Iranian Economic Review 2022, 26(4): 791-807
DOI: 10.22059/IER.2021.81589

RESEARCH PAPER

The Electricity Shortage Cost in Iran: An Input-Output Analysis and Linear Programming

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Received: 21 September 2020, Revised: 01 December 2020, Accepted: 03 May 2021

Abstract
The electricity supply security has played a vital role in the economic development of Iran. However, a large number of electricity supply disruptions has happened in recent years, which lead to electricity shortage costs in the level of economic sectors. Using a combination of Input-Output analysis and the Linear Programming method, this study measures the producer price index as average costs of Iranian economic sectors after imposing a unique scenario of a 30% potential electricity shortage supply. In this regard, we employ an Iranian symmetric Input-Output 14Í14 industry-by-industry Table for the year 2011. The results of this study indicate that the most shortage cost occurs for the manufacture of wood and paper products, while the services have the lowest cost after electricity supply disruption. Besides, increasing the costs of non-electricity sectors in the Iranian economy after the electricity supply shock is 175.63% on average. The quantitative results are useful for policymakers attempting to set strategic plans to reduce the electricity cost in manufacturing sectors and optimal distribution of limited electricity resources to reduce the overall cost of blackouts.
Keywords: Electricity, Input-Output Analysis, Linear Programming, Shortage Cost, Iran.
JEL Classification: C67, L94, O13, Q41, Q42.

Introduction

The electricity supply disruption, as the electricity shortage, leads to the economic cost for the economy and directly affects gross domestic products (GDP). Although it cannot be expected that the developed countries experience the electricity shortages, in the United States, California had an electricity crisis in 2000 and 2001, where electricity supply could not secure the demand (Nooij, Bijvoet, & Koopmans, 2007). In 2003, the electricity grid in London, Copenhagen, and Rome exposed a widespread electricity shortage, or in the warm summer of 2003 in the Netherlands, the consumers underwent a large electricity shortage, which has been unprecedented in recent years. Furthermore, In Iran as a developing country, the problem of electricity shortages has always been one of the main challenges, especially in the summer.

We point out some electricity shortage events in Table 1. For example, in the early summer of 2011, Iran's Ministry of Petroleum made some disruptions to supply natural gas to power plants due to technical and financial issues, which provided the massive electricity shortage in Iran's economy. However, there is no information about the production and economic losses caused by these shortages. For example, in summer 2018, due to a long-time drought and then the loss of hydroelectric power stations supply for the national grid, many provinces of Iran experienced the electricity failure and power blackout. These blackouts failed to promote the

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other economic sectors, such as industries, and sustain economic growth.

Table 1. The Electricity Shortage Reason in Iran for 2008-2021

Year	Electricity shortage reasons	News Sources
2008	In the second month of summer 2008, due to severe drought and water shortages in hydroelectric power plants, there was widespread electricity shortage throughout Iran.	Etemad Newspaper 2008 July 29, Tuesday
2009	In 2009, there was no electricity shortage in Iran, due to the heavy rainfall that occurred that year. However, there has been scattered electricity shortages for no reason.	ISNA News Agency 2009 Sep. 07, Monday
2010	Public reports indicate that Tehran has been plagued by electricity shortages.	Asr Iran News Agency 2010 July 07, Wednesday
2011	In early summer of 2011, the Ministry of Petroleum made some disruptions to supply natural gas to the power plants, which provided the massive electricity shortage that year.	Jahan Sanat Newspaper 2011 June 25, Saturday
2014	According to the announcement of Iranian Minister of Energy (Mr. Chit Chian), the electricity industry has been experiencing a decline in investment, which is the main reason for the electricity shortage in Iran.	SHANA News Agency 2014 June 25, Wednesday
2017	The electricity industry has not faced a massive electricity shortage this year except for some cases, such as spot electricity shortage due to technical problems at peak hours.	Online News 2017 July 28, Friday
2021	The problem of fuel supply has led to the shortage of electricity in Iran. Recently, the hydropower plants try to compensate the electricity shortage of which are utilized in full capacity.	Bargh News 2021 Februrary,11 Thursday.

Source: Research finding.

However, in recent years, efforts have been made to increase the security of electricity supply in Iran. Ministry of Energy (2019) for the 22-year period (1994-2016) showed that the electricity supply had been increased dramatically. For example, the number of electrical transformers increased by up to 290 percent, and the total number of electrified villages grew by 77 percent. From the economic point of view, disruptions in electricity supply in Iran lead to rising costs and power outages over a period of time. Especially, these shortages cannot be secured through imports due to economic sanctions, at least in the short-run. According to this economic situation, the electricity shortage cost illustrates the economic consequence of supply interruption to the consumers, which is accompanied by direct and indirect costs to the economy. As we know, electricity has a special and different characteristic of other energy products. One of the most important features of electricity is that it cannot be stored economically on a large scale. For this reason, supply must be online and secured at the moment demand occurs. Regarding this feature, the time of consumption is important for electricity supply. This feature eliminates the possibility of a power disruption in the system; accordingly, the load management has the first priority in electricity consumption. Any failure in the power supply system at any time will reduce the power supply to a level below the demand level occurred and will lead to power failure. On the other hand, if load management is not implemented accurately, demand increases to any level above the supply due to the probability of simultaneous consumption. It is important to note that most of the developing countries like Iran face the problem of electricity shortages in their supply systems owing to many problems in supply management and security (Ju, et al. 2016).

Direct shortage costs enfold the immediate economic loss of productive activities include loss of production and indirect shortage costs; on the other hand, due to interdependency of the economic sectors in the production process, impact on the economy through raising the costs of production in other economic sectors indirectly. Due to the shortage of electricity in one sector, indirectly, the costs of producing other sectors will also increase, and ultimately the prices of goods and services in the whole economy will increase. Therefore, it is important for policymakers and economic planners to measure these costs incurred by the lack of electricity at the economic level.

According to these power failure situations in Iran, a power outage scenario based on the latest situation of electricity supply is determined. Meanwhile, the new output configuration of economic sectors due to imposing of electricity supply shortage scenario, with respect to maximizing the total value added of economic sectors as the social economic benefit, represents the optimal reallocation of electricity supplied to economic sectors and estimate the cost of these new distributions. In this regard, we propose a combined approach with IO analysis and Linear Programming (LP) with examining the interdependency and sustaining value added of economic sectors to answer the key question of this article in which the impact of unsupplied electricity how can impact on the cost of economic sectors in Iran.

Hence, the remainder of the article is organized as follows. Section 2 represents the literature review to indicate the importance of the main issue of this study and point out the novelty of the paper. Section 3 explains the theoretical foundations of an electricity outage and its effects on economic activities. Section 4 is an overview of the methodology and the database employed in this study. The last part of this section considers whether to how the electricity shortage supply scenario for the Iranian economy is made. Section 5 represents the empirical results with regard to the linkage with methodology and the database. Some concluding remarks and policy recommendations are provided in the final section.

Literature Review

In the 1950s and 1960s, the world economy entered extremely high growth, with an annual gross domestic product (GDP) growth rate of 4.5 percent on average. This high sustainable economic growth leads to an increase in environmental pollution and the considerable consumption of finite natural resources such as fossil fuels. At the end of the 1960s, a thorough analysis of these problems was stimulated and developed by Forrester (1971) and expanded by Meadows et al. (1972). This study pointed quantitatively to approach the shortages of energy or raw materials, and to attend environmental problems, to grow the economy exponentially at rates such as those observed in the leading decades (Dietzenbacher and Lahr, 2004). The new studies raised to measure and estimate the economic cost of these shortages with sustainable economic growth targets or maximizing the value added to the economy. According to the prior studies, estimation of the cost of electricity shortages as one of the main energy resources has developed with *four* different quantitative approaches in the literature. Meanwhile, theoretical models used at the empirical level can be discussed here briefly.

The first technical approach is the willingness-to-pay (WTP) method, which is the most a consumer will spend on one unit of a good or service. Some researchers consider willingness to pay as the limit on the price of a product or service which is called the reservation price. In this method, the cost of electricity shortages is measured according to the expected decreasing of welfare level. It is assumed that electricity production directly satisfies consumers, so the cost of electricity shortages is measured on the basis of lack of satisfaction. Regarding to this method, many empirical studies estimate the WTP in different economies. This method employed by Munasinghe (1979) about the electricity system reliability. This study has been examined the socioeconomic impact of the reliability of electricity supply on consumers in descriptive way in which new models and detailed method such as WTP are presented for analyzing the various ways for the impact of electricity outage on different categories of consumers. Also, Munasinghe (1980) in another study for the Brazilian economy show that the principle cost of power failure to residential electricity consumers is the loss of leisure, while the marginal value of leisure equals the household's net income earning rate. Carlsson and Martinsson (2007) with using contingent valuation survey, they elicit Swedish households WTP to avoid power outages. The results of this study show that the WTP positively depends on the duration of the power outages, and that WTP is significantly higher for unplanned electricity outages. Abdullah and Mariel (2010) estimate WTP to avoid power outage with using a choice experiment valuation study conducted among electrified rural households located in Kenya. Hensher (2014) estimate WTP to avoid electricity outage for Australian households, Ozbafli and Jenkins (2015) examines households' willingness to pay (WTP) for an improved electricity service for North Cyprus, and Morrissey et al. (2018) employ this method to estimate WTP for northwest England. According to the Morrissey et al. (2018) households are also WTP between £1.17 (20 min) and £0.05 (480 min) to avoid a power outage depending on the length of the power outage. This method is used for household consumers willing to pay for avoiding power outages or the amount of money that consumers would need to be paid to accept the electricity outage voluntary. Also, Salem and Bayat (2020) estimated the electricity expenditures for urban Iranian households according to the dependency of households to the electricity supply. they found that the electricity price is the first priority for urban Iranian households' welfare. In addition, some literature evaluated the electricity demand function for sector or province planning. Morovat et al. (2019) estimated the electricity demand in Iran as a sectoral and province approach. They found that the own price elasticity of electricity for economic sectors is significantly smaller than unity and electricity is crucial energy input for economic sectors.

The second approach, the contingent valuation method (CVM), was proposed by Ciriacy-Wantrup (1947) to measure the benefits of preventing soil erosion, but Hoehn and Randall (1987) show that the CVM theoretical structure, based on Hicks's utility function and demand, is a satisfactory benefit cost indicator. Cameron and James (1987), according to estimation of inverse demand functions, can measure the value of electricity shortage for consumers. Another approach proposed by Hanemann (1984) is to estimate WTP by maximizing the utility function. In other words, CVM directly asks respondents to determine their WTP contingent on a proposed situation like power outage. Woo et al. (2014) with ordered-logit regression examined the average residential cost estimate for a one-hour power outage in Hong Kong. The results show that the average residential cost estimate for a one-hour power outage is about US$45 which is the topping of estimates reported in 10 of the 11 studies published in the last 10 years.

The third fundamental approach is costumer surveys, which requires expensive surveys and complicated analytical methods. Woo and Train (1988), for the first time, used this method to investigate the economic costs of the electricity shortages of commercial companies in North California. In this analytical technique, electricity is assumed as intermediate input that utilizes the satisfaction of consumers through the production of goods and services. Therefore, the estimated impacts of power outages on social satisfactions and the amount of reducing the production levels, due to the expensive surveys and sophistications, is not popular in research methods.

Finally, *the fourth method* for measurement of the cost of electricity shortages is Input-Output analysis (IO). Bernstein and Hegazy (1988) measured the average cost effects of electricity shortages with Input-Output analysis (IO) as the starting point of second group of linear quantitative approaches for estimation of power failures. Chen and Vella (1994) applied LP/IO approach for the first time to estimate economic cost of electricity shortage to provide some valuable information for planners in Taiwan for setting economic reliability standards, evaluating the pricing policy of electricity and determining load management strategies. Anderson, Santos and Haims (2007) used the inoperability IO model to measure the financial and inoperability effects of the Northeast Blackout in the US electric power grid system. Employing a CGE approach, Hooshmand et al. (2011) estimated the effect of electricity price shock to the production of Iranian economic sectors and the producer price indexes. Islami et al. (2011) evaluate the impact of electricity supply policy and pricing on the producer price index of economic sectors and employment. The result of this study indicated that the sudden electricity price shock has more negative effect on the cost of economic sectors than the incremental price shock. Vasconcelos and Carpio (2015), estimate the cost of electric energy deficit in the long-term using IO analysis. They obtain a deficit marginal cost (DMC) curve to measure the marginal cost operations and short-term market prices. Ju et al. (2016) also estimate the marginal electricity outage cost for Korean economy with LP/IO approach. They demonstrated that the total economic costs depended not only on the shortage percentage of each non-electricity sector but also on the level of its final demand. Peijun et al. (2017) used the IO approach to estimate the electricity shortage in different countries.

Each of these four-mentioned approaches has its own merits, but they have some disadvantages as well. The target of the first two approaches is the electricity shortage estimation for households. Although households usually are the most important consumers of electricity in different countries, from the national policymaking perspective, the government and electricity utilities need to estimate the economic impacts of power outages on economic sectors and the whole economy. Furthermore, according to Chen and Vella (1994), the third approach is an expensive method, especially in data gathering steps and its results lead to overestimation of power shortage costs. Accordingly, this article is to measure the electricity shortage cost in Iranian economy in order to estimate the impact of electricity supply shortage on other economic sectors. From this national planning point of view and due to the following reasons, it is the first time such an article has been conducted in the context of Iran.

1. Most of the studies, which have estimated power outage costs in Iran, employ the WTP or CVM approaches. For example, by applying the Value of Lost Load (VoLL), Ahmadian and Abbaszadeh (2013) estimated the cost of power outage for Iranian households in terms of lost leisure time. Abbaszadeh, Ahmadian, Rahbar, & Abrishami (2014) estimated the marginal willingness to pay (WTP) among Iranian households to avoid power outages using a choice experiment survey. The results show that power outage has negative welfare effects on Iranian households. In addition, the marginal WTP has increased with the rise of household's expenditure, age of respondent, and electricity consumption over the last period. Evidence shows that the mentioned studies are the only articles, which pay attention to the economic impacts of electricity shortage and estimate the power outages for Iranian households. In this article, we study the economic impacts of electricity shortages on the economic sectors from the macroeconomic point of view, while the other studies just provide the information for decision-making in microeconomic level.
2. The second novelty of this article is applying the Input-Output analysis for measuring the cost of electricity shortage in Iran. In addition to providing an analytical approach for measuring the cost of power outage in the sector level, this method has been combined with Linear Programming approach for the first time in Iran. Moreover, to improve the measurement of empirical results, both fundamental quantitative and price models of IO analysis have been employed. Therefore, for the novelty of this paper, two steps are made in quantitative modeling. In the first step, we use the basic approach of value-added optimizing model for Chen and Vella (1994) and Ju et al. (2016), based on Input-Output structure. In the second step, for measuring the cost of electricity shortage, we need to use the producer price index variations for Iranian sectors with the IO price model. In this regard, the average cost of power outage in sectoral level of Iran denotes the producer price index based on which the value added of the economic sectors after electricity shortage maximized to sustain the economic growth of Iran after this interruption. This methodology employed for the first time in Iranian economic studies represents the second novelty of this article.

Theoretical Foundations

Electricity has a unique feature that distinguishes it from other commodities. One of the important features of electricity is that it cannot save economically, and on a large scale. For this reason, supply must be generate, transmit or distribute online and in proportion to the moment of demand. Thus, the timing of electricity consumption is crucial.

This feature eliminates the possibility of power outages in the system, and therefore load management in electricity consumption has a priority in energy supply management. Any failure in the power supply system when it reduces the supply to a level lower than the demand will cause a malfunction and shortage of electricity in the system. On the other hand, if the load management utilizes unreliably, there is a possibility of simultaneous consumption and increasing demand to a level higher than the possible supply level. These disruptions in electricity supply management accompany with some economic consequences illustrate after denoting a definition of electricity outage in a power supply network.

Definition of Electricity Outage

The definition of power shortage is any uncertainty in the electrical system that takes it out of the defined standard state. Also, the low quality of the electricity supply is another disruption which leads to the electricity shortage. In this sense, the lack of electricity will lead to the interruption of electricity-dependent sectoral activities.

According to the Vasconcelos and Carpio (2015) and Uchendu (1993) electricity shortage or electricity energy supply constraint can occur in two ways. The first way as *unplanned outage* it can cause rationing is due to a loss of continuity in the electric energy supply to meet the demand that persists for a medium or long period. This type of power outage is generally predictable and the power network supplier can notice the consumer. Another way of electricity loss as *planned outage* occurs when continuity of electricity supply disrupts for a short period. This type of electricity outage is not predictable and without receiving any notice by the power network supplier. This disruption the most often causes by failure in the power supply chain like generation, transmission, or distribution of electricity and, it can lead to the output or value added disruption in the macro or sectoral level.

It expects that the planners in the short-, medium- and long-term optimally utilize the electricity generation to provide an electricity service with high reliability and reduce cost to secure electricity supply. Regarding the mentioned ways of electricity shortage, some empirical studies such as He et al. (2015; 2017; 2019) estimate the maximum level of energy disruption resilience in the economy. They suggest that the economy can be recovered after a while through energy import or recovery investment to restore production levels, and the economy can endure without sacrificing domestic demand or value added. The other studies like Vasconcelos and Carpio (2015) and Ju et al. (2016) consider the electricity resilience of economic sectors in which the value added can be endured or maximized by some amount of power disruption even in the short period. Ultimately, what matters is the value added or output variation in the whole economy or at the level of the economic sectors caused by the power outage, the economic consequences of which are essential for planners and policymakers.

The Economic Cost of Electricity Outage

The economic growth of a country measures by its gross domestic product (GDP). It shows the value of all the wealth added by all the production factors within its geographical boundaries in a given period (Vasconcelos and Carpio (2015)). The loss of electricity supply leads to the negative effect of the output variation in the economy, especially the sectoral level.

When an electricity outage disrupts the production, the economic interests derived from all activities that rely on electricity are reduced. Two effects can cause this reduction as output variation. According to the Munasinghe (1979), since the production costs due to power outage are increased as *a direct effect*, and the value of outputs is reduced. The second effect is *indirect effect* in which an outage can cause raw materials or intermediate products to disrupt. The direct and indirect effects lead to an opportunity cost equal to the value of the final activity not produced as a result of the electricity outage, minus the value of additional inputs not employed since the final output not produced. These effects measure as a minimum estimate of the resulting cost of the electricity outage, and the primary assumption of this paper in a theoretical point of view is to estimate the cost of the power outage in the short term through value added maximization and output variation.

Methodology and Database

Since the purpose of this problem set is to measure the effect of unsupplied electricity on the economic sectors, we require an Input-Output approach that is compatible with the sectorial level. Based on the IO structure as Table 2, the standard Input-Output table is divided into the electricity and non-electricity sectors, to clarify the impact of electricity supply on the economy. Assumes that economy is composed of n sectors, and the relationship among those sectors can be represented as the X_{ij} matrix with $(n-1)\times(n-1)$ economic sectors and electricity supply is in the nth sector. The other parts of the IOT include export, import, final demand, value added, and output are categorized into electricity and non-electricity sectors.

Table 2. The Standard Input-Output Table with Partitioning Electricity Sector

Standard Partitioning IOT		Inter-Industry Transaction Matrix		Final Demand			Output
		Non-Electricity Sectors	**Electricity Sector**	**Other Final Demand**	**Export**	**Import**	
Inter-Industry Transaction Matrix	Non-Electricity Sectors	$\begin{bmatrix} x_{1,1} & \cdots & x_{1,n-1} \\ \vdots & \ddots & \vdots \\ x_{n-1,1} & \cdots & x_{n-1,n-1} \end{bmatrix}$	$\begin{bmatrix} x_{1,E} \\ \vdots \\ x_{n-1,E} \end{bmatrix}$	$\begin{bmatrix} F_1 \\ \vdots \\ F_n \end{bmatrix}$	$\begin{bmatrix} B_1 \\ \vdots \\ B_n \end{bmatrix}$	$\begin{bmatrix} M_1 \\ \vdots \\ M_n \end{bmatrix}$	$\begin{bmatrix} X_1 \\ \vdots \\ X_n \end{bmatrix}$
	Electricity Sector	$[x_{E,1} \quad \cdots \quad x_{E,n-1}]$	$x_{E,E}$	F_E	B_E	M_E	X_E
Value Added		$[V_1 \quad \cdots \quad V_n]$	V_E				
Output		$[X_1 \quad \cdots \quad X_n]$	X_E				

Source: Research finding.

For empirical modeling, the problem set is to determine the optimal reallocation of constraint electricity supply to the different productive sectors, which can solve with the linear programming model. The general structure of LP model according to the structural and logical constraints based on the standard input- output table, will be as follows:

$$Max:\ TB = [V_1 \quad \cdots \quad V_n]\begin{bmatrix} x_{1,1} & \cdots & x_{1,n-1} \\ \vdots & \ddots & \vdots \\ x_{n-1,1} & \cdots & x_{n-1,n-1} \end{bmatrix} + V_E.E \tag{1}$$

$S.t.$:

$$E = (1-S)E^0 \tag{1a}$$

$$\hat{X} \le \hat{X}^{\,0} \tag{1b}$$

$$\hat{F} \le \hat{F}^{\,0} \tag{1c}$$

$$F_E \le F_E^0 \tag{1d}$$

$$\hat{X}, \hat{F}, F_E \ge 0 \tag{1e}$$

Where TB is the total economic benefit, V_i is the value-added coefficients of non-electricity sectors, V_E is the value-added coefficient of the electricity sector, and E denotes the electricity supply. This objective function maximizes the value added of the electricity and non-electricity sectors. E^0 in the first constraint, indicates the total electricity supply and S represents the share of unsupplied electricity and E denotes the constrained electricity supply. $\hat{X}^0$ denotes the amount of non-electricity outputs. Also, $\hat{F}$ as $(n-1) \times 1$ matrix represents the final demand matrix for non-electricity sectors and $\hat{F}^0$ and F_E^0 are the amount of final demand for non-electricity and electricity sector, respectively. To determine the $\hat{X}$ and F_E, it is necessary to establish the demand-driven Leontief linear quantitative method based on standard IOT structure as following Equations:

$$X_i = \sum_{j=1}^{n} x_{ij} + F_i = \sum_{j=1}^{n} a_{ij} X_j + F_i \tag{2}$$

Where X_i denotes the total gross output of sector $i = 1, \dots, n$, and a_{ij} is the direct input coefficient, which is calculated as a constant in terms of the ratio of a sector's input to its output. Therefore, a_{ij} is a constant ratio called *Fixed Technical Coefficients*, and F_i represents the final demand for products of sector i. Equation 2 can be rewritten in an abbreviated matrix form as follows:

$$X = AX + F$$
$$(I - A)X = F \tag{3}$$

With import matrix M, Equation 3 can be rewritten again as Equation 4:

$$(I - A)X = F - M \tag{4}$$

Hence, we can represent the Equation 6, according to the electricity and non-electricity sectors in the new structure of IOT as follows:

$$\text{w}\begin{bmatrix} (I - \hat{A}) & -\alpha \\ -e & 1 - f \end{bmatrix} \begin{bmatrix} \hat{X} \\ E \end{bmatrix} = \begin{bmatrix} \hat{F} \\ F_E \end{bmatrix} - \begin{bmatrix} \widehat{M} \\ M_E \end{bmatrix} \tag{5}$$

Where $(n-1) \times (n-1)$ is an identify matrix, $\hat{A}$ is an $(n-1) \times (n-1)$ fixed technical coefficient matrix of non-electricity sectors, α is the electrical column of non-electricity sectors, e is the electrical row of non-electricity sectors, f represents the self-consumption ratio of the electricity sector, and $\widehat{M}$ represents the imports of none-electricity sectors, and M_E is the import of electricity sector.

Hence, we can rearrange Equation 5 for measurement of $\hat{X}$ and F_E to complete the introducing of Equation (5b) to (5d):

$$\hat{X} = \left(I - \hat{A}\right)^{-1} \alpha E + \left(I - \hat{A}\right)^{-1} \left(\hat{F} - \widehat{M}\right) \tag{5a}$$

$$F_E = \left[1 - f - e\left(I - \hat{A}\right)^{-1} \alpha\right] E - e\left(I - \hat{A}\right)^{-1} \left(\hat{F} - \widehat{M}\right) + M_E \tag{5b}$$

By solving this problem set, with imposing the constraint of electricity supply and maximizing the value added, we have a new configuration of the output for each economic sector. These output variations as the optimal reallocation of the economy due to the effects of unsupplied electricity, accompany economic cost in optimal way. For estimating these average economic costs, the price Input-Output model is to measure the producer price index variations as the representative of electricity shortage cost for different sectors. To do so, we employ the supply-driven Ghosh IO linear quantitative method for n sectors as follows:

$$X_j = \sum_{i=1}^{n} x_{ij} + V_j = \sum_{i=1}^{n} b_{ij} X_j + V_j \tag{6}$$

Where X_j the total gross output of sector is $j = 1, \dots, n$, b_{ij} is the direct output coefficient, which is represented in the distribution of sector $i's$ outputs across sectors j that purchases interindustry inputs from i (Miller & Blair, 2009). According to Miller and Blair (2009), the basic assumption of the supply-side approach is that the output distributions in b_{ij} are stable in an economic system. Therefore, b_{ij} is a constant ratio called *Allocation Coefficients*, and V_j indicates the vale added for production of sector j. Equation 7 can be rewritten in an abbreviated matrix form as follows:

$$\begin{bmatrix} \hat{V} \\ V_E \end{bmatrix} = \begin{bmatrix} \hat{X} \\ X_E \end{bmatrix} \begin{bmatrix} (I - \hat{B}) & -\beta \\ -e & 1 - f \end{bmatrix} \tag{7}$$

Where $\hat{V}$ and V_E are the value added of non-electricity and electricity sectors, respectively. Also, β represents the electrical column of non-electricity sector. Besides, e is the electrical row of non-electricity sectors, and f represents the self-consumption ratio of the electricity sector. Based on Miller and Blair (2009), in terms of average changes in V which is recognized as $\hat{\bar{V}}$ and $\bar{V}$, we would find the associated output variations in average as Equation8:

$$\begin{bmatrix} \Delta\hat{\bar{X}} \\ \Delta\bar{X}_E \end{bmatrix} = \begin{bmatrix} (I - \hat{B}) & -e \\ -\beta & 1 - f \end{bmatrix}^{-1} \begin{bmatrix} \Delta\hat{\bar{V}} \\ \Delta\bar{V}_E \end{bmatrix} \tag{8}$$

With respect to average output variations, the Ghosh price model[1] which is the reinterpretation of a cost-push input-output model can be made[2]. In this approach, we can measure the producer price index variations. Hence, the Ghosh price model can be written as

$$\begin{bmatrix} \Delta\widehat{\overline{ec}} \\ \Delta\overline{ec}_E \end{bmatrix} = \begin{bmatrix} (I - \hat{B}) & -e \\ -\beta & 1 - f \end{bmatrix}^{-1} \begin{bmatrix} \Delta\hat{\bar{X}} \\ \Delta\bar{X}_E \end{bmatrix} \tag{9}$$

Where $\Delta\widehat{\overline{ec}}$ and $\Delta\overline{ec}_E$ are the average economic cost of non-electricity and electricity sectors which measures the average producer price index variations according to the new configuration of output for each sector, respectively. With regard to solving the problem set (i.e., maximizing the objective function as Equation 3 and Equation 3a to Equation 3d as the constraint), the output variations after optimization of value added of economic sectors can be measured. Hence, for n sectors after solving the problem set, we can measure a new output for the n sector. Corresponding to each new sector i's output, there is a new value-added matrix with n×1 order. Finally, for measuring the average of the value added changes, we employ a weighted average of new value added for the n sector. For calculation of a weighted average of new value added for n-1 sector, the following formula can be employed:

$$\sum_{i=1}^{n} w_i \, \Delta V_i = w_1 \Delta V_1 + \cdots + w_n \Delta V_n = \bar{V}$$

After simplifying the calculations, these steps are rerun to measure producer price index variations as electricity shortage cost for the n sector. In this step, we have new average value added for n economic sector. Corresponding to each new sector i's value added, there is a (n-1)×1 order of the new price matrix. Finally, to measure the average of the producer price index changes, we use a weighted average of new price for n-1 economic sector. To do this, we employ the following formula:

$$\sum_{i=1}^{n} w_i \, \Delta P_i = w_1 \Delta P_1 + \cdots + w_n \Delta P_n = \bar{P}$$

1 To overcome the implausibility in the original view of the Ghosh model, Dietzenbacher (1997) proposed an alternative interpretation by suggesting that the model be viewed as a price model (Miller and Blair, 2009: 551).
2Miller and Blair (2009) show that the Ghosh price model and the Leontief price model mathematically generate exactly the same results. We use this method instead of Leontief price model.

For measurement of the unsupplied electricity costs in Iran, we employ the symmetric Iran input-output 14×14 Table (industry-by-industry) for the year 2011, which is provided by the Statistical Center of Iran (Statistical Center of Iran, 2019). It is the most up-to-date Table in Iran released in 2016. Therefore, we considered a total of 14 sectors. Sector 5 is the electricity sector, and the other 13 Sectors are non-electricity sectors.

Regarding the optimization model, we need to propose a scenario for determining the electricity shortage in Iran's economy. Diverse resources secure the electricity supply in Iran. According to Table 3, some percentage of this supply, is related to the heat or thermal power plants which equals to 90.94% of total electricity production. Also, the share of the renewables is about 5.05% of the total domestic electricity supply. The international trade is another part of electricity production in which the share of this part is about 5.03%.

Table 3. The Electricity Consumption Outlines of Iran based on Supply Resources in 2011

	Resources of Electricity Production	**Consumption (MkWh)**	**Share of Consumption (%)**
Heat or Thermal Resource Plants	Steam Turbine Plant	95,901	38.35
	Gas Turbine Plant	58,716	23.48
	Combined Cycle Plant	72,749	29. 09
	Diesel Power Plant	62	0.02
	Total Electricity Production of Heat Power Plants	227,428	90.94
Renewables Resources	Hydroelectric Power Plants	12,058	**4.82**
	Renewables and Nuclear Power Plants	578	0.23
	Total Electricity Production of Renewables	12,636	5.05
Total Domestic Electricity Consumption		240,064	97.95
Export of Electricity		8668	**3.47**
Import of Electricity		3656	**1.46**
Self-Consumption and Electricity Distribution Losses		49,040	**20.01**
Net Total Electricity Consumption		245,076	100

Source: Energy Balance Sheet of Iran (2011) and Comprehensive Statistics of Iran's Electricity Industry (2011).

However, the electricity production in Iran secure the electricity supply due to the various resources; there are three critical situations that lead to shortcoming the security of electricity supply in Iran. First of all, the government's statistics in 2011 indicate that more than 20% of total electricity production due to the problem in distribution of national power grid waste in the electricity supply chain. Although, not all of these shares are related to wastage in the national power grid. The other part of this critical situation that is not produced through the national network is the self-consumption of electricity, which is currently produced in power plants, refineries and some manufactures' utilities in practice, as they try to secure their electricity supply due to the uncertainty to the national power grid. Consequently, the economic system can be secured up to 21% due to the electricity distribution wastes and self-production without any requirement to the national power grid. Hence, the economic system depends on the 21% of its self-production or loss of distribution which potentially must have been supplied by the national power network. Another critical shortcoming situation for securing the electricity supply is the dependency of the national power network in Iran to electricity production from the source of renewables. The hydroelectric power plants energies with 4.82 % of electricity supply are often unavailable at the time of demand. Also, they are highly variable in production due to atmospheric and climatic conditions. Hence, the hydroelectric power plants unpredictability leads them to be potentially unsecure as one of the main electricity supply resources. The third critical failure condition for electricity supply is the severe uncertainty of international trade in Iran, especially after economic sanctions. Consequently, the inability to import or export the electricity which is about 5.03% motivates the loss of domestic electricity supply security and potentially activates the vulnerability of national power grid.

In this regard, the overall potential electricity shortcoming, as a case of this study, is about 30% measured by the sum of all potential critical outage conditions. Hence, the mentioned scenario is the maximum percentage of disruption as the sectoral shortage of electricity supply imposed on the final demand for production and distribution of the electricity sector.

Empirical Results

As mentioned in previous sections, this study applies a combination of IO analysis and linear programming to estimate the electricity shortage cost with the IO price model by imposing the scenario of 30% electricity shortage supply as the maximum percentage of electricity disruption in Iran. Unlike Ju et al. (2016) and Vasconcelos and Carpio (2015), we employ a 30% disruption in electricity supply as a unique scenario to estimate the economic shortage cost from the optimization model in which we examine the optimal electricity allocation policy between economic sectors. The impact of power outages through a 30% disruption in electricity supply can accommodate the new output configuration of economic sectors achieved by maximizing the total value added as the social economic benefit concerning electricity supply shortage situation. Thus, to analyze the impact of such a policy on the cost of electricity shortage in the Iranian economy as the average cost of unsupplied electricity, we determined the effect of output variations on the production cost of economic sectors, representing the cost of electricity shortages in each economic sector.

Regarding the 30% potential electricity shortage from the electricity sector proposed in section 3, the output of economic sectors will change after this power outage. The output variations of each sector before and after the electricity shortage are calculated based on percentage change considered in Table 4. Thus, the output estimate after electricity shortage measurement by maximizing equation 6 as the total value added with respect to the equation (6a) to (6b).

The column (1) in Table 4 represents the amount of output produced in each sector before imposing the electricity supply disruption scenario which is provided by IOT of 2011 for 14 economic sectors. For example, according to the Table 4, we found that the amount of output produced by manufacture of basic metals was about 140,974 billion rials. The column (2) is the amount of output for each sector after the electricity supply disruption scenario which are the result of employing the linear programming to optimize the value added of each sector after electricity supply shock. For instance, the amount of 23,136 billion rials as the output of manufacture of textiles and leather products sector after electricity shortage represents the amount of output that must be produced to maximize the value added of the mentioned sector after 30% of electricity shortage supply. Besides, the last column as column (3) denotes the output variations after applying the scenario of 30% electricity shortage supply. The results of the output variation based on Table 2 show that the output variation in Iran is about 28% on average with respect to the 30% of electricity shortage supply. Respect to column (3), the first four sectors included manufacture of textiles and leather products, manufacture of basic metals, manufacture of wood and paper products and manufacture of chemical, rubber, and plastic products have the highest output reduction after electricity disruption, which is more than the average (28%). It denoted that the mentioned economic sectors are high electricity-intensive industries. Meanwhile, textile and leather products' manufacture faces the most electricity shortage in which its output has reduced more than 80%. It indicates that the production of the mentioned sector predominantly relies on the electricity supply directly and indirectly.

Table 4. Output Variations of Iranian Economic Sectors in 2011 Due to 30% Potential Electricity Shortage (Values: Billion Rials)

Ranking Sectors	Sector	Output before Electricity shortage (1)	Output after Electricity shortage (2)	Output Variations (%) (3)
1	Manufacture of textiles and leather products	140,974	23,136	-83.59
2	Manufacture of basic metals	1,085,540	212,271	-80.44
3	Manufacture of wood and paper products	86,319	31,217	-63.83
4	Manufacture of chemical, rubber, and plastic products	481,549	274,938	-42.90
5	Production and distribution of electricity	108,138	75,697	-30.00
6	Transportation	495,021	375,069	-24.23
7	Agriculture, Forestry and fisheries	696,732	561,619	-19.39
8	Manufacture of glass and glass products	10,069	8,299	-17.58
9	Manufacture of food, beverages and tobacco products	523,153	433,962	-17.04
10	Manufacture of gas; distribution of gaseous fuels	335,993	284,720	-15.26
11	Manufacture of other non-metallic mineral products	166,780	143,156	-14.16
12	Manufacture of coke and refined petroleum products	863,327	779,302	-9.73
13	Services*	4,273,984	3,975,279	-6.98
14	Manufacture of mining and quarrying	1,815,486	1,708,832	-5.87

Source: Research finding, based on Iran IOT of 2011.
Note: *Services include wholesale trade, retail trade, telecommunication services, real-estate services, public administration, financial and insurance activities, education, and health services. For calculating and providing the sector, called "Services" here, the authors aggregate 50 economic sectors together.

Based on the results of Table 4, the manufacture of mining and quarrying, as the last sector, indicates the lowest dependency on the electricity supply. The output reduction for the mentioned sector is about 5.87%, which is the lowest output variation. In addition, the manufacture of coke and refined petroleum products and services experiences output reduction of less than 10%. This amount of variation represents the low electricity intensity of the two mentioned sectors and shows that these sectors can produce their electricity needs without any dependence on the national electricity grid. The output variations calculation is the first step for the electricity shortage cost estimation.

By applying the results of output variations in Equation 10, the electricity shortage cost for each sector can estimate with respect to the scenario of 30% electricity supply disruption as the second step for the electricity shortage cost measurement—the results of employing this process represented in Table 3. As can be understood from the results of Table 5 and the application of Equation 10, the cost of electricity shortage shows the producer price index changes of each sector after output variations. It is worth noting that the value added maximization is the underlying assumption in all steps.

Table 5. Electricity Shortage Cost of Iranian Economic Sectors in 2011 Due to 30% Potential Electricity Shortage (%)

Rank of Sector	Sector	Electricity Shortage Cost (PPI%)
1	Manufacture of wood and paper products	1734.35
2	Manufacture of basic metals	124.82
3	Manufacture of textiles and leather products	99.91
4	Manufacture of other non-metallic mineral products	94.26

5	Manufacture of chemical, rubber, and plastic products	63.17
6	Manufacture of glass and glass products	46.80
7	Transportation	35.70
8	Agriculture, Forestry, and fisheries	29.49
9	Production and distribution of electricity	29.24
10	Manufacture of food, beverages, and tobacco products	18.56
11	Manufacture of gas; distribution of gaseous fuels	16.60
12	Manufacture of mining and quarrying	8.17
13	Manufacture of coke and refined petroleum products	7.57
14	Services	3.79

Source: Research finding, based on Iran IOT of 2011.

Table 5 shows that the highest producer price index variation is in the manufacture of wood and paper products due to curtailing electricity supply and output reduction, while the services have the lowest dependency on the electricity supply.

One of the main reasons for the high electricity intensity of the manufacture of wood and paper products is the strong dependence of this sector on manufacturing the basic metals and the manufacture of other non-metallic mineral products. These two mentioned sectors also have a high economic cost variation after imposing the electricity shortage scenario.

The manufacture of the basic metals ranks second after the manufacture of wood and paper products. This sector experiences a 124.82% increase in a producer price index, which has the most economic cost for the economy after the manufacture of wood and paper products.

In addition, the manufacture of other non-metallic mineral products is in the fourth place and experiences a 94.26% increase in the economic cost because the two mentioned sectors (manufacture of the basic metals and manufacture of other non-metallic mineral products) also have the high electricity consumption in the Iranian economy, 22.71%, and 6.31% respectively[1].

In addition, Table 5 shows that electricity shortage cost with 30% electricity supply disruption leads to the economic cost for other non-electricity sectors at 175.63 % on average. In other words, the above result shows that Iran's economic sectors are highly dependent on electricity consumption. The results which are estimated for measuring economic cost of economic sectors after electricity disruption in Iran is comparable with similar studies such as Hooshmand et al. (2011), Islami et al. (2011) and Permeh (2005). These studies indicated that the structure of Iranian economic sectors have a potential to response unwarrantedly to the energy price shocks or any similar supply energy disruptions. Also, Ju et al. (2016) estimated the shortage cost of electricity with 30% of unsupplied electricity. The empirical results of this study indicated that the average cost of unsupplied electricity increased from KRW 147 to KRW 5,891 per kWh from t - 1 to t, which denoted that an increase in the output multiplier. The result of studies with identical approach shows that the economic sectors are very sensitive to the electricity outage, and the average cost could be raised unpredictably.

The other notable point in Table 5 is about the lowest economic cost caused by electricity shortages in the manufacture of coke and refined petroleum products and the manufacture of mining and quarrying sectors. According to the Energy Balance sheet of Iran (2011), about 95 percent of the electricity consumption of the manufacture of coke and refined petroleum products and the manufacture of mining and quarrying sectors provide by intra-industry utilities, and only the remaining 5 percent supplies from the national electricity grid. The results show that the more the Iranian economic sectors depend on electricity consumption, the more they will experience the cost of electricity shortages.

1 The electricity consumption of the economic sector of Iran retrieved from the Energy Balance sheet of Iran (2011)

Conclusion

One of the highly important infrastructures of the Iranian economy is the electricity sector. The Iranian government endeavors to secure electricity supply, especially as one of the primary inputs of the other economic sectors. There are many experiences about electricity shortages in recent years happening in Iran due to such reasons as both natural disasters like droughts or floods and human-made problems. These conditions require researchers to contribute policymakers with reliable information for securing the electricity supply. In this regard, this study employs IO a combining method of Input-Output analysis and Linear programming to measure the economic cost of unsupplied electricity for all sectors based on Iranian IOT of 2011 by providing the optimal solution in which constrained electricity resources can be allocated to various sectors while maximizing the total value added.

The results of this study indicate that the economic shortage cost of unsupplied electricity for the non-electricity sectors is about 175%, which shows the high electricity intensity of non-electricity sectors as an input of production in Iran.

Table 6. Ranking Economic Sectors Based on Three Different Estimations

Rank of Sector	**Ranking based on Electricity shortage Cost**	**Ranking based on Output Variations**	**Ranking based on Electricity Consumption**
1	Manufacture of wood and paper products	Manufacture of textiles and leather products	Production and distribution of electricity
2	Manufacture of basic metals	Manufacture of basic metals	Manufacture of basic metals
3	Manufacture of textiles and leather products	Manufacture of wood and paper products	Agriculture, Forestry and fisheries
4	Manufacture of other non-metallic mineral products	Manufacture of chemical, rubber, and plastic products	Services
5	Manufacture of chemicals, rubber and plastics products	Production and distribution of electricity	Manufacture of other non-metallic mineral products
6	Manufacture of glass and glass products	Transportation	Manufacture of chemicals, rubber and plastics products
7	Transportation	Agriculture, Forestry, and fisheries	Manufacture of food products, beverages, and tobacco products
8	Agriculture, Forestry and fisheries	Manufacture of glass and glass products	Manufacture of mining and quarrying
9	Production and distribution of electricity	Manufacture of food, beverages, and tobacco products	Manufacture of textiles and leather products
10	Manufacture of food, beverages and tobacco products	Manufacture of gas; distribution of gaseous fuels	Manufacture of coke and refined petroleum products
11	Manufacture of gas; distribution of gaseous fuels	Manufacture of other non-metallic mineral products	Manufacture of wood and paper products
12	Manufacture of mining and quarrying	Manufacture of coke and refined petroleum products	Manufacture of gas; distribution of gaseous fuels
13	Manufacture of coke and refined petroleum products	Services	Manufacture of glass and glass products
14	Services	Manufacture of mining and quarrying	Transportation

Source: Research finding, using Tables 2,3,4.

According to the main empirical results of this article, some key policy implications should be considered by policymakers and planners in Iran. The electricity shortage cost of economic sectors can be comparable with output variations and electricity consumption share in Iran's economy. This informative comparison represented in Table 6 denotes the ranking of the Iranian sectors from three points of view. This ranking provides by electricity shortage cost and output variation, as extracted from the empirical results and the electricity consumption of

Iranian sectors. The key point of this comparison indicates that the economic sectors with high electricity intensity do not necessarily experience the high economic cost of electricity shortages. For example, although the services have high electricity consumption, their electricity shortage cost is placed in the lowest rank. Meanwhile, the only sector that has maintained its rank in all three types of ranking is the manufacture of basic metals.

Regarding the ranking of sectors based on electricity shortage cost, many of the highly reliable manufactures cannot reduce their electricity consumption due to employing high electricity-intensive technologies, economic sanctions, and inadequate project financing. Therefore, based on the highest shortage of electricity cost of economic sectors, policymakers should employ a strategic plan to reduce the electricity cost of manufacturing by providing financial support to improve the technology of production or construction of electricity utility for self-consumption.

It should be mentioned that the data of electricity consumption for each sector obtained from the Energy Balance Sheet of Iran (2011) provided by Power Ministry of Iran for the year 2011 (Ministry of Energy, 2019). The electricity consumption data in Energy Balance Sheet classified into nine general sectors extend to the 14 economic sectors, according to the International Standard Industrial Classification of All Economic Activities (ISIC), Revision 4 (Statistical Center of Iran 2019) as shown in Table 4. According to Table 2, the production and distribution of electricity have the highest electricity consumption, which is called the self-use or self-consumption of this industry. Also, as we expect, the manufacture of basic metals has a high electricity consumption.

Finally, it is notable that, if the dependence of different economic sectors on the national electricity grid continues, it is useful for policymakers to achieve an optimal electricity distribution to reduce the total output variation and the overall cost of blackouts at the level of economic sectors.

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