Iranian Journal of Economic Studies, 13(2) 2024, 619-646

Shiraz University

Iranian Journal of Economic Studies

Journal homepage: ijes.shirazu.ac.ir

The Electricity Outage Cost in Iran: An Input Output Analysis[1]

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Article History

Received date:17 June 2025
Revised date: 28 September 2025
Accepted date: 01 October 2025
Available online: 05 October 2025

JEL Classification

C61
C67
Q11
Q41

Keyword

Electricity shortages
Input-Output analysis
Economic and social scenarios
Optimal electricity allocation
Outage cost
Sectoral vulnerability

Abstract

Electricity is the backbone of modern economies, and its absence, even temporarily, can lead to far-reaching consequences. This study estimates the cost of electricity shortages across Iranian economic sectors in 2023 through an Input–Output (I–O) framework. According to the most recent I-O table published by the Central Bank of Iran, the research evaluates how unsupplied electricity affects industries in terms of lost value-added, expressed in million Tomans per kilowatt-hour (kWh). The analysis is conducted under two main scenarios: (i) a purely economic perspective and (ii) an integrated socio-economic perspective that incorporates social considerations alongside economic factors. The findings reveal considerable variation in sensitivity across sectors. Industries such as forestry, mining, and chemicals show relatively low vulnerability, while others, especially food production, furniture manufacturing, construction, pipeline transport, and key public services, face significantly higher losses when electricity is disrupted. Notably, the food sector registers an outage cost nearly three times the national average, and public services such as defense and healthcare emerge as particularly exposed. Beyond quantifying these costs, the study demonstrates how I-O analysis can support optimal electricity allocation strategies during shortage periods. By identifying which sectors are most sensitive, the results provide actionable insights for policymakers tasked with balancing economic efficiency and social welfare when planning resilience strategies and infrastructure investment.

Highlights

- Used Iran's 2023 I-O table to estimate electricity shortage costs, averaging 10.9 million Tomans/kWh, with high sectoral variation.
- Manufacturing averaged 4.8 million Tomans/kWh, with glass, plastics, and furniture most vulnerable; services/infrastructure at 14.4 million, pipeline transport hit hardest; public services/governance at 49.1 million, severely affecting defense and administration.
- Food production, electrical equipment, vehicles, and pipeline transport showed high outage sensitivity.

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DOI: 10.22099/ijes.2025.53520.2047

1. Introduction

Electricity is a fundamental pillar of modern life and a leading indispensable energy sources in today's interconnected global economy (Kim & Cho, 2017). In 2023, Iran produced approximately 382.9 terawatt-hours (TWh) of electricity, accounting for about 1% of total global generation. The country's electricity output has been growing at an average annual rate of 4%, driven by industrial expansion, increasing urbanization, and rising residential demand.

Electricity consumption in Iran is heavily concentrated in the residential, industrial, and agricultural sectors, with the industrial sector consuming the largest share according to Figure 1. This distribution highlights the essential role of electricity in maintaining economic productivity, public welfare, and societal stability.

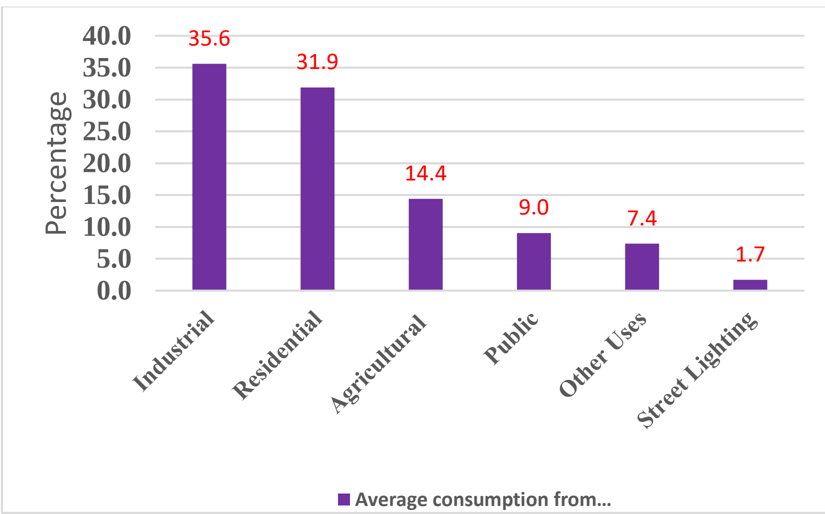

Figure 1. The Consumption Percentage for each Electricity Sector
Source: *Detailed report of the Ministry of Energy*

However, electricity supply systems are vulnerable infrastructures. When disrupted, whether by natural disasters, technical failures, or capacity shortages, these outages causes wide-ranging economic detriment and major social fallout. On a macroeconomic scale, power outages undermine national competitiveness and deter foreign investment. On the micro level, they diminish business productivity, disrupt services, and contribute to public dissatisfaction and unrest (Chen, Yan, Gong, Geng, & Yuan, 2022).

The total economic cost of electricity outages, often referred to as outage cost, includes all damages incurred by consumers and businesses due to both planned and unplanned power interruptions, or from poor electricity quality resulting from insufficient grid reliability (Najafi-Shad, Mollashahi, & Sadr, 2024). To properly assess these costs, it is important to understand their primary components. Prior research typically classifies the socio-economic impacts of outages into three major categories:

Direct Damage Costs: These include physical damage to equipment and infrastructure, and in severe cases, injuries or fatalities.

Emergency Response and Clean-Up Costs: These refer to the expenses involved in mitigating outages, such as activating emergency generators, replacing lost goods or materials, and rescheduling production cycles.

Business Interruption Costs (BICs): These represent the immediate production losses in affected sectors, as well as the broader "ripple effects" across interconnected industries due to supply chain disruptions (Chen et al., 2022).

Quantifying these costs is particularly crucial in the case of long-duration outages, which are becoming more frequent due to the rising prevalence of extreme weather events and increasing pressure on electricity infrastructure (Ghodeswar, Bhandari, & Hedman, 2025).

Numerous methods have been proposed to estimate the economic cost of electricity shortages. Some studies focus on the impact of specific blackout events on national or regional economies, while others calculate average outage costs on a per-hour or per-kWh basis, regardless of the event's context. Still others adopt a sectoral approach, estimating outage costs separately for residential, commercial, industrial, and transportation sectors (Ghodeswar et al., 2025).

Among these methods, Input-Output (I-O) analysis has emerged as a particularly powerful and widely used approach. By modeling the transfer of goods and services among various industries, the I-O framework enables researchers to quantify both the direct and indirect economic impacts of electricity shortages. It provides a theoretical and empirical lens through which to understand how disruptions in one sector propagate across the economy (Mukhopadhyay, 2018). This technique also reveals the often-overlooked structural interdependencies that define modern economies.

This study builds upon that foundation by applying the I-O method to Iran's economy for the purpose of assessing the monetary damages from power outages in 2023. It introduces several innovations: (1) the use of the most recent input-output table published by the Central Bank of Iran, (2) a detailed analysis of electricity dependence across multiple sectors, including manufacturing, services, and public administration, and (3) a dual application of the I-O model to not only estimate outage costs but also recommend optimal electricity allocation strategies.

In doing so, this research addresses key theoretical and empirical gaps in the literature. While most previous studies have focused narrowly on cost estimation, this paper expands the scope by linking outage analysis to decision-making frameworks for electricity resource management and infrastructure resilience. The insights generated can support Iranian policymakers in designing more effective, data-driven responses to electricity shortages, while identifying which sectors are most economically vulnerable to supply disruptions.

2. Previous Work

To date, few studies have quantitatively addressed VoLL estimation using I-O models. Accordingly, we included selected international research to provide readers with sufficient background and context for the proposed framework, ensuring clarity in the methodology and literature foundation.

The field of disaster impact assessment has long drawn interest from economic theory, recognizing the profound and multifaceted consequences of disruptions on societal well-being and economic functionality. A leading role in disaster impact analysis and resilience assessment has been assumed by Input-Output (I/O) economic models over the past few decades. These models, rooted in general equilibrium and economic production theory, are particularly valuable for distinguishing between direct economic losses and the cascading ripple effects that propagate within a multi-industry system following disruptions. Their linearity and ability to outline inter-industry linkages make them valuable for rapid assessment of economic consequences (Galbusera & Giannopoulos, 2018).

Input-Output (I/O) Economic Models

I/O models typically fall into two main categories based on the direction of shock propagation and underlying economic assumptions:

Demand-driven (Leontief) Model: This widely recognized model defines production levels by propagating backward from exogenously assigned final demand. It assumes infinite supply elasticity and fixed technical coefficients, meaning inputs are used in constant proportions, implying irreplaceability. Multiplier analysis, which gauges the economic effects of exogenous changes, is a primary application.

Supply-driven (Ghosh) Model (Ghosh, 1958): Developed by Ghosh, this model describes economies where scarce resources or central planning dominate. It calculates output changes based on exogenously specified primary factor input changes. This approach assumes fixed output (allocation) coefficients and is considered plausible in monopolistic markets or for small perturbations, though it has faced criticism for assumptions like perfect demand elasticity.

Both static and dynamic extensions of I/O models exist, along with nonlinear, stochastic, and mixed formulations that attempt to integrate demand- and supply-driven aspects and overcome limitations like supply constraints. However, a major point of debate is the sufficiency of I/O models in assessing the disequilibrium conditions caused by large disasters, particularly in incorporating substitution effects relevant for long-term analysis, which can lead to overestimation of losses. Time resolution differences between economic models and actual disaster impacts also pose a challenge, as unexpected events often generate impacts within time periods shorter than the model's observation or solution interval.

Disasters are often modeled as demand-side, supply-side, or mixed perturbations. Demand perturbations, such as altered consumption due to security concerns, can lead to demand redirection. Supply-side disruptions, common in natural disasters, can be internally or externally constrained. Mixed-sided approaches attempt to blend these, linking simultaneous perturbations to short- and long-term impacts. The joint stability of Leontief and Ghosh matrices remains a challenge in analyzing causal paths.

Direct vs. Indirect Losses: In the literature, direct losses are often associated with material damages and capital losses (stock input losses), while indirect losses relate to flow output losses over time, such as production in businesses affected by the hazard itself or interactions between businesses. The challenge of quantitatively precise evaluation of indirect losses persists due to economic complexity, diverse disaster contingencies, and data constraints. Neglecting indirect economic impacts, such as business interruption costs (BICs), can lead to a significant commonly understated of the total cost of power outages (Chen et al., 2022). There are many studies on direct economic loss of power outages, but few studies have been made on the indirect economic loss (Shuai et al., 2018). Double counting of losses, especially concerning stock and flow losses, is a recognized issue that requires careful interpretation.

Static I/O methods include:

Structural analysis and network theory: This involves multiplier analysis for direct and indirect effects, and interpreting I/O tables as complex networks to understand shock propagation and economic stability. This area has seen growth with multi-country I/O databases to analyze global value chains and assess the role of industries and countries in a global perspective.

Optimization techniques: Linear and nonlinear programming are combined with I/O models to introduce flexibility, address production bottlenecks, or minimize constrained production costs. These methods are valuable for describing inefficiencies caused by constraints, which is highly relevant for disaster impact analysis.

I/O Inoperability Model (IIM): The IIM, inheriting the Leontief model's demand-driven nature, translates critical events into demand perturbations to evaluate inoperability (normalized difference between as-planned and actual output) and economic losses. It has been applied to terrorism, blackouts, and transportation disruptions. Extensions like the Supply-driven IIM (SIIM) and integrations with optimization have been developed.

Dynamic I/O methods include:

Temporal analysis and lagged models: These investigate the evolution of economic networks over time, enriching static methods with dynamic features.

Sequential Interindustry Model (SIM): SIM describes dynamic inter-industry production, integrating Leontief's framework with technological aspects. It accounts for sequential production over time and allows for comparison of production modes.

Basic equation and dynamic inequalities: These approaches characterize disequilibrium, with the "basic equation" depicting system imbalances from disasters and dynamic inequalities tracing economic recovery progress.

Dynamic Input-Output Inoperability Model (DIIM): An extension of the IIM, DIIM uses a resilience matrix to model inoperability dynamics. It has been applied to various events, incorporating recovery processes and mitigating factors like inventories. The DIIM is particularly useful for assessing business interruption costs (BICs).

Adaptive Regional Input-Output (ARIO) Model: ARIO extends the Leontief model for disaster modeling by incorporating supply constraints, rationing, price dynamics, and adaptation capabilities like overproduction and inventories.

Economic resilience is a central theme in disaster assessment, defined as a system's ability to maintain function when shocked (static) or hasten recovery speed (dynamic). I/O models contribute to understanding resilience by analyzing structural factors and integrating resilience concepts into dynamic frameworks like the DIIM.

Economic Costs of Electrical System Instability and Power Outages

Power outage accidents result in significant economic loss to the social economy, making their economic loss evaluation highly important. The economic impact of power outages can be categorized into direct and indirect economic impacts. While considerable research exists on direct economic losses, studies on indirect economic losses are fewer.

Valuation Methodologies for Outage Costs: Because there is no market price for electricity interruptions, various methods have been developed to calculate their effects (De Nooij, Koopmans, & Bijvoet, 2007).

Production-function approach: This macroeconomic technique estimates costs through lost production for firms or lost time for households, treating electricity as a necessary input (Castro, Faias, & Esteves, 2016). It is suitable for capturing production losses that cannot be avoided or rescheduled. This approach has been applied to estimate the average Value of Lost Load (VoLL), defined as the foregone value added due to electricity outage, in countries like the Netherlands (€8.56/kWh in 2001), Ireland (€12.9/kWh in 2008), Spain (€5.98/kWh in 2008), Cyprus (€6.5/kWh in 2009), Germany (€7.41/kWh), and Portugal (€5.12/kWh). Studies also disaggregate VoLL by sector and household, revealing differences in impact (Castro et al., 2016).

Survey-based methods (Customer Surveys): These are popular tools where customers estimate their losses for hypothetical outage scenarios (Lawton, Sullivan, Van Liere, Katz, & Eto, 2003).

Willingness to Accept (WTA): Customers define compensation they would accept for an outage.

Willingness to Pay (WTP): Customers state an amount they would pay to avoid an outage. For residential customers, WTP measures are more common due to the intangible nature of their costs (e.g., "hassle" or "inconvenience"). WTP studies have explored heterogeneity based on socio-demographic factors like gender, age, employment status, and heating system type (Ezzati et al., 2025).

Direct Worth (DW): Customers directly provide the economic value of distinct outage scenarios, considered more reliable by some as it reduces biases.

Challenges with surveys include strategic responses (exaggeration of losses) and zero/extreme responses. Data processing techniques, such as z-score tests and logarithmic transformations, are used to handle outliers and skewed distributions.

Hybrid approaches: These combine direct analytical methods with customer surveys to overcome limitations and provide more objective and credible estimations. For instance, a hybrid model can use publicly available Value-Added data with a customer survey focused on perishable losses. The Adaptive Regional Input-Output (ARIO) model can also be viewed as an integrated dynamic I/O-based analysis.

Case studies: These list and monetize the effects of actual supply interruptions. While providing real-world data, they may lack generalizability.

Factors Influencing Outage Costs: Many factors can affect the Business Interruption Costs (BICs) of power outages, including the scale of affected economies, the resilience of the electricity system, recovery time length, interdependencies among different sectors, outage duration, frequency, time of day, season, and advance warning.

Outage Duration: The cost of an outage generally increases with duration, but often at a slower rate (logarithmic specification), meaning additional minutes for short outages are valued more than for long ones (Baarsma & Hop, 2009). Najafi-Shad et al (Najafi-Shad et al., 2024). propose using third-order polynomial regression to describe Composite Customer Damage Functions (CCDFs) as a function of outage duration. Longer recovery periods lead to increased BICs.

Time of Day/Season: The economic impact of power failures is typically greater in winter compared to summer, even for outages of the same length and time. Outages during working hours or evenings/weekends for households can lead to significant lost productivity or leisure time.

Advance Warning/Preannouncement: Advance warning of an outage can significantly reduce costs for companies (Kim & Cho, 2017).

Customer Type/Sector: Costs vary considerably between sectors and regions. Commercial and public sectors often experience higher economic value of lost power (Baarsma & Hop, 2009). In South Korea, the agricultural sector is found to be the most sensitive to supply interruption, while outage costs are often less substantial in the commercial and public sectors. In Portugal, manufacturing has the lowest VoLL, while construction and public works have the greatest.

Backup Systems (Emergency Generators): The presence and capacity of emergency generators can reduce outage costs. Studies show that the difference between simple VoLL calculation and estimated outage costs (including various damages) increases when companies have emergency generators.

Empirical Case Studies:

Guam: The introduced Brown Tree Snake causes frequent electrical power outages on the Island of Guam, with over 1600 outages between 1978 and 1997 (Fritts, 2002). A single island-wide outage lasting 8 or more hours was estimated to cost over $3,000,000 in lost productivity. Annually, these outages cost Guam's economy more than $4.5 million during a seven-year period, excluding repair costs or lost revenues.

China: A study in China, using a DIIM, assessed Business Interruption Costs (BICs) from a provincial extremely big electricity outage. It found a weak negative relationship between peak inoperability and BIC, meaning sectors with bigger inoperability do not necessarily have larger BICs. Neglecting BICs significantly underestimates total economic impacts; the estimated BIC (1.56 million yuan/h) was found to be relatively bigger than average direct economic losses from historical events.

United States (Meta-Analysis): A significant effort compiled 24 datasets from 8 utilities (1989-2002) into a meta-database to synthesize Customer Damage Functions (CDFs). This revealed that the average cost for a one-hour summer afternoon outage was approximately $3 for residential, $1,200 for small-medium commercial and industrial (C&I), and $82,000 for large C&I customers. The study highlighted the challenge of collinearity in combining diverse datasets, where regional, temporal, and methodological differences are intertwined.

Energy Transition and Renewable Energy Investment

The global push for energy transition is driven by concerns over fossil fuel depletion and escalating environmental issues like CO2 emissions. Countries like Iran, heavily reliant on fossil fuels, aim for significant renewable energy generation targets (e.g., 10% by 2025) (Robson, 2012).

Key policies to promote renewable energy include:

Feed-in Tariff (FiT) policy: This provides guaranteed purchase prices for renewable electricity, enhancing investment certainty and reducing risk. However, poorly designed FiTs can burden governments and consumers (Sayadi, 2021).

Carbon Emission Trading (CET) scheme: Derived from the Kyoto Protocol, CET allows companies to buy or sell carbon credits, incentivizing pollution reduction. It can complement FiT by reducing the required government subsidy for renewable energy, lowering the actual cost of clean electricity. The scheme has been implemented in various regions, including the European Union.

The Real Options Approach (ROA) is increasingly favored over traditional Net Present Value (NPV) for evaluating renewable energy investments due to uncertainty and the flexibility in timing investment decisions (Aghaei Marzebali & Arasteh, 2023). ROA provides the right, but not the obligation, to act at a fixed cost, making it suitable for high-risk, irreversible decisions.

ROA is particularly useful for renewable energy projects like wind, solar photovoltaic (PV), hydropower, and concentrated solar power (CSP), considering uncertainties in non-renewable energy costs, certified emission reductions, FiT, energy production, and operation and maintenance costs.

Monte Carlo simulation is commonly used within ROA to model uncertain variables like electricity or CO2 prices, helping to estimate project values and optimal subsidy levels.

Studies show that the CET scheme significantly decreases the required subsidy for renewable energy projects when evaluated using ROA, making the subsidy more realistic than with NPV. Raising unit production capacity and the price of electricity can lead to a further reduction in subsidies.

In Iran, ROA studies indicate that switching to renewable energy (solar PV) is preferable to continued reliance on oil, emphasizing investment timing flexibility and the impact of electricity costs on investment decisions. Electricity price volatility tends to increase the needed subsidy for renewables.

Computable General Equilibrium (CGE) models are used to analyze the macroeconomic and environmental effects of energy transition policies. Gholami et al. (2023) (A. Gholami, Nikpour, & PO744, 2023) utilized a dynamic multi-regional CGE model for Iran, testing three scenarios for energy transition by 2050:

Scenario 1 (S1) (2% biennial renewable electricity increase, fulfilling Seventh Development Plan target): Showed a "double dividend" with increased GDP and welfare alongside reduced carbon emissions (0.07% GDP increase in 2030, 1.63% carbon emission reduction in 2050).

Scenario 2 (S2) (5% biennial renewable electricity increase, fossil fuels constant): Demonstrated more significant positive economic and environmental impacts (0.7% GDP increase in 2050, 4.27% total carbon emission reduction in 2050), approximately three times greater than S1.

Scenario 3 (S3) (5% biennial renewable electricity increase, 5% fossil fuel decrease): Led to decreased GDP and welfare, and increased inflation (GDP decline by 4.88% in 2050), due to reduced fossil fuel production dominating Iran's energy mix. However, this scenario achieved the largest carbon emission reduction (10.89% in 2050). These CGE findings underscore that increasing renewable energy production while maintaining fossil fuel-based electricity is a "win-win strategy," but reducing fossil fuel production significantly could harm economic indicators, necessitating compensatory measures. International comparisons indicate consistency with these results, showing similar trends in economic growth, welfare, and carbon emission reductions in other transitioning economies.

Social Vulnerability to Power Outages

Social vulnerability (SV) describes how individuals are susceptible to harm from power outages, and its neglect can lead to uneven recovery from disasters. Traditional SV indices often focus solely on demographic and socio-economic characteristics. However, recent research suggests the need to integrate environmental and infrastructural factors, as well as accessibility to essential services, which are often overlooked but crucial during outages (Ezzati et al., 2025).

To address these gaps, the Power Outage-Risk integrated Social Vulnerability Index (PO-RSVI) was proposed. The PO-RSVI offers a more comprehensive metric than traditional indices by directly integrating the risk of extended power outages into its social vulnerability (SV) calculation. This approach considers not only the physical risks but also underlying social factors. The PO-RSVI is structured around three key dimensions:

Prolonged Outage Susceptibility (SI1): Represents the exposure risk to extended outages. Factors include load-shedding policies (influenced by population density, critical facilities), power restoration policies (affected by race/ethnicity composition, utility type), redundancy in power supply, proactive maintenance measures (e.g., vegetation trimming), and transportation blockages.

Community Coping Capacity (SI2): Focuses on individuals' ability to cope with outage impacts. Indicators cover socio-economic status (education, income), health sensitivity (age, health impairments), and emergency management (household head gender, language, crime rate, generator presence).

Community Accessibility (SI3): Assesses access to essential and emergency facilities during outages. This includes availability and access to food, water, medical aid, shelters, and transportation means.

The PO-RSVI calculates vulnerability by multiplying SI1 by the aggregation of SI2 and SI3, emphasizing SI1's role as a multiplier effect. It provides a more accurate, context-specific vulnerability measure for power outages compared to broader SV indices.

The concept of Willingness to Pay (WTP) for emergency power supplies is also explored. While extensive research exists on WTP for electricity reliability, the direct relationship between WTP and social vulnerability (SV) had been less explored. The PO-RSVI study found a negative correlation between PO-RSVI and WTP, indicating that more vulnerable communities are less willing to pay for emergency power. This highlights the need for equitable policies that consider the financial capabilities and risks of vulnerable populations. Key factors influencing WTP estimation include medical aid access, PO-RSVI, food/water access, household leadership, and the presence of children under 5.

3.Theoretical Framework

Understanding the economic cost of electricity outages requires a robust theoretical foundation that combines microeconomic valuation, production theory, and macroeconomic modeling. This study's framework integrates three interconnected pillars: (1) outage cost valuation methodologies, (2) economic modeling of production and welfare loss, and (3) inter-industry propagation analysis through the Input-Output (I-O) approach.

Valuation Foundations of Electricity Outage Costs

From a microeconomic perspective, electricity outages are interpreted as negative shocks to consumer and producer welfare. The primary valuation methodologies for outage costs include:

Willingness to Pay (WTP) and Willingness to Accept (WTA): These methods rely on consumer preferences and estimate the loss of utility during outages. Electricity's absence is interpreted as a reduction in consumer surplus, measurable by the area under the demand curve (De Nooij et al., 2007; Herriges, Caves, & Windle, 1990). Recent applications incorporate socio-demographic heterogeneity to refine estimates (Ezzati et al., 2025).

Direct Production Loss Method: This method estimates losses from halted production, idle labor, and materials spoilage. Adjustments account for outage duration, timing, and the firm's ability to compensate via overtime or inventory use (Baarsma & Hop, 2009; Castro et al., 2016).

Opportunity Cost of Backup Supply: Here, the cost of generating electricity via alternative technologies (e.g., diesel generators) is used to approximate the economic value of outages. This approach includes investment, maintenance, and fuel costs and aligns with cost-minimization principles under uncertainty (Bose, Shukla, Srivastava, & Yaron, 2006).

The integration of these methods reflects a dual consideration of business interruption costs (BICs) and consumer welfare loss, forming a complete valuation structure.

Economic Theory of Interruption Losses

Electricity is a foundational input in production, and its disruption generates both direct and indirect losses:

Direct losses refer to immediate reductions in output and capital utilization.

Indirect losses arise from supply chain disturbances and demand shocks propagating through the economic network.

Adjustment costs emerge when firms attempt to mitigate outages via increased work shifts, deferred production, or resource reallocation (Shuai et al., 2018).

These dynamics are further shaped by outage characteristics. Research indicates that losses increase non-linearly with outage duration, and that predictable outages cause lower losses than sudden disruptions (Baarsma & Hop, 2009; Najafi-Shad et al., 2024). Models such as the Composite Customer Damage Function (CCDF) are used to capture these nonlinearities (Li, Zio, Chen, Xiang, & Wang, 2023).

The Input-Output Framework for Outage Cost Estimation

At the macroeconomic level, the Input-Output (I-O) model provides a structural lens through which outage costs can be traced across the economy. Rooted in Leontief's general equilibrium theory, the I-O model captures inter-industry dependencies, allowing the quantification of ripple effects from a sectoral shock (Miller & Blair, 2009).

In this study, a demand-driven I-O model is used, which assumes fixed technical coefficients and infinite supply elasticity. Electricity shortages are modeled as exogenous reductions in sectoral inputs, with the resulting output reduction interpreted as a loss in value-added, in the $VoLL_i = \Delta Value\ Added_i / \Delta Electricity\ Supplied_i$.

This Value of Lost Load (VoLL) represents the marginal cost of unsupplied electricity for each sector. The model also employs the Leontief inverse $(I-A)^{-1}$ to account for indirect losses propagated through supply chains.

I-O models have been widely applied in outage cost studies due to their transparency and ability to rapidly simulate economic disruptions (Galbusera & Giannopoulos, 2018; Okuyama, 2007). Despite their limitations in modeling substitution and market dynamics, they remain essential tools for static assessment of interconnected losses.

Integration with Iranian Sectoral and Social Context

The I-O model is implemented using Iran's most recent national I-O table. Sector-specific parameters, such as electricity dependency, availability of emergency power systems, and adaptation capacity, are embedded to ensure contextual relevance. This framework draws from empirical findings on Iran's energy sector (M. Gholami, Sadeghi, Jalaee Esfandabadi, & Nejati, 2024), and acknowledges the unique vulnerability of sectors like healthcare, public services, and food production.

In addition, this study reflects new interdisciplinary advances, such as the Power Outage-Risk Social Vulnerability Index (PO-RSVI), which integrates socio-economic, infrastructural, and service accessibility dimensions into vulnerability assessments (Ezzati et al., 2025). These tools help capture how electricity outages translate into unequal welfare impacts across communities, adding a human-centered layer to the theoretical model.

Justification and Contribution of This Framework

The theoretical framework adopted in this study is both comprehensive and policy-relevant, offering:

Conceptual completeness by combining microeconomic and macroeconomic valuation perspectives.

Operational utility through the I-O model's ability to simulate direct and indirect losses.

Equity considerations by integrating social vulnerability into outage cost analysis.

Policy implications, enabling data-driven prioritization of electricity supply, resilience planning, and investment in backup infrastructure.

By situating Iran's case within a broader theoretical and empirical context, the framework enhances the robustness and applicability of outage cost estimates, providing both quantitative rigor and qualitative insight for decision-makers.

4. Methodology

To assess the economic cost of unsupplied electricity across different sectors of the Iranian economy in 2023, this study adopts a methodological framework rooted in Input-Output (I-O) analysis. This approach is particularly well-suited for examining the ripple effects of energy disruptions in an interconnected economy like Iran's. Inspired by the methodology used in (Ju, Yoo, & Kwak, 2016) for the Korean electricity sector, the current analysis adapts and applies these concepts to the Iranian context using the most recent available data.

4.1 Rationale for Using Input-Output Analysis

The choice of I-O analysis is driven by its ability to capture the interdependencies between sectors. When electricity supply is reduced, it doesn't only affect the directly impacted sector, but also has indirect consequences throughout the supply chain. For example, a power cut in the manufacturing sector can reduce output in the logistics, trade, and even education sectors. The I-O model provides a systematic way to trace and quantify these cascading effects throughout the entire economy.

In this research, the core of the I-O model is built upon the national I-O table published by the Central Bank of Iran (CBI), with data corresponding to the year 2016. Although not the most recent year, this dataset remains the latest official I-O table available and offers detailed coverage of Iran's industrial and service sectors. It is assumed that, structurally, the relative inter-sectoral relationships have not drastically changed in the short period leading to 2023, especially for purposes of energy allocation modeling.

4.2 Structuring the Model

To make the analysis more suitable for estimating the cost of electricity shortages, the electricity sector was isolated from the rest of the economic system. This separation allows for a more precise calculation of how electricity flows into other sectors and how its absence would affect economic performance.

The model is structured around a linear system of equations, representing the relationship between sectoral output, intermediate consumption, and final demand. The starting point is the fundamental I-O identity, which for an economy with n sectors is given by equation 1.

$$X_i = \sum_{j=1}^{n} a_{ij} X_j + F_i \qquad \text{for } i = 1,2,\dots,n \tag{1}$$

Where:

- X_i : total output of sector i
- a_{ij} : direct input coefficient from sector j to sector i
- F_i : final demand for goods from sector i

In matrix form, incorporating imports M, the system is written as equation 2.

$$(I - A)X = F - M \tag{2}$$

To explicitly analyze electricity shortages, we rearrange the I-O system by isolating the electricity sector as the n-th sector. Using matrix partitioning, the system becomes as follows in equation 3:

$$\begin{bmatrix} I-\bar{A} & -\alpha \\ -e & 1-F \end{bmatrix}\begin{bmatrix} \bar{X} \\ E \end{bmatrix} = \begin{bmatrix} \bar{F}-\bar{M} \\ F_E - M_E \end{bmatrix} \tag{3}$$

Where:

- $\bar{A}$: technical coefficient matrix of non-electricity sectors $(size\ (n-1)\times(n-1)$
- α : column vector representing electricity input coefficient for each non-electricity sector
- e : row vector representing electricity consumption by each non-electricity sector
- f : self-consumption ratio of the electricity sector
- $\bar{X}$: output vector of non-electricity sectors
- E : electricity output (i.e., total electricity supply)
- $\bar{F}$, F_E : final demand for non-electricity and electricity sectors respectively
- $\bar{M}, M_E$: imports for non-electricity and electricity sectors respectively

Solving equation 3, we derive following equation 4a and 4b.

$$\bar{X} = (I-\bar{A})^{-1}\alpha E + (1-\bar{A})^{-1}\,(\bar{F}-\bar{M}) \tag{4a}$$

$$F_E = [1-f-e(I-\bar{A})^{-1}\alpha]E + e(I-\bar{A})^{-1}(\bar{F}-\bar{M}) + M_E \tag{4b}$$

These expressions show how total sectoral output and electricity final demand vary as a function of available electricity $\bar{\boldsymbol{E}}$.

By rearranging the system and using matrix partitioning, the model is adjusted so that the electricity sector is placed at the end of the sectoral list. This facilitates easier tracking of how electricity inputs (both direct and indirect) contribute to production and how their removal affects the economy.

4.3 Value-Added Maximization under Electricity Constraints

A central aim of this study is to explore how a limited electricity supply should be distributed to minimize total economic loss. To do so, we model the scenario as a value-added maximization problem. That is, given a certain amount of electricity (less than the full demand due to shortage), how should it be distributed across sectors to yield the highest total value-added in the economy? The model assumes that under electricity shortages, the total supply E is constrained by equation 5.

$$E = (1-S).E_0 \tag{5}$$

Here E0 is the total electricity demand under normal conditions, and S represents the proportion of the shortage.

Using this constraint, we set up an objective function to maximize total economic benefit, TB described in equation 6.

$$TB = V_{non-elec}.X_{non-elec} + V_{elec}.E \tag{6}$$

Where:

- $V_{non\text{-}elec}$ is the vector of value-added coefficients for non-electricity sectors
- $X_{non\text{-}elec}$ is the vector of non-electricity sector outputs
- V_{elec} is the value-added from the electricity sector

This setup ensures that electricity is not just viewed as an energy source, but as a critical economic input whose allocation has real consequences for national output.

4.4 Estimating the Marginal Cost of Unsupplied Electricity

To measure how costly electricity shortages are, we estimate the marginal cost of unsupplied electricity. This is calculated as the reduction in total value-added per kilowatt-hour (kWh) of electricity not delivered. The marginal cost helps us identify which sectors should be prioritized in electricity distribution. Sectors with higher marginal costs suffer greater economic damage when electricity is cut and should, in theory, be protected from curtailment. Mathematically, the marginal cost at any given stage t is calculated as equation 7.

$$MB_t = \frac{\Delta TB_t}{\Delta E_t} = \omega\alpha + V_E \tag{7}$$

Where:

- $\omega = \bar{V}(1 - \bar{A})^{-1}$
- $\epsilon = e(I - \bar{A})^{-1}$

Note that:

$$MB_t = \frac{(1-f+\epsilon\alpha)\omega_t}{\epsilon^t} \tag{8}$$

Which captures the loss in value added due to one additional unit (kWh) of electricity not being supplied. The calculation considers not only direct effects but also the multiplier effect through interconnected sectors.

4.5 Modeling Two Allocation Scenarios

The model explores two distinct scenarios to reflect real-world decision-making:

- Economic Efficiency Scenario: In this case, electricity is allocated purely based on maximizing value added. Sectors are ranked based on their value multipliers, and electricity is first cut from the least productive sectors (those with the lowest value-added per unit of electricity).
- Non-Economic Consideration Scenario: Recognizing that some sectors provide critical social functions (such as healthcare, education, or defense), this scenario introduces restrictions. Specifically, a maximum reduction threshold σ is applied to each sector’s final demand, ensuring that even less productive but socially vital sectors are not disproportionately affected.

This dual-scenario approach enables a more nuanced understanding of both economic efficiency and social equity in electricity planning.

4.6 Sectoral Aggregation and Data Handling

The original I-O table from the CBI includes numerous sectors. For clarity and computational feasibility, the sectors were aggregated into broader categories such as manufacturing, agriculture, services, public administration, and so on. However, care was taken to preserve sectoral distinctions relevant to electricity sensitivity, particularly those with high electricity intensity or high value-added potential.

Sector-specific electricity consumption data were matched with each aggregated sector using direct use coefficients. Where specific electricity usage data were missing, estimates were made based on historical consumption patterns and comparable economies.

All final results are expressed in millions of Tomans per kilowatt-hour (kWh). This normalized unit allows for straightforward cross-sectoral comparisons and helps identify sectors that are especially vulnerable to electricity shortages. According to flowchart 1, the overall process of the modelling is represented.

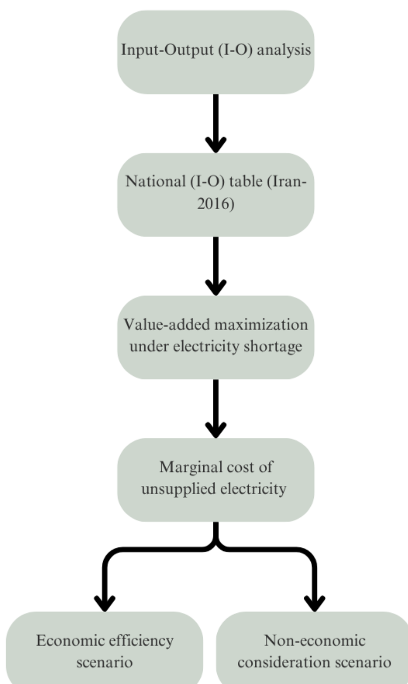

Figure 2. The process of methodology overview
Source: *Background studies*

5. Results and Discussion

The estimation of electricity shortage costs across Iranian economic sectors in 2023, derived from the Input-Output (I-O) framework, highlights significant heterogeneity in vulnerability to power disruptions. Outage costs are expressed in million Tomans per kilowatt-hour (kWh), and results are presented under both the Economic Efficiency Scenario (purely economic considerations) and the Non-Economic Consideration Scenario (integrating critical social services). Before presenting sector-specific findings, Table 1 summarizes the scenario design and abbreviations used throughout the analysis. The Economic Efficiency Scenario (TB_S1–S5_2023) focuses on incremental reductions in final demand from 0% to 50%, allowing for an assessment of how progressively constrained electricity supply affects economic output. In contrast, the Non-Economic Consideration Scenario (TB_S30_RES_2023 and TB_S50_RES_2023) introduces explicit safeguards for critical social functions, assuming that essential services such as healthcare, education, and defense remain protected even under shortage conditions.

Table 1. Description of scenarios and abbreviations used for electricity shortage cost estimation in Iranian economic sectors (2023).

Two Scenarios		The Abbreviations and Descriptions	
Total Benefit (TB) Calculation in Different Predefined Scenarios	Non-Economic Consideration Scenario	TB_S30_RES_2023 / S = 0.3	In this scenario, we assume 30% reduction to the final demand (But not to critical social functions)
		TB_S50_RES_2023 / S=0.5	In this scenario, we assume 50% reduction to the final demand (But not to critical social functions)
	Economic Efficiency Scenario	TB_S1_2023/ Base, S=0	We assume the base model
		TB_S2_2023/ S=0.1	10% reduction in final demand was assumed
		TB_S3_2023/ S=0.3	30% reduction in final demand was assumed

	TB_S4_2023/ S=0.4	40% reduction in final demand was assumed
	TB_S5_2023/ S=0.5	50% reduction in final demand was assumed

Source: *Summarized by researchers*

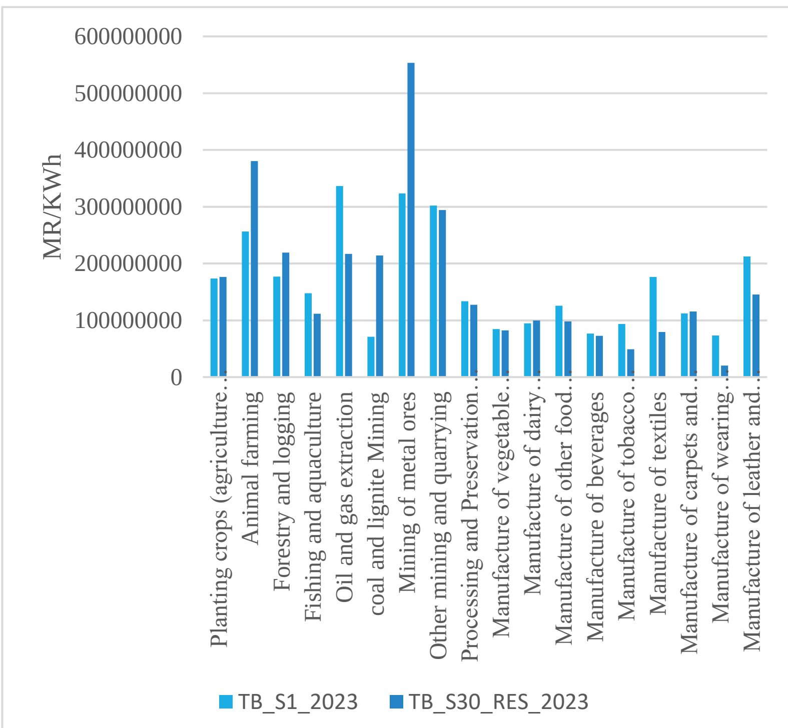

Figure3. Estimated economic cost of electricity shortages across Iranian economic sectors in 2023 (million Tomans per kWh). Higher values indicate greater vulnerability due to operational complexity, perishability of goods, or reliance on continuous power supply.

Source: *Research Finding*

As illustrated in Figure 3, the average economic cost of unsupplied electricity across all sectors in Iran is approximately 10.9 million Tomans per kWh. However, these average masks considerable variation. Sectors such as forestry, mining of ores, tobacco, textiles, and basic metals exhibit below-average costs, indicating a relatively lower reliance on uninterrupted electricity supply. Even energy-intensive activities such as chemicals and steel production fall near or slightly below the national average, reflecting either process flexibility or the ability to withstand short-term interruptions.

In contrast, industries such as food production, machinery, motor vehicles, furniture manufacturing, and pipeline transport record substantially above-average outage costs. The food industry in particular shows an estimated 31.1 million Tomans per kWh, nearly three times the national mean, underscoring its extreme sensitivity due to refrigeration, continuous processing, and perishability of raw materials. Public services, including healthcare and defense, also emerge as highly exposed, reflecting their dependence on continuous electricity for critical operations.

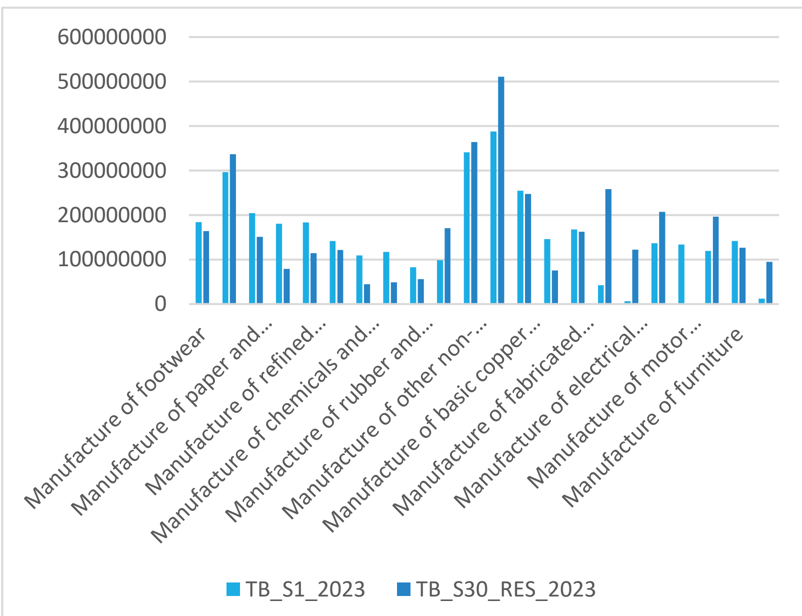

Figure 4. Estimated cost of electricity shortages in Iranian manufacturing subsectors (Sections 19–40) in 2023, expressed in million Tomans per kWh. Furniture, refined petroleum, and transport equipment manufacturing demonstrate the highest vulnerability, while chemicals and basic metals remain comparatively resilient..
Source: *Research Finding*

A more detailed breakdown of industrial subsectors (Sections 19–40) is presented in Chart 3. Within this group, the average cost of electricity outages is 4.8 million Tomans per kWh. Sectors such as chemicals, pharmaceuticals, and basic metals fall below this benchmark, suggesting resilience against temporary power shortages.

Conversely, subsectors including glass, rubber and plastics, refined petroleum, and transport equipment exhibit above-average costs, with furniture manufacturing standing out as the most vulnerable. This elevated cost reflects the industry's reliance on continuous production lines and precision machinery, where interruptions can result in disproportionate losses.

Service-oriented and infrastructure-intensive activities (Sections 41–59) show a distinct vulnerability profile (Figure 5). The average estimated cost in this group is 14.4 million Tomans per kWh, significantly higher than in manufacturing.

Relatively resilient activities include telecommunications, trade, and household services, which display outage costs below the sub-sectoral mean. In contrast, non-residential property services, passenger transport, construction, and pipeline transport register particularly high costs. The pipeline sector emerges as the single most sensitive activity, reflecting its critical reliance on electricity for safe operation of pumping, compression, and monitoring systems.

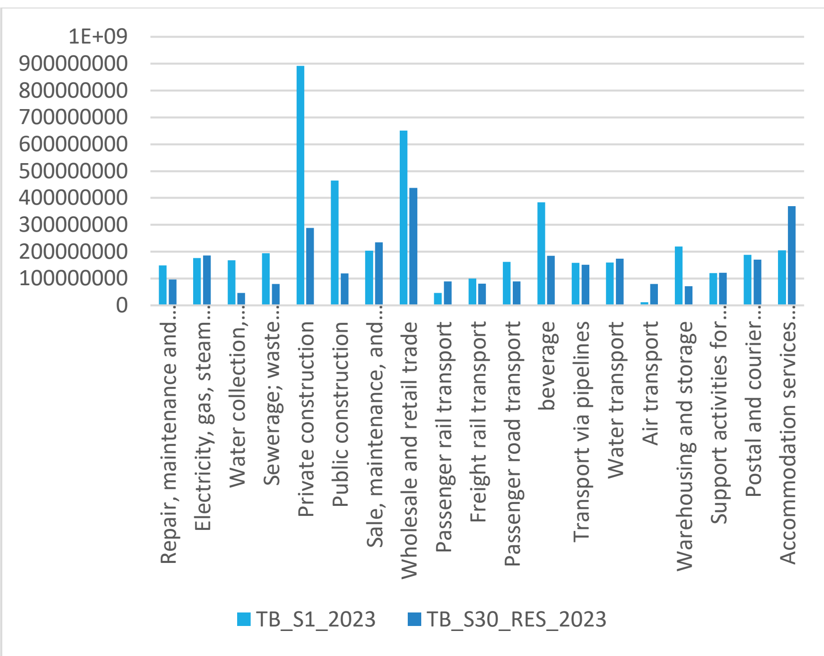

Figure5. Economic impact of electricity shortages across service and infrastructure subsectors (Sections 41–59) in 2023, measured in million Tomans per kWh. Pipeline transport, construction, and property services record the highest costs, signaling the need for targeted resilience policies.
Source: *Research Finding*

Expanding the scope to sectors 60–76, Figure 6 highlights the impact of shortages on household-related and social services. While certain activities such as telecommunications and financial services remain relatively stable, others, including accommodation, food services, and education, display heightened vulnerability. Particularly, government-provided education and public services register above-average costs due to their dependence on uninterrupted power for delivery of essential activities.

Finally, Figure7 presents results for critical public services (Sections 77–88), where vulnerability is highest from a socio-economic perspective. Public health, defense, compulsory social security, and public administration stand out as sectors with exceptionally high outage costs, reflecting the dual economic and social consequences of disruptions. While their share in aggregate economic value-added may be moderate, their societal role amplifies the importance of resilience.

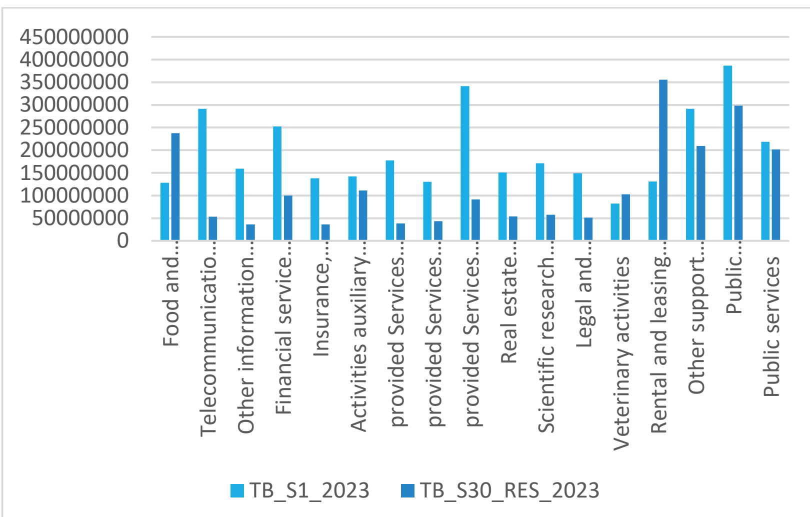

Figure 6.Estimated cost of electricity shortages across social and household service sectors (Sections 60–76) in 2023. Government education and public services appear most exposed, highlighting the broader societal impact of outages beyond economic production.

***Source:** Research Finding*

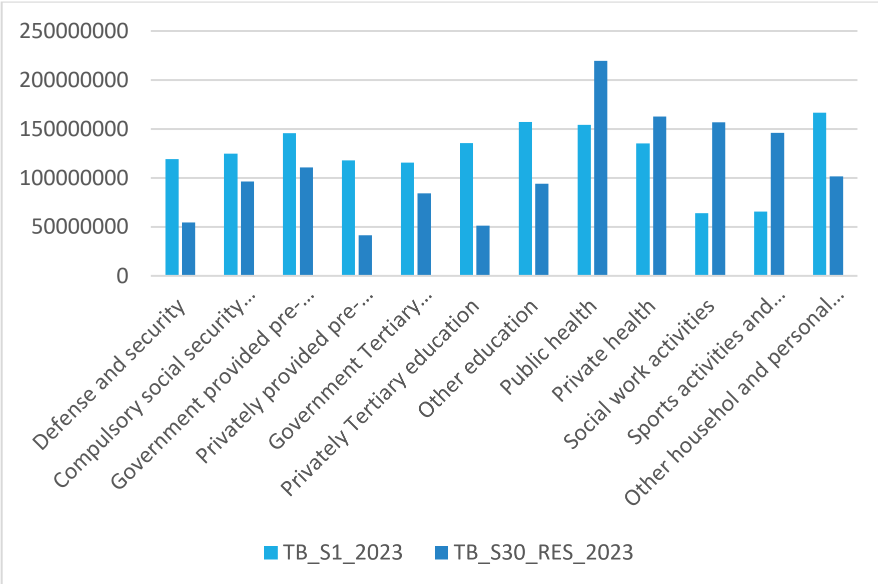

Figure 7. Estimated cost of electricity shortages in critical public services (Sections 77–88) in 2023, expressed in million Tomans per kWh. Public health, defense, and social security exhibit the greatest vulnerability, emphasizing the need to safeguard essential services under shortage conditions.

Source: *Research Finding*

Under the Economic Efficiency Scenario, prioritization of electricity allocation would favor sectors with the highest economic output losses per kWh (e.g., food production, furniture, pipeline transport). In contrast, the Non-Economic Consideration Scenario modifies this prioritization by accounting for critical social functions such as healthcare, education, and defense, where continuity is essential regardless of pure economic return.

This distinction has important policy implications. A purely economic approach may overlook social welfare and resilience, while a socio-economic framework better aligns with long-term stability and societal needs. The dual-scenario analysis demonstrates how I-O modeling can guide differentiated strategies: one focusing on maximizing economic efficiency during mild shortages, and the other on preserving critical social functions under severe conditions.

A noteworthy observation emerging from the analysis is that traditionally energy-intensive sectors, such as chemicals and basic metals, exhibit outage costs at or below the national average. This outcome may initially appear counterintuitive, given their substantial electricity consumption. However, the I-O framework reveals that the relative economic impact of outages depends not only on energy intensity but also on the degree of flexibility in production processes, capital-labor substitution, and the ability to defer or reschedule energy use without immediate loss of value-added. Large-scale producers in these industries often operate with buffer inventories, integrated supply chains, and partial redundancy in production capacity, which collectively mitigate the short-term economic damage of outages. In contrast, sectors such as food processing or furniture manufacturing rely on continuous workflows and perishable inputs, leaving them less able to absorb shocks, and thereby explaining their disproportionately higher outage costs.

From a policy perspective, these findings suggest the need for differentiated resilience strategies rather than uniform electricity allocation rules. For example, sectors with high outage costs but limited substitution possibilities—such as food, healthcare, and pipeline transport—would benefit from priority access to backup power or guaranteed baseline electricity supply. Conversely, industries with relatively lower outage sensitivity, despite high energy use, could be managed through flexible demand response mechanisms, such as time-of-use or critical peak pricing tariffs, incentivizing them to shift or defer consumption during shortage periods. This targeted approach allows policymakers to allocate scarce electricity resources more efficiently, reducing aggregate economic and social costs.

Furthermore, the results point to the importance of strategic infrastructure investment. For high-vulnerability sectors, investment in distributed energy storage systems, localized microgrids, and emergency backup capacity should be prioritized to ensure operational continuity during blackouts. For sectors with systemic importance, such as pipeline transport or healthcare, reinforcing grid reliability and ensuring redundant supply pathways is crucial. In parallel, grid reinforcement and modernization, including digital monitoring and smart dispatch systems, can enhance the ability to balance loads dynamically and prevent cascading failures. By linking outage cost estimations to concrete resilience measures, this study underscores how an I-O–based evaluation can move beyond descriptive analysis to support actionable, evidence-based energy policy.

6. Conclusion

This study employed an Input-Output (I-O) analytical framework to estimate the economic cost of electricity shortages across Iran’s economic sectors in 2023. Using the most recent I-O table published by the Central Bank of Iran and disaggregating the economy into sectoral groupings, the analysis provides a comprehensive, data-driven picture of how outages affect both production and services. Beyond cost quantification, the study identifies sectoral vulnerabilities and demonstrates how scenario-based modeling can guide electricity allocation strategies under constrained supply conditions. The results reveal substantial heterogeneity in outage sensitivity across the economy. At the aggregate level, the average cost was estimated at 10.9 million Tomans per kWh, with relatively low exposure observed in sectors such as forestry, tobacco, mining, and apparel. By contrast, industries including electrical equipment, vehicles, and especially food product manufacturing recorded significantly above-average costs, reflecting their reliance on continuous electricity inputs.

A closer look at manufacturing subsectors (19–39) indicated a lower average cost of 4.8 million Tomans per kWh, yet vulnerability was unevenly distributed. While basic metals and chemicals demonstrated resilience, subsectors such as glass, plastics, refined petroleum, and furniture manufacturing were highly sensitive to disruptions, the latter showing some of the steepest losses within the industrial group. In services and infrastructure (41–68), the average cost rose to 14.4 million Tomans per kWh. Telecommunications, trade, and household services exhibited relative resilience, but electricity shortages imposed disproportionate costs on non-residential property services, passenger transport, construction, and particularly pipeline transport. The latter stood out as the most exposed subsector, reflecting its dependence on uninterrupted power for pumping and monitoring systems. The highest vulnerability was observed in public services and governance (77–88), with an average cost of 49.1 million Tomans per kWh. While privately provided education and healthcare showed moderate impacts, public health, administration, defense, and security were severely affected, highlighting the indispensable role of electricity in maintaining critical state functions and societal stability.

Importantly, the study incorporated two complementary scenarios. The Economic Efficiency Scenario highlights sectors where outages generate the greatest economic losses per unit of electricity, suggesting that allocation during mild shortages should prioritize industries such as food production, furniture, and pipeline transport. By contrast, the Non-Economic Consideration Scenario underscores the strategic necessity of protecting critical social functions, including healthcare, education, and defense, even if their pure economic contribution is smaller. Together, these scenarios illustrate that resilience planning must balance economic efficiency with social welfare.

Overall, the findings underscore that electricity shortages impose highly uneven consequences across sectors. Industries with complex production processes, reliance on perishable inputs, or critical public responsibilities are most at risk. The I-O framework proves effective in uncovering these interdependencies, offering a robust basis for resilience planning. For policymakers, the results highlight the need for targeted strategies that both minimize economic disruption and safeguard essential social services, ensuring a more resilient and equitable response to electricity shortages.

Looking ahead, future research could extend this analysis by incorporating dynamic modeling approaches. While the present study provides a static, economy-wide snapshot of outage costs under different scenarios, a dynamic framework would allow for capturing temporal adjustments, feedback effects, and longer-term structural changes in response to electricity shortages. Such an approach could provide deeper insights into how sectors adapt over time, how cascading impacts unfold across supply chains, and how resilience strategies evolve under varying shortage intensities. Integrating dynamic modeling would therefore complement the current I-O analysis, offering policymakers an even more robust foundation for designing adaptive and forward-looking electricity allocation strategies.

Author Contributions

Ali Abazari Askaria**,**Conceptualization, methodology, validation, formal analysis, resources, Zeinolabedin Sadeghia**,**Conceptualization, methodology, validation, formal analysis,Seyyed Abdolmajid Jalaeea**,**Conceptualization, validation, resources.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data used in the study were derived from publicly available literature and governmental documents.

Acknowledgements

Not applicable

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