exiting from the h' th division and entering the h[th] division. The subscript (a, p) indicates the a[th] intermediate measure (a=1,…A_h) in the p[th] supply chain (p=1,…,n). Also, $\lambda_p^h = (\lambda_1^h, \lambda_2^h, ..., \lambda_n^h)^T$ is an unknown column vector from the h th division in the p[th] supply chain. Moreover, d_i^x , d_r^y show the slack variables input and desirable output.

The production technology set of the h th division in the j[th] supply chain is defined as follows:

$Y = \left\{ \left(v_j^h, z_j^h, y_j^h, x_j^h \right) \middle| \, x_j^h \, can\ produce \left(v_j^h, z_j^h, y_j^h \right) \right\}$. Thus, the outputs set of the h th division in the j[th] supply chain can be shown as follows:

$$P_j^h(x) = \left\{ \left(v_j^h, z_j^h, y_j^h \right) \middle| \left(v_k^h, z_j^h, y_j^h, x_j^h \right) \in Y \right\} \tag{6}$$

Let us now suppose a supply chain (DMU) is concluded from five stages, as we treat each supply chain as a DMU: supplier, manufacturer, transmitter, distributor, and customer. Let us

[DOI: 10.71885/ijorlu-2024-1-672]

consider h_s, h_m, h_t, h_d, h_c the number of divisions in the supplier, manufacturer, transmitter, distributor, and customer. The general structure of the supply chain depicts in Figure 1.

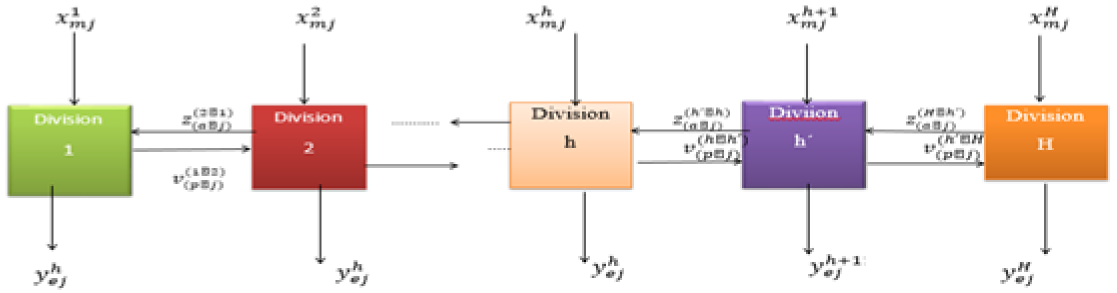

Fig. 1 The general structure of supply chain.

Figure 2 shows an electricity supply chain structure in the power industry. The electricity supply chains are power suppliers in power production activities. They are comprised of fuel suppliers (oil and gas fields), power producers (power plants), electricity transmitters (transmission lines), power distributors (distribution lines) and final customers. These entities collaborate to power production and management in economic business In the current study, supply chains have been built in the northern, southern, eastern, western, and central districts of Iran. Oil and gas fields and refineries provide demand-fed fuel for power plants and district power plants in this configuration. The produced power is transferred by regional power companies to the area's distribution companies to be dispatched to consumers or residents of their area. In other words, each supply chain or DMU is built up of five stages, and the partners of each stage are connected by intermediate measures to the succeeding stage. Supply chains are comparable and compete in the power industry. Moreover, divisions of each of the 10 supply chains contribute to pollutants' emission reduction and wasted energy inhibition. In this case, in addition to greenhouse gas abatement while investing in technology transfer and creating jobs, sustainability development and environmental protection in the electricity supply chain are achieved.

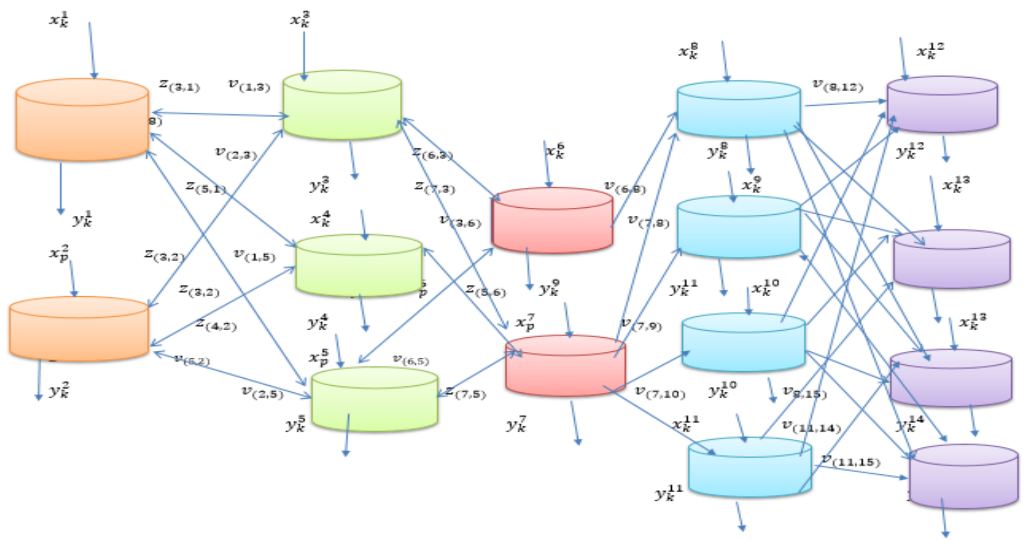

Fig. 2 The supply chain structure

[DOI: 10.71885/ijorlu-2024-1-672]

In Figure 2 is depicted intermediated measures sent from oil and gas fields to power plants, from power plants to transmissions companies, from transmissions companies to distributions companies and finally from them to customers. Furthermore, the inverse intermediate measures exit from transmitter divisions and enter to manufacture divisions and exit from manufacture divisions and enter to supplier divisions. These measures indicate entities' relationship in the supply chain. However, each division of entities operates independent from other divisions of per stage in production activities and supply chains compete to high efficiency earn in economic business (see [36]).

The production factors of the jth supply chain (DMU) are summarized as follows:

$X_j^h=(x_{1j}^h,x_{2j}^h,...,x_{ij}^h)^T>0$: The input ith from the hth division in the jth supply chain with $i=1,...,m,\ h=1,...,H\quad j=1,...,n$,.

$Y_j^h=(y_{1j}^h,y_{2j}^h,...,y_{rj}^h)^T>0$: The desirable output rth from the hth division in the jth supply chain with $r=1,...,s,\ h=1,...,H,\ j=1,...,n$.

$V_j^{(h,h')}=(v_{1j}^{(h,h')},v_{2j}^{(h,h')},...,v_{pj}^{(h,h')})^T>0$: The pth material flow or intermediate measure from division h to division h' in the jth supply chain with $p=1,...,P,\ h=1,...,H,\ j=1,...,n$.

$Z_j^{(h',h)}=(z_{1j}^{(h',h)},z_{2j}^{(h',h)},...,z_{aj}^{(h',h)})^T>0$: The ath intermediate measure from division h' to division h in the jth supply chain with $a=1,...,A,\ h=1,...,H,\ j=1,...,n$.

$s_{pj}^{(h,h')}$: The slack variables of the pth intermediate measure from divisions h to divisions h' in the jth supply chain with (p = 1,…, P) and (j = 1,…, n).

$s_{aj}^{-(h',h)}\geq 0$: The input slack variables of the ath intermediate measure from division h' to division h in the jth supply chain with (a = 1,…, A) and (j = 1,…, n).

$s_{aj}^{+(h',h)}\geq 0$: The output slack variables of the ath intermediate measure from division h' to division h in the jth supply chain with (a = 1,…,A) and (j = 1,…,n).

$\lambda^h=(\lambda_1^h,\lambda_2^h,...,\lambda_n^h)^T$: An unknown column vector.

$R_i^h=(M_h+S_h+P_h+A_h)^{-1}\left(\max\left\{x_{ij}^h\,|\,j=1,...,n\right\}-\min\left\{x_{ij}^h\,|\,j=1,...,n\right\}\right)^{-1}$: A data range related to the ith input in the hth division with $h=1,...,H$, $i=1,...,m$

$R_y^h=(M_h+S_h+P_h+A_h)^{-1}\left(\max\left\{y_{rj}^h\,|\,j=1,...,n\right\}-\min\left\{y_{rj}^h\,|\,j=1,...,n\right\}\right)^{-1}$: A data range related to the rth desirable output in the hth division with $h=1,...,H$, $r=1,...,s$

$R_p=(M_h+S_h+P_h+A_h)^{-1}\left(\max\left\{v_{pj}^{(h,h')}\,|\,j=1,...,n\right\}-\min\left\{v_{pj}^{(h,h')}\,|\,j=1,...,n\right\}\right)^{-1}$: A data range related to the pth intermediate measure sent from the h th division to the h' th divisions with $p=1,...,P,\ h\neq h',\ h,h'\in\{1,...,H\}$: A data range related to the ath intermediate measure $R_a=(M_h+S_h+P_h+A_h)^{-1}\left(\max\left\{z_{aj}^{(h',h)}\,|\,j=1,...,n\right\}-\min\left\{z_{aj}^{(h',h)}\,|\,j=1,...,n\right\}\right)^{-1}$ sent from the h' th division to the h th division with $a=1,...,A,\ h\neq h',\ h,h'\in\{1,...,H\}$.

ε : A small amount, considered as 10^{-4} for computation convenience.

ρ_{ij}^h : The weight of the i th input variable from the h th division in the jth supply chain.

θ_{ij}^h : The efficiency of the i th input variable from the hth division in the jth supply chain.

[DOI: 10.71885/ijorlu-2024-1-672]

In the proposed approach, $s_p^{(h,h')}$ is the slack variable of the p^th intermediate measure $(p=1,....,P)$ sent from the h^{th} division to the h'^{th} division, and, $s_a^{+(h',h)}$ is defined as slack variables of the a^th intermediate measures $(a=1,...,A)$ sent from the h'^{th} division to the h^{th} division. Also, the intermediate measures that enter divisions are considered non-discretionary inputs set. These intermediate measures that exit divisions are the desirable outputs set in the model. The column vectors of structural variables (λ^h) are applied for connecting the input, desirable output vectors, and the set of intermediate measures by convex combination under variable return to scale in the h^{th} division.

Model (3) can be further developed as a network model by incorporating the two categories of intermediate measures for each supply chain division to achieve an efficient assessment of the overall supply chain. We shall assume inputs as harmful emissions (greenhouse gases) from the energy and power plant sectors and loss of power in transmission and distribution lines. We also assume inputs under the natural disposability and free disposability of desirable outputs, convexity, and variable returns to scale in the production process to calculate the efficiency score. Moreover, $M_h, S_h, (h=1,...,H)$ indicate the total number of inputs and the desirable outputs in the h^{th} division. Also, P_h, A_h show the total number of intermediate measures sent from the h^{th} division to the h'^{th} division and the intermediate measures that exit the h'^{th} division and enter the h^{th} division, $(h,h'=1,...,H)$, respectively. In proposed model $R_i^h, R_r^h, R_p^h, R_a^h$ are specified by the decision-maker for the h^{th} division as follows:

$$R_i^h=(M_h+S_h+P_h+A_h)^{-1}\left(\max\left\{x_{ij}^h \,\middle|\, j=1,...,n\right\}-\min\left\{x_{ij}^h \,\middle|\, j=1,...,n\right\}\right)^{-1}$$

$$R_r^h=(M_h+S_h+P_h+A_h)^{-1}\left(\max\left\{y_{rj}^h \,\middle|\, j=1,...,n\right\}-\min\left\{y_{rj}^h \,\middle|\, j=1,...,n\right\}\right)^{-1}$$

$$\begin{aligned}&R_p^h=(M_h+S_h+P_h+A_h)^{-1}\left(\max\left\{v_{pj}^{(h,h')} \,\middle|\, j=1,...,n\right\}-\min\left\{v_{pj}^{(h,h')} \,\middle|\, j=1,...,n\right\}\right)\\&R_a^h=(M_h+S_h+P_h+A_h)^{-1}\left(\max\left\{z_{aj}^{(h',h)} \,\middle|\, j=1,...,n\right\}-\min\left\{z_{aj}^{(h',h)} \,\middle|\, j=1,...,n\right\}\right)^{-1}\end{aligned} \tag{7}$$

Moreover, the weighted average of inputs efficiency scores is applied as the unified efficiency score of inputs for the h^th division as follows:

$$\bar{\rho}^h=\frac{\sum_{i=1}^{m}(\rho_i^h\theta_i^h)}{\sum_{i=1}^{m}\rho_i^h} \qquad i=1,2,...,m \qquad h=1,2,...,H \tag{8}$$

The objective function of DMU (supply chain) is calculated by the weighted average of the average efficiency related to inputs and optimal efficiency scores of each division of the supply chain, so the objective function weights could be obtained through an expert opinion process. As a result, the efficiency of the overall supply chain can be formed by the weighted average of all of its partners' efficiency in production processes. Moreover, the slack variables of input and desirable output play an important role in the efficiency score computation of the supply chain. Also, slack variables corresponding to intermediate flows that are considered non-discretionary input sets are not included in the objective function, and their corresponding constraints set is followed by the "*" symbol. Moreover, slack variables corresponding to inputs, outputs constraints, the intermediate measure constraints and the slack variables related to output constraints set of the inverse intermediate measures included

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in the objective function. Therefore, the efficiency scores and all slack variables are determined in the optimality model as follows:

$$\beta = Min \sum_{h=1}^{H} W_h \left[\left(\frac{\sum_{i=1}^{m}(\rho_i^h \theta_i^h)}{\sum_{i=1}^{m}\rho_i^h}\right) - \varepsilon \left(\sum_{i=1}^{m^-} R_i^h d_i^h + \sum_{r=1}^{S} R_r^h d_r^h + \sum_{h'=1}^{H}\sum_{p=1}^{P} R_p s_p^{(h,h')} + \sum_{h'=1}^{H}\sum_{a=1}^{A} R_a s_a^{+(h',h)} \right) \right]$$

$$\begin{array}{lll}
\sum_{j=1}^{n} x_{ij}^h \lambda_j^h + d_i^h & = \theta_i^h x_{ik}^h & i=1,\dots,m,\ h=1,\dots,H \\
\sum_{j=1}^{n} y_{rj}^h \lambda_j^h - d_r^h & = y_{rk}^h & r=1,\dots,S_h,\ h=1,\dots,H \\
\sum_{j=1}^{n} \lambda_p^h v_{mj}^{(h,h')} + s_m^{(h,h')} & = \sum_{j=1}^{n} \lambda_j^{h'} v_{mj}^{(h,h')} & h=1,\dots,h_s,\ m=1,\dots,M_s,\ h'=1,\dots,h_m \\
\sum_{j=1}^{n} \lambda_p^h v_{mp}^{(h,h')} + s_m^{(h,h')} & = \sum_{j=1}^{n} \lambda_j^{h'} v_{mj}^{(h,h')} & h=h_s+1,\dots,h_m,\ m=1,\dots,M_m,\ h'=h_m+1,\dots,h_t \\
\sum_{j=1}^{n} \lambda_p^h v_{mp}^{(h,h')} + s_m^{(h,h')} & = \sum_{j=1}^{n} \lambda_j^{h'} v_{mj}^{(h,h')} & h=h_m+1,\dots,h_t,\ m=1,\dots,M_t,\ h'=h_t+1,\dots,h_d \\
\sum_{j=1}^{n} \lambda_p v_{mp}^{(h,h')} + s_p^{(h,h')} & = \sum_{p=1}^{n} \lambda_j^{h'} v_{mj}^{(h,h')} & h=h_t+1,\dots,h_d,\ m=1,\dots,M_d,\ h'=h_d+1,\dots,h_c \\
\sum_{j=1}^{n} \lambda_p^h z_{ap}^{(h',h)} - s_a^{+(h',h)} & = z_{ak}^{(h',h)} & h=1,\dots,h_s,\ h'=h_s+1,\dots,h_m,\ a=1,\dots,A_m,\ k=1,\dots,K \quad * \\
\sum_{j=1}^{n} \lambda_p^h z_{ap}^{(h',h)} + s_a^{+(h',h)} & = z_{ak}^{(h',h)} & h=1,\dots,h_s,\ h'=h_s+1,\dots,h_m,\ a=1,\dots,A_m,\ k=1,\dots,K \\
\sum_{j=1}^{n} \lambda_p^h z_{aj}^{(h',h)} - s_a^{-(h',h)} & = z_{ak}^{(h',h)} & h=h_s+1,\dots,h_m,\ h'=h_m+1,\dots,h_t,\ a=1,\dots,A_m,\ k=1,\dots,K \quad * \\
\sum_{j=1}^{n} \lambda_p^h z_{aj}^{(h',h)} + s_a^{-(h',h)} & = z_{ak}^{(h',h)} & h=h_s+1,\dots,h_m,\ h'=h_m+1,\dots,h_t,\ a=1,\dots,A_c,\ k=1,\dots,K
\end{array} \tag{9}$$

$$\lambda_p^h \geq 0,\ s_a^{+(h,h')} \geq 0,\ s_a^{-(h,h')} \geq 0,\ s_m^{(h,h')},\ \rho\ UR,\ \ h=1,\dots,H$$

The first constraint categories correspond to the inputs set under natural disposability. Also, the second category of constraints relates to the desirable outputs. The third, fourth, fifth, and sixth constraints categories correspond to intermediate measures sent from supplier divisions to manufacturer divisions, manufacturer divisions to transmitter divisions, and from transmitter divisions to distributor divisions and from them to customer divisions, respectively. The seventh and eighth category constraints are related to intermediated measures that exit the manufacturer divisions and enter the supplier divisions. Also, the ninth and tenth category constraints correspond to intermediate measures that exit transmitter divisions and enter manufacturing divisions. The last category of constraints is related to the variable returns to scale in the production process.

3.2 ZSG-DEA model for initial emission or undesirable outputs reallocation

In this section, we focus on the zero-sum gains orientation input model for environmental and operational assessment of the electricity supply chain in the presence of inputs such as greenhouse gases, energy losses, and desirable outputs. Model (4) is further developed as a

[DOI: 10.71885/ijorlu-2024-1-672]

network model by incorporating the two categories of intermediate measures for each supply chain division into an efficiency assessment of the overall supply chain as follows:

$$\beta = Min \sum_{h=1}^{H} W_h \left[(\frac{\sum_{i=1}^{m}(\rho_i^h \theta_i^h)}{\sum_{i=1}^{m}\rho_i^h}) - \varepsilon \left(\sum_{i=1}^{m^-} R_i^h d_i^h + \sum_{r=1}^{S} R_r^h d_r^h + \sum_{h'=1}^{H}\sum_{p=1}^{P} R_p s_p^{(h,h')} + \sum_{h'=1}^{H}\sum_{a=1}^{A} R_a s_a^{+(h',h)} \right) \right]$$

$$\begin{array}{lll}
\sum_{j=1}^{n} x_{ij}^h \lambda_j^h + d_i^h & = \theta_i^h x_{ik}^h & i=1,\dots,m,\ h=1,\dots,H \\
\sum_{j=1}^{n} x_{ij}^h \lambda_j^h \ (1+\frac{x_{ij}^h\left(1-\theta_{Zi}^h\right)}{\sum_{j\neq o} x_{ij}^h}) & \le \theta_Z^h x_{ik}^h & i=1,\dots,m, \quad h=1,\dots,H \\
\sum_{j=1}^{n} y_{rj}^h \lambda_j^h - d_r^h & = y_{rk}^h & r=1,\dots,S_h\ ,h=1,\dots,H \\
\sum_{j=1}^{n} \lambda_p^h v_{mj}^{(h,h')} + s_m^{(h,h')} & = \sum_{j=1}^{n} \lambda_j^{h'} v_{mj}^{(h,h')} & h=1,\dots,h_s, m=1,\dots,M_s, h'=1,\dots,h_m \\
\sum_{j=1}^{n} \lambda_p^h v_{mp}^{(h,h')} + s_m^{(h,h')} & = \sum_{j=1}^{n} \lambda_j^{h'} v_{mj}^{(h,h')} & h=h_s+1,\dots,h_m, m=1,\dots,M_m, h'=h_m+1,\dots,h_t \\
\sum_{j=1}^{n} \lambda_p^h v_{mp}^{(h,h')} + s_m^{(h,h')} & = \sum_{j=1}^{n} \lambda_j^{h'} v_{mj}^{(h,h')} & h=h_m+1,\dots,h_t, m=1,\dots,M_t, h'=h_t+1,\dots,h_d \\
\sum_{j=1}^{n} \lambda_p v_{mp}^{(h,h')} + s_p^{(h,h')} & = \sum_{p=1}^{n} \lambda_j^{h'} v_{mj}^{(h,h')} & h=h_t+1,\dots,h_d, m=1,\dots,M_d, h'=h_d+1,\dots,h_c \\
\sum_{j=1}^{n} \lambda_p^h z_{ap}^{(h',h)} - s_a^{+(h',h)} & = z_{ak}^{(h',h)} & h=1,\dots,h_s,\ h'=h_s+1,\dots,h_m,\ a=1,\dots,A_m,\ k=1,\dots,K \quad * \\
\sum_{j=1}^{n} \lambda_p^h z_{ap}^{(h',h)} + s_a^{+(h',h)} & = z_{ak}^{(h',h)} & h=1,\dots,h_s, h'=h_s+1,\dots,h_m, a=1,\dots,A_m, k=1,\dots,K \\
\sum_{j=1}^{n} \lambda_p^h z_{aj}^{(h',h)} - s_a^{-(h',h)} & = z_{ak}^{(h',h)} & h=h_s+1,\dots,h_m,\ h'=h_m+1,\dots,h_t,\ a=1,\dots,A_m, k=1,\dots,K \quad * \\
\sum_{j=1}^{n} \lambda_p^h z_{aj}^{(h',h)} + s_a^{-(h',h)} & = z_{ak}^{(h',h)} & h=h_s+1,\dots,h_m,\ h'=h_m+1,\dots,h_t,\ a=1,\dots,A_c, k=1,\dots,K \\
\lambda_p^h \ge 0,\ s_a^{+(h,h')} \ge 0,\ s_a^{-(h,h')} \ge 0,\ s_m^{(h,h')},\ \rho\ UR,\ h=1,\dots,H & &
\end{array} \tag{10}$$

We assume the cooperative case in the ZSG-DEA model. The cooperative strategy implies that the supply chain divisions belonging to the cooperative group try to reduce harmful emissions amounts, and divisions of other supply chains have to receive surplus emissions from the cooperative group.

The proposed model is a non-radial model. Moreover, the rate of the input variables' changes is not equal for DMUs in non-radial DEA models. In other words, the efficiency changes through the variation of all input variables. The undesirable outputs, such as harmful emissions and wasted energy, considered as supply chain division inputs as input constraints, comprise different efficiency scores, and the weighted average of these efficiency scores plays

[DOI: 10.71885/ijorlu-2024-1-672]

a basic role in the objective function values. The model (10) is a nonlinear programming problem. Using all the theorems, Gomes and Lins [16] calculated the ZSG-DEA model efficiency for each supply chain division as follows:

$$\xi_{ik}^{h}=\theta_{ik}^{h}\left(1+\frac{\sum_{j\in W_{ik}^{h}}\left[x_{ik}^{h}\left(1-q_{ij}^{hk}\xi_{ik}^{h}\right)\right]}{\sum_{j\in W_{ik}^{h}}x_{ik}^{h}}\right)\qquad i=1,\dots,m,\quad h=1,\dots,H,\ j=0,1,\dots,n,\ k=1,\dots,n \tag{11}$$

θ_{ik}^{h} : The non-radial model initial efficiency of the i^th^ input from the h^th^ division in the k^th^ under-considered supply chain.

W_{ik}^{h} : The cooperative set of the i^th^ input from the h^th^ division in the k^th^ supply chains.

ξ_{ik}^{h} : The ZSG-DEA model efficiency of the i^th^ input from the h^th^ division in the k^th^ supply chain.

$q_{ij}^{hk}=\frac{\theta_{ik}^{h}}{\theta_{ij}^{h}}$: The ratio of non-radial model initial efficiency of the i^th^ input from the h^th^ division in the k^th^ supply chain to initial efficiency of the i^th^ input from the h^th^ division in the j^th^ supply chain belonging to the cooperation set.

The cooperative set of the i^th^ input from the h^th^ division is formed by supply chain divisions whose i^th^ input (undesirable emissions) efficiency belonging to the h^th^ division is not equal to one. By resource reallocation or inputs redistribution product, the ZSG-DEA model enables a new DEA frontier while the total amount of the i^th^ inputs from the h^th^ divisions remains constant in all supply chains. Therefore, the efficiency score of the i^th^ input from the h^th^ division in the k^th^ supply chain based on the ZSG-DEA model is calculated by equation (11).

3.3 A real case in the power industry

In this section, we apply the proposed ZSG-DEA model to the analysis of the power industry in Iran. In the following subsection, the dataset, specifying the inputs and outputs, will be described. And in the next subsection, the results will be presented.

3.3.1 Dataset

The stylized supply chain in the power industry can be summarized in five main actors: gas and fuel suppliers, power generators, transmission networks, distribution facilities, and final consumers. Conventional power plants consume fuel oil, natural gas and diesel to produce electricity, while renewable ones are solar, wind and hydro plants. Conventional plants can be further divided depending on the kind of technology adopted, in thermal, gas and combined cycle plants. In general, thermal power plants operated by fossil fuels produce huge amounts of air pollutants. The pollutants which have been considered in the study are sulfur dioxide (SO_2), nitrogen oxides (NO_X) ,carbon dioxide (CO_2) and metan gas (CH).

Our purpose is to highlight the theoretical and practical quality of the model. Therefore, each of the DMUs, or the supply chain, is built in five stages, and each stage includes a set of partners connected to the predecessor stage members by some sustainable intermediate measures. In our application, we consider 10 supply chains (DMUs), including oil and gas

[DOI: 10.71885/ijorlu-2024-1-672]

fields (suppliers) that provide different fuels to power stations, power plants (manufacturers), regional power companies (transmitters), distribution companies (distributors), and customers. For each supply chain, we consider two suppliers: oil and gas companies that satisfy the fuel demand of power plants (intermediate products) and those that can also sell fuels as final output. We consider the undesirable outputs as inputs to pollutant emissions abatement and energy wastage inhibition in supply chain divisions. In our application, suppliers have harmful emissions as two inputs, as they emit sulfur dioxide gas (SO_2) emissions and CO_2 to produce one desirable output, namely, selling oil and gas to other companies. Each manufacturer includes at least three power plants with different technologies (thermal, combined cycle, gas, hydro, wind, and solar). The four inputs as greenhouse gases emissions are considered for manufacturers: NOx, SO_2, CO_2, and CH. Also, the desirable output is the total produced electricity from power plants. The transmitters transfer electricity from manufacturers to distributing companies, and the transmitter lines have two inputs as the first input is considered the power loss, and the second input is actual cost of one kilowatt-hour of produced power in the transmission lines, while the transferred electricity to distribution companies is a desirable output. Distribution companies receive electricity from transmitters and dispatch it to the final consumers. They have one input, power losses, while the dispatched electricity to distribution companies is a desirable output. Finally, customers are classified as residential, agricultural, public, or industrial. They include one input (cutting off the power) and one desirable output (the sale of electricity to customers) (See [33]).

In more detail, the parameters used to characterize this supply chain are defined as follows:

h_s : Numerator of divisions in the supplier level (h_s : 1, 2).

$x_{1j}^{h(s)}$: Emissions of SO_2 gas of the h_s th supplier in the j th supply chain (tone/hr)

$x_{2j}^{h(s)}$: Emissions of CO_2 gas of the h_s th supplier in the j th supply chain (tone/hr).

$y_{1j}^{h(s)}$: Oil (10^3 Barrels) and gas (10^6 m^3) sold to other companies from the h_s th supplier in the j th supply chain.

$\Delta x_{1k}^{h(S)}$: Rate of emission reduction of SO_2 gas by the ZSG model.

$\Delta x_{2k}^{h(s)}$: Rate of emission reduction of CO_2 gas by the ZSG model.

h_m : Numerator of division at the manufacturer level (h_m : 3, 4, 5).

$x_{1j}^{h(m)}$: Emissions of No_x harmful substances of the h_m th manufacturer in the j th supply chain (10^3kg /10^6 kWh).

$x_{2j}^{h(m)}$: Emissions of SO_X gas of the h_m th manufacturer in the j th supply chain (10^3kg/10^6 kWh).

$x_{3j}^{h(m)}$: Emission of CO_2 gas of the h_m th manufacturer in the j th supply chain (10^3kg/10^6 kWh).

$x_{4j}^{h(m)}$: Emission of CH gas of the h_m th manufacturer in the j th supply chain (10^3kg/10^6 kWh).

$y_{1j}^{h(m)}$: The total of produced electricity of the h_m th manufacturer in the j th supply chain (10^6 kWh).

h_t : Numerator of the divisions at the level of the transmitters (h_t : 6, 7).

$x_{1j}^{h(t)}$: Loss of transmission line of the h_t th transmitter in the j th supply chain (10^6 kWh).

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$x_{2j}^{h(t)}$: Actual cost of one kilowatt-hour of produced power of the h_t th transmitter in the jth supply chain ($).

$y_{1j}^{h(t)}$: The transferred electricity of the h_t th transmitter in the jth supply chain (10^6 kWh).

h_d : Numerator of division in the distributer level (h_d : 8, 9, 10, 11).

$x_{1j}^{h(d)}$: Percentage of losses of the distribution line of the h_d th distributer in the jth supply chain (%).

$y_{1j}^{h(d)}$: The dispatched electricity of the h_d th distributer in the jth supply chain (10^6kWh).

h_c : Numerator of division at the customer level (h_c : 12, 13, 14, 15).

$x_{1j}^{h(c)}$: Cut off the power of the h_c th customer in the jth supply chain (minute/year).

$y_{1j}^{h(c)}$: Sales of electricity of the h_c th customer in the jth supply chain (10^6 kWh).

$v_{pj}^{(h,h')}$: Material flow from division h to division h'.

$z_{aj}^{(h_m,h_s)}$: Power flow sent from power plants to oil and gas fields (10^6 kWa).

$z_{aj}^{(h_t,h_m)}$: Labor sent from regional companies to power plants for repair and maintenance of systems.

We consider 10 supply chains (DMUs), including oil and gas fields (suppliers) that provide different fuels to power stations, power plants (manufacturers), regional power companies (transmitters), distribution companies (distributors), and customers. All the data from the two oil and gas fields (suppliers), power plants (manufacturers), regional power companies (transmitters), distribution companies (distributors), and customers (residential, public, agriculture, industrial) are available on the TAVANIR website (2015). For each supply chain, we consider two suppliers: oil and gas companies that satisfy the fuel demand of power plants (intermediate products) and those that can also sell fuels as final output. Suppliers (oil and gas fields) emit SO_2 and CO_2 emissions to produce one desirable output (oil or gas). Desirable output is computed as the difference between the average annual production and the amount of oil and gas delivered to power plants. The most important compounds in flaring gas are CO_2 and sulfur oxides, and the emission amounts of SO_2 and CO_2 gases are calculated based on the amount of flare gas emissions in oil and gas fields.

Table 1 indicates the pollutants emission abased on the amount of emitted flare gas in oil and gas companies. In this way the amount of SO_2 and CO_2 gas emissions calculate by total amount of flaring gas of oil and gas fields in supply chains. The dataset has been collected from the power industry companies in Iran and the reference year is 2015 (see the TAVANIR website for the detailed data) [43].

Table 1 The amount of flare and greenhouse gases emitted in oil and gas companies

Oil companies	Flaring gas mm^3/daily	Methane (ton/h)	NO_X (ton/h)	SO_2 (ton/h)	CO (ton/h)	CO_2 (ton/h)
South oil company	11.6	7.6	0.8	15.6	26.4	1486.7
Continental plateau of company	8.5	3.7	0.4	32.3	15.2	877.7
National gas company	6.5	3.1	0.3	8.1	10.4	584.0

[DOI: 10.71885/ijorlu-2024-1-672]

Central regions oil company	3.3	1.8	0.2	3.5	6.9	387.1
Ardovan oil and gas company	1.7	1.1	0.1	1	4.3	241.8
Iran National petrochemical industries company	1.3	0.1	0.1	14.8	4.9	253.5
Pars oil and gas company	0.9	0.5	0.1	0.0	1.5	87.4
Total	33.8	17.9	2.0	75.3	69.7	3918.2

The total emissions due to electricity generation in Iran and the amount and type of fuel used in all power plants have been considered in the computation of undesirable outputs. Information related to the demand for fuel for power plants is collected from TAVANIR Company (2015) in the power industry, and they are considered as intermediate measures from oil and gas fields to power plants.

Table 2 The amount of pollutant and greenhouses gases due to Iran power plants operation by type of power plants in 2015

Description	Nominal Capacity (MW)	NO_X	SO_X	CO_2	CO	CH	SPM
steam	15830	85528	328795	55400306	107.2	3729.6	10841.2
Gas	26870	78857.3	49330.6	51111032	112.9	2172.4	7905.9
Combined Cycle	18494	72969.3	42948.6	47448380	105.2	1972.8	7214.6
Diesel	439	0.1	0.3	52	0	0	0
Total	61633	237353.9	421074.5	153959770	325.3	7874.8	25961.7

Four undesirable outputs as inputs are considered for manufacturers: NOx, SO_X, CO_2, and CH emissions. Undesirable outputs for manufacturers are computed based on the amount of electricity produced by the different power plants using different technologies and fuels. Table 2 shows the amount of emitted pollutant and greenhouse gases in term used technologies of power plants in 2015.

The transmitters transfer electricity from manufacturers to distributing companies, which is considered a desirable output. Desirable outputs of regional power companies are collected from the transmission section of TAVANIR Company in the power industry. Also, the first input is considered a fixed cost for power production of one kilowatt-hour, and the second input is as losses of the transmission line (undesirable output) and is estimated with a 3.02% factor based on the amount of transmission loss in Iran.

Distribution companies receive electricity from transmitters and dispatch it to the final consumers. They have one input (undesirable output), that is, losses in the distribution lines. The distributers dispatch electricity from transmitters to customer companies, which is considered a desirable output. All of the data for distribution companies is obtained from the dispatch section of TAVANIR Company in the power industry.

Finally, customers are classified as residential, agricultural, public, or industrial. They have one input or the undesirable output is computed by the time cut off of electricity in different divisions of consumers, and the desirable outputs of customers are computed as the

[DOI: 10.71885/ijorlu-2024-1-672]

total sale of electricity to residential, public, agricultural, and industrial divisions in 2015 (see [33]). The datasets corresponding to the 10 supply chains (DMUs) under analysis are presented in Tables 3–13.

Table 3 The first and second suppliers' input

DMU	Supplier 1 (division 1)		Supplier 2 (division 2)	
	Emissions of SO_2 (tone/hr)	Emissions of CO_2 (tone/hr)	Emissions of SO_2 (tone/hr)	Emissions of CO_2 (tone/hr)
	x_{1k}^{1}	x_{2k}^{1}	x_{1k}^{2}	x_{2k}^{2}
1	0.00005297	0.002756882	0.932920354	48.55274336
2	0.001271336	0.066165165	2.132389381	110.9776991
3	0.000423779	0.022055055	1.132831858	58.95690265
4	0.000953502	0.049623874	0.866283186	45.08469027
5	0.000211889	0.011027528	2.265663717	117.9138053
6	0.000741612	0.038596346	1.132831858	58.95690265
7	0.000741612	0.038596346	1.06619469	55.48884956
8	0.000635668	0.033082583	2.132389381	110.9776991
9	0.0001907	0.009924775	2.265663717	117.9138053
10	0.001271336	0.066165165	0.866283186	45.08469027

Table 4 The first manufacturer's inputs

DMU	Manufacturer 1 (Division 3)			
	Emission of NO_x (10^3 Kg/10^6 Kwh)	Emission of SO_x (10^3 Kg/10^6 Kwh)	Emissions of CO_2 (10^3 Kg/10^6 Kwh)	Emissions of CH (10^3 Kg/10^6 Kwh)
	x_{1k}^{3}	x_{2k}^{3}	x_{3k}^{3}	x_{4k}^{3}
1	454610.278	23891876.280	288025420.100	287.2646062
2	302399.805	4207069.806	191952930.500	138.5646034
3	235104.740	195553.061	149621794	95.26261739
4	229464.218	12059407.75	145380628.200	144.9966228
5	43498.708	38755.471	27536231.770	16.95219849
6	256638.343	217529.667	163094448.800	102.9248773
7	6683.633	5954.829	4230977.926	2.604727408
8	15138.687	184259.151	9585079.623	6.700302382
9	92035.892	76552.691	58572086.910	37.29222967
10	236364.062	196600.528	150423232.700	95.77288498

Table 5 The second manufacturer's inputs

DMU	Manufacturer 2 (Division 4)			
	Emissions of NO_x (10^3 Kg/10^6 Kwh)	(10^3 Kg/10^6 Kwh)	(10^3 Kg/10^6 Kwh)	Emissions of CH (10^3 Kg/10^6 Kwh)
	x_{1k}^{4}	x_{2k}^{4}	x_{3k}^{4}	x_{4k}^{4}
1	5715.366	5092.145	3618030.390	2.227377
2	283431.105	14895617.700	179572190	179.0978717
3	174773.192	9070013.802	110729096.200	109.898135
4	182851.984	152090.788	116367887.400	117.314205
5	49845.037	2619587.603	3158009.070	31.49668404

[DOI: 10.71885/ijorlu-2024-1-672]

6	27420.014	24430.049	17357845.530	10.68605339
7	273496.466	14373506.370	173277944.500	172.8202516
8	311634.456	21776302.480	197440862.200	89.15778064
9	176752.534	147351.908	112467128.500	71.53130852
10	79593.197	66419.786	50641168.170	32.19392567

Table 6 The third manufacturer's inputs

DMU		Manufacturer3 (Division5)		
	Emissions of NOx (10^3 Kg/10^6 Kwh)	(10^3 Kg/10^6 Kwh)	(10^3 Kg/10^6 Kwh)	Emissions of CH (10^3 Kg/10^6 Kwh)
	x_{1k}^{5}	x_{2k}^{5}	x_{3k}^{5}	x_{4k}^{5}
1	19603.894	17519.680	12447945.190	7.663359291
2	27423877.76	24433491.25	17360291475	10.68755919
3	212448.268	690393.877	135090771.800	87.94056578
4	140748.540	117070.408	89573051.780	57.03021688
5	300157.654	9178172.226	190308335.200	159.7110054
6	77463.980	64432.212	49298451.340	31.38780376
7	471751.939	21768344.370	299051808	284.8404319
8	510495.755	21776302.480	323709891.900	300.4327604
9	94829.614	78876.425	60350025.180	38.42422421
10	59895.401	3147780.793	37947663.670	37.84742949

Table 7 Transmitter level inputs

DMU	Transmitter 1 (division 6)		Transmitter 2 (division 7)	
	Cost (10^4 $)	Loose of power (10^6 kWh)	Cost(10^4 $)	Loose of power (10^6 kWh)
	x_{1k}^{6}	x_{2k}^{6}	x_{1k}^{7}	x_{2k}^{7}
1	12227.54086	508.8448132	1246.670018	51.8797344
2	8585.10198	200.5663842	8866.740496	301.8293096
3	4214.395502	175.3805868	8597.665257	357.7888164
4	7886.570767	328.1968692	2822.745971	117.467581
5	1628.253199	67.75918432	6343.613422	263.9872419
6	6124.329453	254.8618166	2589.942389	107.7795418
7	10757.38721	447.6048861	1487.905868	61.91867948
8	8981.799005	373.7744072	4854.526831	202.019427
9	6568.780836	273.3575046	2029.629867	84.4623332
10	7068.327092	294.1459464	933.0416556	38.8282004

[DOI: 10.71885/ijorlu-2024-1-672]

Table 8 The distributor level inputs

DMU	(division 8) Loss of power (%) x_{1k}^{8}	(division 9) Loss of power (%) x_{1k}^{9}	(division 10) Loss of power (%) x_{1k}^{10}	(division 11) Loss of power (%) x_{1k}^{11}
1	14.21	15.52	13.59	14.2
2	7.2	10.04	10.73	7.99
3	15.57	11.39	11.05	13.25
4	15.57	10.73	7.67	12.03
5	13.25	12.67	11.05	11.39
6	15.57	11.51	7.99	7.25
7	13.6	11.05	13.25	15.57
8	11.23	13.33	8.03	8.10
9	14.24	7.25	13.59	8.03
10	12.54	11.23	8.03	8.10

Table 9 The customer level inputs

DMU	Customer 1 (Division 12) Cut off electricity (10^6 Kwh) x_{1k}^{12}	Customer 2 (Division 13) Cut off electricity (10^6 Kwh) x_{1k}^{13}	Customer 3 (Division 14) Cut off electricity (10^6 Kwh) x_{1k}^{14}	Customer 4 (Division 15) Cut off electricity (10^6 Kwh) x_{1k}^{15}
1	778.276573	147.5103848	6.955767331	3.257274814
2	725.0808319	200.177615	4.248558312	6.492994734
3	725.3231688	199.9371521	4.743479679	5.99619943
4	727.3273736	198.5850036	4.155272657	5.932350176
5	752.5591399	169.3080814	8.399627431	5.733151262
6	734.466084	190.587568	4.168585336	6.785849494
7	693.426703	184.1543359	52.35543143	6.06352974
8	718.109727	191.8005009	21.25942548	4.830346555
9	752.0787675	161.7571646	15.10303586	7.061031981
10	722.7709543	187.0110425	21.59472477	4.623278406

Table 10 The level desirable outputs of supplier 1, 2, and manufacture 1and 2

DMU	Supplier 1 Sold oil (10^3 Barrels) y_{1k}^{1}	Supplier 2 Sold gas (10^6 mm^3) y_{1k}^{2}	Manufacture 1 Produced electricity (10^6 kWh) y_{1k}^{3}	Manufacture 2 Produced electricity (10^6 kWh) y_{1k}^{4}
1	1739.6933	1186.216	17583.707	225.038
2	40572.9964	7203.23	16900	6081.337
3	8995.88282	3726.203	7144.31	3791.732

[DOI: 10.71885/ijorlu-2024-1-672]

4	26527.1913	1930.025	4923.416	5556.65
5	4552.85776	10438.19	1677.428	1069.482
6	23324.3911	3350.675	8439.133	1214.901
7	17080.4711	2353.13	259.243	5970.148
8	15872.9136	9455.104	550.87	6689.385
9	6062.77171	9849.593	2796.766	5426.567
10	25603.3995	2208.415	7291.361	2448.571

Table 11 The level of desirable outputs of manufacture 3, transmitter 1, 2, and distributer 1

DMU	Manufacture 3 (Division 5) Produced electricity (10^6 kWh) y_{1k}^{5}	Transmitter 1 (Division 6) Transferred electricity (10^6 kWh) y_{1k}^{6}	Transmitter 2 (Division 7) Transferred electricity (10^6 kWh) y_{1k}^{7}	Distributer 1 (Division 8) Dispatched electricity (10^6 kWh) y_{1k}^{8}
1	758.293	16340.32119	1665.992266	11438.22483
2	1066.752	11472.734	11849.10271	8030.9138
3	6718.574	5631.923613	11489.52298	8042.666089
4	4277.035	10539.24913	3772.187419	2640.531193
5	8238.071	2175.922416	8477.312158	652.7767247
6	2353.958	8184.271183	3568.859	356.8859
7	10644.237	14375.67571	1988.368721	10062.973
8	11825.766	12002.86159	6285.346146	8402.003115
9	3625.006	8778.215495	2712.303667	813.6911
10	1285.702	9445.786054	1246.8738	872.8116597

Table 12 The level of desirable outputs of distributers 2, 3, and 4

DMU	Distributer 2 (Division 9) Dispatched electricity (10^6 Kwh) y_{1k}^{9}	Distributer 3 (Division 10) Dispatched electricity (10^6 Kwh) y_{1k}^{10}	Distributer 4 (Division 11) Dispatched electricity (10^6 Kwh) y_{1k}^{11}
1	499.7976797	1166.194586	4902.096356
2	3441.8202	3554.730814	8294.371899
3	3446.856895	3942.346529	1689.577084
4	7377.474392	3916.212223	377.2187419
5	2543.193647	5934.118511	1523.145691
6	8184.271183	2498.2013	713.7718
7	1391.858104	596.5106162	4312.702714
8	4399.742302	1885.603844	8402.003115
9	1898.612567	2633.464649	6144.750847
10	6612.050238	2833.735816	374.0621399

[DOI: 10.71885/ijorlu-2024-1-672]

Table 13 The level of desirable outputs of customers

DMU	Customer 1 (Division 12) Sold electricity (10^6 Kwh) y_{1k}^{12}	Customer 2 (Division 13) Sold electricity (10^6 Kwh) y_{1k}^{13}	Customer 3 (Division 14) Sold electricity (10^6 Kwh) y_{1k}^{14}	Customer 4 (Division 15) Sold electricity (10^6 Kwh) y_{1k}^{15}
1	6122.1466	3241.136421	2700.947017	5942.083438
2	5485.295924	2903.980195	2419.983496	5323.963691
3	5821.291843	3081.860387	2568.21699	5650.077377
4	4865.888427	2576.058579	2146.715482	4722.774061
5	3622.099755	1917.582223	1597.985186	3515.567409
6	3996.064262	2115.563433	1762.969528	3878.532961
7	5563.775108	2945.527998	2454.606665	5400.134663
8	6217.990631	3291.877393	2743.231161	6035.108554
9	3906.776515	2068.293449	1723.577874	3791.871324
10	3635.50435	1924.678774	1603.898978	3528.577752

4 Results

We now describe the results obtained using the proposed approach. The model (9) is applied to estimate the efficiency score of the supply chain 10 (DMUS). The model (9) is solved by a linear programming solver using the GAMS software on an 8GB RAM, 2.0 GHz desktop computer. The runtime of the computation in this study is negligible in the model. The results are listed in Table 14.

Table 14 The efficiency scores of supply chains (DMUs) under VRS.

DMU	β_o	$\overline{\rho}_k^{S1}$	$\overline{\rho}_k^{S2}$	$\overline{\rho}_k^{M1}$	$\overline{\rho}_k^{M2}$	$\overline{\rho}_k^{M3}$	$\overline{\rho}_k^{T1}$	$\overline{\rho}_k^{T2}$	$\overline{\rho}_k^{D1}$	$\overline{\rho}_k^{D2}$	$\overline{\rho}_k^{D3}$	$\overline{\rho}_k^{D4}$	$\overline{\rho}_k^{C1}$	$\overline{\rho}_k^{C2}$	$\overline{\rho}_k^{C3}$	$\overline{\rho}_k^{C4}$
1	0.77	1	0.91	1	1	1	1	0.99	1	0.47	0.56	0.54	0.92	1	1	1
2	0.78	1	0.81	1	0.43	1	1	1	1	0.82	0.72	1	0.96	0.74	1	1
3	0.71	0.67	0.99	0.98	0.35	1	1	1	0.46	0.72	0.70	0.55	0.97	0.74	1	1
4	0.69	0.87	1	0.11	1	1	0.75	1	0.46	1	1	0.60	0.96	0.74	1	1
5	0.76	0.90	1	1	1	1	1	0.93	0.54	0.61	1	0.64	0.93	0.87	0.50	1
6	0.75	0.99	0.94	1	1	0.21	0.77	1	0.46	1	0.96	1	0.95	0.77	1	1
7	0.73	0.72	0.84	1	1	1	1	1	0.84	0.66	0.58	0.49	1	0.80	0.08	1
8	0.75	0.78	0.98	1	1	1	0.81	0.90	0.71	0.66	0.96	1	1	1	1	1
9	0.76	1	0.96	0.75	1	1	1	0.95	0.51	1	0.57	0.97	0.92	0.91	0.28	1
10	0.69	0.63	1	1	0.76	0.11	0.91	1	0.57	0.91	0.96	0.90	0.96	0.79	0.19	1

In Table 14, columns from 3 to 17 report the weighted average of inputs efficiency score in 15 divisions of 10 supply chains. The allocated weights are the preferences of the decision-makers for each emission in the divisions. The second column of Table 12 represents the global efficiency score of the 10 supply chains. It can be easily seen that supply chain number 2 is the one that reaches the highest score (0.78). In this way, we can exploit which divisions are more efficient in the various supply chains (looking at the data in the columns). Looking

[DOI: 10.71885/ijorlu-2024-1-672]

horizontally at the same table, it is possible to see, for each supply chain, the number of efficient divisions.

Columns 5-7 of Table 14 indicate the weighted average of four greenhouse gas emission efficiencies in three power plants. The manufacturer 1 of supply chain number 4, the manufacturer 2 of supply chain number 3, and the manufacturer 3 of supply chain number 10 have the worst efficiency scores in 15 divisions of 10 supply chains, while the first power plant of supply chain number 3 obtained the highest weighted average of NO_X, SO_X, CO_2, and CH emissions in power plant sectors. Indeed, the low-efficiency score of the SO_X gas in the first power plant of supply chain 4, the second power plant of supply chain 3, and the third power plant of the supply chain 10 created an efficiency reduction in power plant sectors in supply chains

Figure 3 indicate the stages of emissions allocation abased on ZSG model. Lins et.al [42], and Gomes et al. [44] proved that there is a linear relationship between initial efficiency and efficiency based on ZSG-DEA model as the equation (11). According to solve the regional allocation issue of the total air pollutant emission amount, Lins et al. [42], Gomes et.al [44], and Gomes and Lins [16] put forward the ZSG-DEA model. They proposed that several iterative calculations of input or output be carried out to make each DMU achieve its valid boundary of efficiency. After measuring the optimal efficiency of inputs related to the supply chain divisions by the model (9), we apply the equation (11) to the input-orientation ZSG model efficiency calculation of 15 supply chain divisions. Now, the efficiency scores of supply chain divisions are incorporated into equation 11 to determine optimal resource allocation, while the inputs of all divisions remain constant. Using the BCC efficiency scores to determine new targets for the ZSG-DEA model (Equation (11)) and with the reallocation of the undesirable outputs of NO_X, SO_X, CO_2, and CH emissions and for the variable returns to scale case, a uniform BCC DEA frontier is built, where all supply chain divisions are replaced on an efficient frontier.

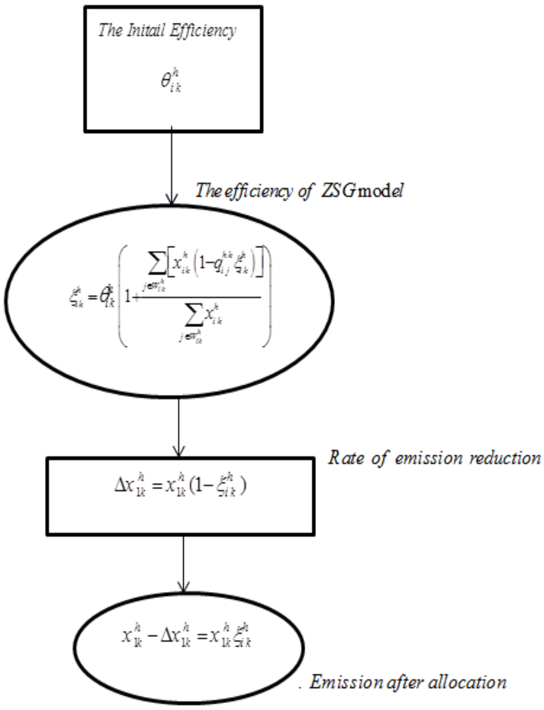

Fig. 3 The results structure

Tables 15–22 depict the initial efficiency of emissions and the efficiency in terms of the ZSG model for energy and power plant sectors in 10 supply chains. Moreover, the value changes of inputs after appropriate allocation based on the ZSG model and the new quantities are presented.

Table15 The emissions efficiency scores of supplier 1 and allocation results in supply chains

DMU	Emission of SO2 after allocation $\bar{x}^1_{1k}$	Emission of CO2 after allocation $\bar{x}^1_{2k}$	Initial efficiency of SO2 emission before allocation θ^1_{1k}	Initial efficiency of CO2 emission before allocation θ^1_{2k}	Emission reduction of SO2 gas Δx^1_{1k}	Emission reduction of CO2 gas Δx^1_{2k}
1	0.00005297	0.002756882	1	1	0	0
2	0.001271336	0.066165165	1	1	0	0
3	0.000413634	0.020192328	0.667	0.667	0.0000101449	0.001862727
4	0.000829351	0.04317816	0.872	0.872	0.000124151	0.006445714
5	0.000181148	0.009495502	0.90	0.90	0.0000307409	0.001532026
6	0.0000600935	0.032090714	0.986	0.986	0.000140677	0.006505632
7	0.000703934	0.035061488	0.722	0.722	0.0000376784	0.003534858
8	0.000583146	0.029623892	0.783	0.783	0.0000525217	0.003458691
9	0.0001907	0.009924775	1	1	0	0
10	0.001261171	0.060683379	0.631	0.631	0.0000101648	0.005481786

According to Table 15, θ^1_{1k} , θ^1_{2k} indicate the values of the initial emission efficiency of SO_2 and CO_2 gases for the oil field of 10 supply chains. In the following Table, $\bar{x}^1_{1k}$, $\bar{x}^1_{2k}$ denote CO_2 and SO_2 emission amounts of oil fields in 10 supply chains after allocation through the ZSG-DEA model. The emission reduction amounts of CO_2 and SO_2 gases are denoted as Δx^1_{1k} , Δx^1_{2k} in Table 13. The initial emission amounts of gases based on 2015 emissions are presented in Table 1. Moreover, the CO_2 and SO_2 gases are undesirable outputs of the oil and gas fields and are modeled as inputs. Also, the maximum emissions concentration is considered as the sum of the 2015 CO_2 and SO_2 emissions.

First, the initial efficiency of CO_2 and SO_2 emissions are computed by model 9 for oil fields in 10 supply chains. Then the values of the initial efficiency of oil fields are applied by model 11 to the efficient computation of oil field divisions based on the ZSG-DEA model in 10 supply chains. Thus, we verify the emission change rate and determine how the emissions should be reallocated among efficient oil fields as total emission amounts are kept unchanged and all energy sectors are DEA efficient. It can be easily seen that the oil field division of supply chains numbers 3, 4, 5, 6, 7, 8, and 10 have emissions inefficient of SO_2 and CO_2 gases. Therefore, they should apply financing projects for SO_2 gas abatement and CO_2 emission management. Also, the oil field divisions of supply chains numbers 1, 2, and 9 have obtained emission efficiency for SO_2 and CO_2 gases.

In other words, the efficient divisions are equipped with the necessary techniques for pollution emissions management as they have adequate facilities to confront excessive emissions in industrial activities. In this case, the fair allocation of inputs determines the stabilization of SO_2 and CO_2 concentration in the atmosphere. The inefficient oil field sectors

[DOI: 10.71885/ijorlu-2024-1-672]

of 10 supply chains belong to the cooperation group as they make an effort to take harmful emissions amounts out of inefficient oil fields of supply chains to oil fields of supply chains that obtain emission efficiency and are not in this group. Indeed, the efficient oil fields of 10 supply chains that obtained emission efficiency under variable return to scale have the necessary capacities and appropriate technologies for pollutant emissions inhibition. The initial emission amount and the emission amount of each supply chain oil field after ZSG DEA reallocation differ greatly, but the total emission amount of oil fields concerning 10 supply chains remains the same.

According to columns 6 and 7 of Table 15, the oil fields of supply chains numbers 1, 2, and 9 have obtained the emission efficiency of SO_2 gas in 10 supply chains. Therefore, the oil field sectors of supply chains numbers 3, 4, 5, 6, 7, 8, and 10 should decrease the huge amounts of SO_2 and CO_2 emissions by means of new technology innovation and investments in harmful emissions reduction that can earn an appropriate profit by putting their surplus emissions right on the carbon market.

As an illustration, the oil fields of supply chains 1, 2, and 9 gain a total rise of 0.0876 (Ton/h) from SO_2 gas, while the oil fields of supply chains 3, 4, 5, 6, 7, 8, and 10 get a total drop of 0.0876 units. In other words, the oil field in supply chain number 2, which has the highest capacity for oil production at 61200 (1000 barrels), obtained the highest emission efficiency of SO_2 gas in 10 supply chains; therefore, this field enables the reduction of huge emissions in energy sectors. Also, the oil field of supply chain number 2 received the largest rise of nearly 0.0767 units from the oil fields of supply chains numbers 3, 4, 5, 6, 7, and 10, while the oil field of supply chain number 9 with a production capacity of 9360 (1000 barrels) obtained the highest emission efficiency. In addition, it has fewer production capacities compared with the oil field of supply chain number 2, but this field is efficient under SO_2 and CO_2 emissions and has special abilities in emissions abatement.

In similarity, the oil fields in supply chains 1, 2, and 9 obtained the highest emission efficiency of CO2 gas in 10 supply chains as they have significant capacities for CO2 gas reduction compared to other oil fields in supply chains. Additionally, the oil fields in supply chains 2 and 9 have marketable capacities for harmful emission reductions of CO_2 gas in other supply chains. In particular, supply chain number 2 with maximum operating capacity has special abilities to decrease the huge amount of SO_2 and CO_2 emissions.

Table 16 depicts the initial efficiency and emission reduction rate and emission after reallocation of SO_2 gas and CO_2 for gas fields in 10 supply chains.

Table 16 The emissions efficiency scores of supplier 2 and allocation results in supply chains

DMU	Emission of SO_2 after allocation $x^{s_2}_{zk}$	Emission of CO_2 after allocation $x^{s_2}_{zk}$	Initial Efficiency of SO_2 emission Before allocation $\theta^{s_2}_{1k}$	Initial Efficiency of CO_2 emission Before allocation $\theta^{s_2}_{2k}$	Emission reduction of SO_2 $\Delta x^{s_2}_{1k}$	Emission reduction of CO_2 $\Delta x^{s_2}_{2k}$
1	0.905257234	47.00230308	0.929	0.929	0.02766312	1.550440278
2	2.132389381	110.9776991	0.805	0.805	0	0
3	1.063334993	55.34001999	0.993	0.993	0.069496865	3.616882662
4	0.866283186	45.08469027	1	1	0	0
5	2.265663717	117.9138053	1	1	0	0
6	1.093042742	56.88612486	0.936	0.936	0.039789116	2.070777787

7	69.45337621	44.29828939	0.836	0.836	0	0
8	2.075200441	104.6310021	0.984	0.984	0.05718894	6.346696975
9	2.165329234	115.992618	0.956	0.956	0.100334483	5.374729726
10	0.866283186	45.08469027	1	1	0	0

According to Table 16, the gas fields of supply chains numbers 1, 2, 3, 6, 7, 8, and 9 have inefficient emissions. Therefore, they should belong to a cooperation group for the harmful emissions reduction of SO_2 and CO_2 gases. Also, the gas field of supply chains numbers 4, 5, and 10 obtained emission efficiency in 10 supply chains. For example, according to Table 1, the initial emission amount of CO_2 gas for supply chain number 8 is 88.5966 units, and its emission reducing potential is 5.0667 units. After allocation through the ZSG-DEA model, the emission amount is 83.5298, and its reduction emission amount is 5.0667 units. Therefore, under the control mechanism of greenhouse gases and air pollutants, the gas field of supply chain number 8 should further reduce its CO2 emissions. Also, the gas field of supply chains numbers 4, 5, and 10 obtained emission efficiency may increase their CO2 emissions and still remain efficient. Therefore, they can trade their excess quota as efficient gas fields can propose a carbon trade market and increase their emissions through negotiations concerning emissions reductions with other gas fields in supply chains.

Tables 17–22 show the initial emission efficiency, emission reduction rate, and the emission amount after reallocation of NO_X, SO_X, CO_2 gases, and CH concentration for three manufacturers in 10 supply chains. Also, in Tables 17, and 18, the initial emissions efficiency and the emission reduction amount for four greenhouse gases, and the emissions after allocation through the ZSG-DEA model, are described.

According to Table 17, supply chain numbers 3, 4, and 9 have emissions inefficiencies due to NO_X and SO_X gases. In this case, the divisions' emissions should be decreased based on the emission-reducing potential of the ZSG model and the other power plants becoming more efficient. They will increase their emissions values at the expense of the emissions decrease of other power plant sectors, especially for the ones that belong to cooperation groups, such as the first power plant sector of supply chains numbers 3, 4, and 9.

Table 17 The emissions efficiency and results of Emission of $NO_{X,}$ and SO_X gases of manufacturer1

DMU	Emission of NO_X after allocation $x_{zk}^{m_1}$	Emission of SO_X after allocation $x_{zk}^{m_1}$	Initial efficiency of NO_X emission before allocation $\theta_{1k}^{m_1}$	Initial efficiency of SO_X emission before allocation $\theta_{2k}^{m_1}$	Emission reduction of NO_X $\Delta x_{1k}^{m_1}$	Emission reduction of SO_X $\Delta x_{2k}^{m_1}$
1	559787.2389	29720226.8	1	1	0	0
2	353506.0538	4284441.285	1	1	0	0
3	199830.8051	140224.7967	0.984	0.984	35273.94	55328.26457
4	124287.2563	6231057.234	0.427	0.080	105176.9615	5828350.516
5	43498.7082	38755.47129	1	1	0	0
6	256638.3438	217529.6665	1	1	0	0
7	6683.633257	5954.828711	1	1	0	0
8	15138.68666	184259.1512	1	1	0	0
9	76203.57814	54509.47593	0.890	0.917	15832.31391	22043.21457
10	236364.0624	76552.6905	1	1	0	0

[DOI: 10.71885/ijorlu-2024-1-672]

Table 18 The emissions efficiency and results of emission of CO_2 gas and CH of manufacturer1

DMU	Emission of CO_2 after allocation $x_{zk}^{m_1}$	Emission of CH after allocation $x_{zk}^{m_1}$	Initial efficiency of CO_2 emission before allocation $\theta_{3k}^{m_1}$	Initial efficiency of CH emission before allocation $\theta_{4k}^{m_1}$	Emission reduction of CO_2 $\Delta x_{3k}^{m_1}$	Emission reduction of CH $\Delta x_{4k}^{m_1}$
1	66618773.74	375.9918371	1	1	0	0
2	224493390.6	175.4243051	1	1	0	0
3	127194270.6	68.97353787	0.984	0.984	22427523.42	26.28907952
4	78761854.46	56.2693919	0.427	0.295	66618773.74	88.7272309
5	27536231.77	16.95219849	1	1	0	0
6	163094448.8	102.9248773	1	1	0	0
7	4230977.926	2.604727408	1	1	0	0
8	9585079.623	6.700302382	1	1	0	0
9	48459150.23	26.72160751	0.888	0.876	10112936.68	10.57062216
10	150423232.7	95.77288498	1	1	0	0

According to columns 6 and 7 of Tables 17, and 16, the first power plant in supply chain number 4 obtained the most emission decrease of NOX, SOX, CO2, and CH gases in all 10 supply chains, as after allocation through the ZSG-DEA model, the emissions amount significantly reduced. Also, the initial emission of CO2 gas is 145380628.2 (10^3kg/10^6kWh) in the first power plant of supply chain 4, while the emission reducing the potential of CO2 is 66618773.74 (10^3kg/10^6kWh). Therefore, supply chain number 4 should decrease the number of gases emitted and the concentration of pollutants in manufacture 1. Nevertheless, this power plant sector should apply fundamental policies to technology promotion and the improvement of consumption fuels for environmental preservation. The initial emission efficiency of sulfur monoxide and carbon dioxide gases of the manufacturer1 of supply chain 4 are relatively low as this power plant division needs to reduce significantly harmful emissions, while the power plant sector of supply chain 9 is confronted with less reduction of emissions after reallocation by the ZSG-DEA model. We can also see from the results of the ZSG-DEA model that emissions are allowed to increase in 70% of the power plant sector in supply chains.

In addition to the first power plant, supply chains 1, 2, and 6 earned emission efficiency for four greenhouse gases while they produced the most power in 10 supply chains, respectively. Nevertheless, since the first power plants in supply chains 1, 2, and 6 have appropriate interactions regarding economic improvement and environmental preservation, they can obtain more emission rights under the efficiency allocation system of the ZSG-DEA model. Indeed, these supply chains have the necessary facilities to confront greenhouse gas emissions and air pollutants. Therefore, they can decrease surplus emissions of inefficient power plants in the supply chains 3, 4, and 9 by emissions reallocation under the ZSG-DEA model. According to the relevant parameters in the ZSG model, the amount of allocation of emissions among power plants can be revised, which not only keeps the total amount of emissions unchanged, but also improves the emission efficiency of each inefficient division in supply chains.

[DOI: 10.71885/ijorlu-2024-1-672]

Table 19 The emissions efficiency and results of Emission of NO_X, SO_X gases of manufacturer2

DMU	Emission of NO_X after allocation $x_{zk}^{m_1}$	Emission of SO_X after allocation $x_{zk}^{m_1}$	Initial Efficiency of NO_X emission Before allocation $\theta_{1k}^{m_1}$	Initial Efficiency of SO_X emission Before allocation $\theta_{2k}^{m_1}$	Emission reduction of NO_X $\Delta x_{1k}^{m_1}$	Emission reduction of SO_X $\Delta x_{2k}^{m_1}$
1	5715.366203	13670442.67	1	1	0	0
2	281310.0785	1230267.173	0.931	0.777	2121.026629	13665350.53
3	227117.8577	170401.9363	0.680	0.011	56313.24743	8899611.866
4	184904.8857	213746.4689	1	1	0	0
5	49845.03657	2619587.603	1	1	0	0
6	27420.01393	24430.04873	1	1	0	0
7	283231.1405	14373506.37	1	1	0	0
8	367947.7035	30043184.99	1	1	0	0
9	176752.534	9046963.774	1	1	0	0
10	71979.54877	4764.105766	0.894	0.910	7613.648285	61655.68048

Table 20 The emissions efficiency and results of Emission of CO_2 gas and CH of manufacturer2

DMU	Emission of CO_2 after allocation $x_{zk}^{m_1}$	Emission of CH after allocation $x_{zk}^{m_1}$	Initial Efficiency of CO_2 emission Before allocation $\theta_{3k}^{m_1}$	Initial Efficiency of CH emission Before allocation $\theta_{4k}^{m_1}$	Emission reduction of CO_2 $\Delta x_{3k}^{m_1}$	Emission reduction of CH $\Delta x_{4k}^{m_1}$
1	3618030.39	2.227377	1	1	0	0
2	164433976	119.6337405	0.931	0.507	15138214.04	59.46413122
3	89349484.6	63.3812432	0.682	0.436	21379611.60	46.51689180
4	116367887.4	117.314205	1	1	0	0
5	3158009.07	31.49668404	1	1	0	0
6	17357845.53	10.68605339	1	1	0	0
7	209795770.1	228.2184561	1	1	0	0
8	202268948.8	148.6219119	1	1	0	0
9	112467128.5	71.53130852	1	1	0	0
10	45813081.53	23.31261293	0.893	0.886	4828086.639	8.881312737

According to Tables 21 and 22, manufacturers 2 of supply chains numbers 2, 3, and 10 obtained emission inefficiencies of NO_X, SO_X, CO_2, and CH gases in 10 supply chains. Based on emission-reducing potential, they should belong to cooperation groups and invest in harmful emissions and air pollution reduction. Indeed, verifying the power plant sector of which supply chains under four emissions are efficient and determining fair allocation for harmful gas emissions, that is how the emissions should be allocated among these divisions, keeps the total emissions amount unchanged while the second power plant sector is efficient for all supply chains.

At the same time, from Table 17, it can be easily seen that the manufacturer 2 of supply chains numbers 1, 4, 5, 6, 7, 8, and 9 are emission efficient as they have been enabled to increase their emissions values at the cost of decreasing emissions from other inefficient divisions in supply chains. According to column 6 of Table 17, the greatest emission reduction amount of NO_X and CO_2 gases related to manufacturer 2 of supply chain number 3

[DOI: 10.71885/ijorlu-2024-1-672]

is related to manufacturer 2. Moreover, based on the results of the ZSG model, most emissions reduction of SO_X and CH gases should happen in the second power plant of supply chain number 2. In this way, the second power plant in supply chains 2 and 3 should create appropriate strategies for this problem's solution.

Based on the ZSG model, cooperation strategy implies inefficient power plant divisions of supply chains belonging to the cooperation group take out inputs amounting to those of other supply chains that are not in this group and have emission efficiency. For instance, the second power plant sector of supply chains 8, 7, 4, and 9 produced the highest amount of energy in 10 supply chains, as the second power plant division of supply chain number 8 with the highest energy production amount of 6689.385 (106 kWh) among 10 supply chains obtained the most emission efficient of four greenhouse gases and air pollutants. Thus, they have the necessary capacity to confront surplus emissions in economic activities. Based on Tables 17, and 18, it can be seen that the power plants in supply chains 2, 3, and 10 have emission inefficiency. Thus, according to the ZSG-DEA model, they must decrease their emissions and should search for partners that enable them to reduce their emissions, in order to keep the global emissions unchanged. In this way, the second power plant in supply chains 2, 3, and 10 with high emission levels could keep their emission levels if they invested in providing an acceptable reduction to achieve an admissible emission level. Supply chains 8, 7, 4, and 9 with low emission levels can decrease emissions from supply chains 2, 3, and 10 and contribute to the carbon market.

Table 21 The emissions efficiency and results of emission of NO_X and SO_X gases of manufacturer3

DMU	Emission of NO_X after allocation $x_{zk}^{m_1}$	Emission of SO_X after allocation $x_{zk}^{m_1}$	Initial efficiency of NO_X emission before allocation $\theta_{1k}^{m_1}$	Initial efficiency of SO_X emission before allocation $\theta_{2k}^{m_1}$	Emission reduction of NO_X $\Delta x_{1k}^{m_1}$	Emission reduction of SO_X $\Delta x_{2k}^{m_1}$
1	19603.89376	17519.68048	1	1	0	0
2	27423877.76	24433491.25	1	1	0	0
3	212448.268	690393.8765	1	1	0	0
4	140748.5401	117070.4081	1	1	0	0
5	300157.6535	9178172.226	1	1	0	0
6	61523.57432	13857.05047	0.794	0.802	15940.40528	50575.16105
7	487692.3443	21818919.53	1	1	0	0
8	536885.4349	24894598.16	1	1	0	0
9	94829.61418	78876.42476	1	1	0	0
10	33505.72059	29485.11782	0.558	0.009	26389.67997	3118295.675

Table 22 The emissions efficiency and results of emission of CO_2 and CH of manufacturer3

DMU	Emission of CO_2 after allocation $x_{zk}^{m_1}$	Emission of CH after allocation $x_{zk}^{m_1}$	Initial efficiency of CO_2 emission before allocation $\theta_{3k}^{m_1}$	Initial efficiency of CH emission before allocation $\theta_{4k}^{m_1}$	Emission reduction of CO_2 $\Delta x_{3k}^{m_1}$	Emission reduction of CH $\Delta x_{4k}^{m_1}$
1	12447945.19	27.88885666	1	1	0	0
2	17360291475	38.89466682	1	1	0	0

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3	135090771.8	316.7338506	1	1	0	0
4	89573051.78	208.5615383	1	1	0	0
5	190308335.2	501.8102132	1	1	0	0
6	39105344.3	88.99074057	0.793	0.790	10193107.04	25.79557783
7	309244915	871.5449305	1	1	0	0
8	340353483.6	972.1420421	1	1	0	0
9	60350025.18	140.5187591	1	1	0	0
10	21304071.99	40.86633511	0.560	0.352	16643591.68	69.14855989

Finally, according to Tables 21, and 22, manufacturer 3 of supply chains numbers 6 and 10 with high emission levels of NO_X, SO_X, CO_2, and CH gases in 10 supply chains has an inefficient emission system. In other words, supply chain number 10 needs the greatest emission reduction amount of four greenhouses compared with the inefficient power plant of supply chain number 6. Indeed, the third power plant in supply chain number 10 must create the most emission reduction of greenhouse gases in 10 supply chains. Moreover, manufacturer 3 of supply chains 8, 7, 5, 3, and 9 produced the highest amount of power among 10 supply chains, respectively, and they obtained the highest emission efficiency of greenhouse gases, thus having the necessary capacities to meet the high emissions level.

It is worth noting that the average emission efficiencies of SO_2 and CO_2 gases for oil fields are 0.816 and 0.856, respectively. Also, the average initial emission efficiency of SO_2 and CO_2 gases is equal to 0.944 for gas fields. Moreover, oil fields in supply chains 4, 5, and 6 obtained greater emission efficiencies than the average emission efficiency of SO_2 and CO_2 gases in 10 supply chains, while the oil field in supply chain 3 has the least emission efficiency of SO_2 gas among 10 supply chains. Similarly, supply chain numbers 3, 8, and 9 of gas fields have reached the efficiency greater than the average emission efficiency of SO_2 and CO_2 gases.

According to columns of initial emission efficiency of four greenhouse gases, the average initial emission efficiencies of NO_X, SO_X, CO_2, and CH gases are 0.939, 0.883, 0.938, and 0.904 for manufacturers 1, 2, and 3, respectively, in 10 supply chains. Based on the initial emission efficiency of NO_X gas, the emission efficiency of the first power plant in supply chain number 3 is above the average efficiency and is near the frontier (0.984). Also, the efficiency of manufacturer 1 of supply chains numbers 3, 9, manufacturer 2 of supply chains numbers 3, 10, and manufacturer 3 of supply chains numbers 6, 10 are below the average efficiency and are far away from the frontier. Efficient supply chains are on the common frontier as they well adjust the relationship between economic activities and environmental developments. They can obtain more emission rights under the ZSG-DEA efficiency allocation system. Furthermore, based on the results of the initial emission efficiency of SO_X gas, the first power plant of supply chain number 4, the second power plant of supply chain number 3, and the third power plant of supply chain number 10 have very low efficiency, which indicates an excessively high emission amount of SO_X gas in production activities. These three supply chains, in reality, urgently need to reduce their emission amounts.

Moreover, in terms of the initial emission efficiency amount of CO_2 and CH gases of three manufacturers, the first and second power plants in supply chain number 4 and the third power plant in supply chain number 10 obtained the least efficiency amount in all 10 supply chains related to three power plants. In this case, these divisions should further reduce CO_2 and CH gas emissions; otherwise, they will not only create an environmentally harmful impact but also affect their surrounding areas in the same climatic zone.

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Generally, the energy and power plant sectors of supply chains are evaluated to control the total emission amount of greenhouse gases, allocate the initial emission rights at the local level, and trade surplus emission rights on the market. According to the obtained results, supply chains are divided into two categories based on the emission efficiency amount of SO_2 and CO_2 gases in oil and gas fields and the control of four greenhouse gases (NO_X, SO_X, CO_2, and CH) in power production sectors: (1) supply chains that are emission efficient in energy and power plant sectors. For instance, supply chain numbers 1, and 5 obtained emission efficiency of SO_2 and CO_2 gases in oil and gas fields, respectively. They have an emission efficiency of four greenhouse gases of manufacturers numbers 1, 2, and 3 in 10 supply chains, while supply chain 1 reaches an emission efficiency of 0.93% in the gas field sector and supply chain 5 is emission efficient in energy and power plant sectors except for oil field with an emission efficiency of 0.90. (2) Supply chains that are efficient in terms of four greenhouse gas emissions: NO_X, SO_X, CO_2, and CH in the power plant sector. The first, second, and third power plant divisions of supply chains numbers 1, 5, 7, and 8 obtained emission-efficiency under greenhouse gas emissions. In other words, supply chains 1 and 5 have high emission efficiency (close to one) of SO_2 and CO_2 gases in oil and gas fields, respectively, but supply chains 7, and 8 are inefficient for oil and gas fields. (3) supply chains with high levels of harmful emissions in the energy and power plant sectors. For example, the first power plant of supply chain number 4, the second power plant of supply chain number 3, and the third power plant of supply chain number 10 have excessive emissions of SO_X gas in 10 supply chains. According to obtained results, manufacturer number 3 of supply chain 10 emitted the most harmful emissions of SO_X gas compared to other supply chains. Therefore, this power plant sector needs to attract and retain participation in pollution abatement by creating a cooperative group to utilize appropriate policy to confront greenhouse emissions.

5 Conclusion

One of the most effective ways to control greenhouse gases and pollutants in the energy and power plant sectors is the allocation of initial emission rights based on a determined total emission amount for emission right trading. The current paper applies the input-oriented ZSG-DEA model to the allocation efficiency evaluation of several greenhouse gases for the energy and power plant sectors of the electricity supply chain as the total emission amount is fixed. Indeed, each division can reduce its pollutant emissions by means of technological innovation or industrial restructuring and can earn a profit by putting its surplus emissions right on the market.

In the proposed approach, the initial efficiency of electricity supply chain divisions is calculated based on the average efficiency of inputs or harmful emissions. In other words, an important feature of the proposed approach is that it was able to identify supply chain divisions that had a significant impact on reducing the number of undesirable outputs. Indeed, all supply chain divisions that do not belong to the efficient frontier compose the cooperative group and search for efficiency directly on the piecewise linear frontier. The proposed approach allows for total SO_2 gas and CO_2 emissions control in oil and gas fields, as well as NO_X, SO_X, CO_2, and CH emissions control in power plant sectors and mission-right trading among supply chain divisions, and it also establishes a foundation for pollutant emission control policy across supply chains. This study has three empirical results concerning supply chain divisions. First, the energy sectors of electricity supply chains need to make definitive decisions on controlling sulfur monoxide and carbon dioxide emissions, especially the

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management of SO2 gas in oil fields. The results show supply chains have an emission inefficiency of 70% in oil and gas fields, while the average emission efficiency of SO_2 and CO_2 gases in oil and gas fields is above 0.80 and 0.94, respectively.

Finally, the three manufacturers proposed acceptable results in 10 electricity supply chains, as the first and second manufacturers are efficient in 70% of supply chains, while the third manufacturer, with an average efficiency of 0.91, is efficient in 80% of supply chains. That indicates the best productivity among divisions, but the third manufacturer of supply chain 10 lacks the necessary technology to confront SO_X gas.

Second, supply chain management should instill competitive motivation among supply chain divisions to reduce greenhouse gas emissions and pollution. Also, all energy and power plant sectors of supply chains, especially oil and gas fields, should follow emission rights trading as it means the increment of emission efficiency and fossil fuel consumption management together for greenhouse gas reduction in other supply chain divisions.

Third, power producers and electricity supply chain managers should promote the emission rights trading of four gases: nitrate monoxide, sulfur monoxide, carbon dioxide, and CH. On the other hand, there are some limitations to the study in leading emission rights trading. The source of energy is different among districts. The supply chains of each region have their own essential structure and different conditions for business activity. For instance, the southern regions of Iran have noticeable energy resources and a high capacity of power plants in comparison to other regions. Such regional differences affect the number of efficiency measures in each region, so they can account for a large share of carbon and other greenhouse gases, and they can provide more contributions from the greenhouse gas trading rights. The problem considered in this study needs further research in the future. This study, like others, can be conducted on transmission and distribution lines.

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[DOI: 10.71885/ijorlu-2024-1-672]