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Scenario-Based Analysis of Iran's Gas and Electricity Imbalance and Its Consequences on Smart Energy Infrastructure Using the LEAP Model Up to the 2050 Horizon

Mohammad Hassan Vaghef¹, Ali Asghar Esmaeil Nia^{2*}, Houshang Momeni Vesalian³

¹ Ph.D. Candidate, Department of Economics, Faculty of Economics and Accounting, Islamic Azad University, Central Tehran Branch, Tehran, Iran. mohammadhassan.vaghef@iau.ir

² Assistant Professor, Department of Economics, Faculty of Economics and Accounting, Islamic Azad University, Central Tehran Branch, Tehran, Iran. (Corresponding author) ali.smaeel_niyaktabi@iauctb.ac.ir, 0009-0001-6815-2794.

³ Assistant Professor, Department of Economics, Faculty of Economics and Accounting, Islamic Azad University, Central Tehran Branch, Tehran, Iran. h.momenivesalian@iauctb.ac.ir

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ABSTRACT

In recent years, Iran's gas and electricity imbalance has transcended simple supply-demand technicalities, emerging as a critical strategic challenge threatening national energy security, infrastructure sustainability, and broader economic development. Given the country's profound reliance on natural gas for power generation—and the increasing integration of smart grids and digital energy management—analyzing future imbalances is vital. This research utilizes the LEAP model to conduct a scenario-based analysis of Iran's energy deficit through the 2050 horizon, specifically evaluating its impact on the resilience of smart energy infrastructure. The study examines two distinct scenarios: the continuation of current trends and a comprehensive demand optimization strategy, both framed within a stress test regarding supply stabilization post-2025. Findings reveal that under the "status quo" scenario, the widening gap between supply and demand will severely erode energy export capacity, diminish critical foreign exchange earnings, and heighten the risk of failures within smart energy networks. Conversely, while the demand optimization scenario successfully reduces energy intensity and mitigates part of the deficit, it is not a panacea. Ultimately, the results demonstrate that demand management alone cannot resolve the imbalance. Instead, it must be coupled with expanded generation, transmission, and storage capacities. This study concludes that a synergistic approach—combining aggressive infrastructure investment, persistent improvements in energy efficiency, and intelligent demand-side management—is essential. By implementing such a comprehensive strategy, Iran can effectively reduce its chronic energy imbalance while significantly enhancing the overall resilience and long-term stability of its smart energy infrastructure by 2050. ©authors

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Introduction

Energy, as one of the most important infrastructures for economic, social and technological development, plays a fundamental role in the sustainability and national security of countries (Heidary et al, 2025; Kaif et al, 2025). Within the context of the Fourth Industrial Revolution, this importance is magnified as energy forms the backbone of the digital transformation and the burgeoning Metaverse ecosystem (Elshennawy et al, 2025). In recent decades, population growth, industrial development, urbanization, increasing welfare levels and changing consumption patterns have led to a significant increase in energy demand in many countries (Faryadras et al., 2025; Rajaperumal et al, 2025). Meanwhile, the Islamic Republic of Iran, despite having the world's largest natural gas reserves and significant oil resources, has faced a contradictory and at the same time worrying phenomenon called "energy imbalance"; a phenomenon that manifests itself as a supply deficit relative to demand in the natural gas and electricity sectors (Masoomi et al, 2022). Its effects have been evident in recent years in the form of power outages, restrictions on industrial consumption, gas pressure drops in the household sector and increased economic and social costs (Mohammadi et al., 2026). Such outages pose a critical threat to the high-availability servers and data centers required to sustain immersive virtual environments and decentralized digital ledgers (Rao et al, 2025).

Based on current trends, natural gas consumption in Iran is increasing at a faster rate than the growth of production capacity (Pourarshad et al, 2022; Sharma et al, 2025). This deficit creates a ripple effect throughout the entire digital economy. The extensive dependence of the domestic, commercial, industrial, and power plant sectors on natural gas has caused the country's gas network to face supply shortages and pressure drops in the winter season. On the other hand, the dependence of more than 80 percent of the country's electricity production on natural gas-based thermal power plants has caused the gas imbalance to directly spread to the electricity imbalance (Shoaei et al, 2026). Consequently, the shortage of gas in winter and the increase in electricity demand in summer have become two simultaneous and structural challenges in the Iranian energy system that can pose serious risks to the country's energy security (Masoomi et al., 2020; Arun et al, 2025). For a nation aiming at digital integration, this instability threatens the "Industrial Metaverse" where virtual reality simulations and digital twins require uninterrupted power to function (Khan et al, 2025).

As energy imbalances intensify, technological developments in the world are moving towards the development of smart grids, digital energy infrastructures, smart demand management, the Internet of Things, artificial intelligence, and advanced energy monitoring and control systems (Sabeti Motlagh et al, 2022; Lund et al, 2025). In such circumstances, the sustainability and efficiency of smart energy infrastructures are directly dependent on the reliability of gas and electricity networks. These infrastructures represent the convergence of the physical and virtual worlds, where digital transformation meets energy governance. Any long-term imbalance in energy supply can disrupt the performance of these infrastructures and pose serious constraints to the smart energy transition process. From this perspective, energy imbalance is not simply a technical or economic issue, but has become a strategic issue in the field of energy governance, digital transformation, and sustainable development (Khorramfar et al, 2022; Mansouri et al, 2025).

Studies conducted in Iran have mainly focused on energy demand forecasting, greenhouse gas emission reduction, renewable energy development, or sectoral analysis of the electricity and gas market. For example, Ataei and Fararian (2015) examined different scenarios of electricity development in Iran using the LEAP model. Masoomi et al. (2020) also evaluated the emission reduction capacity of thermal power plants using the LEAP model. Other studies have also analyzed energy consumption, renewable energy development, and modeling the country's electricity sector. Despite the scientific value of these studies, most

of them have focused on a specific part of the energy system and have rarely analyzed the simultaneous gas and electricity imbalance in the form of long-term scenarios (García-Gusano et al, 2019).

On the other hand, recent developments show that the energy imbalance in Iran has acquired a multidimensional nature (Alsenani et al, 2025). Factors like increasing energy intensity, aging of production and transmission infrastructure, limited investment, demand growth, declining energy efficiency, and slow development of renewable energies have all led to an increase in the gap between supply and demand (Faryadras et al., 2025). In such circumstances, analyzing past trends alone is not enough for policymaking, and decision-makers need tools that can simulate different possible futures and assess the consequences of each development path (Khatri et al, 2022). One of the most reliable tools used in long-term energy planning is the Long-range Energy Alternatives Planning System (LEAP) model, which is used by international institutions and energy researchers to analyze energy development scenarios, forecast demand, evaluate policies, and examine environmental consequences. The main advantage of this model is its ability to combine economic, demographic, technological, and policy variables into different scenarios and provide a comprehensive picture of the future of the energy system (Heaps, 2024). This capability has led to LEAP being used in several studies on the future of Iran's energy (Sharma, 2026).

Despite the increasing importance of smart energy infrastructure as a prerequisite for the Metaverse and digital twinning, limited research has so far examined the relationship between gas and electricity imbalances and their consequences on these infrastructures (Caulker et al, 2026). The main gap in the existing literature lies in the lack of a comprehensive analytical framework for simultaneously assessing gas and electricity imbalances and their cascading effects on the digital resilience of energy networks. This research gap is especially important in a situation where Iran is on the path of digitalizing energy networks, developing smart cities, deploying smart consumption management systems, and increasing dependence on new technologies (Parhamfar, 2025).

Accordingly, the present study uses the LEAP model with the aim of scenario-based analysis of Iran's gas and electricity imbalance up to 2050 and assessing its consequences on smart energy infrastructure. This study attempts to simulate the future trend of energy supply and demand by designing different development scenarios and evaluate the impact of each scenario on energy security, grid stability, and the reliability of the digital energy layer. By addressing these issues, the research seeks to answer: How will the projected energy imbalances impact the feasibility of Iran's digital transformation and the stability of its smart energy infrastructure by 2050? The results of this study can provide a scientific basis for policymakers to ensure that the transition to a virtualized and digitally-driven economy remains physically sustainable.

Literature Review

The theoretical foundation of this study is built upon the interdisciplinary integration of energy system transition theory, energy security theory, smart energy infrastructure theory, scenario planning, and integrated energy system modeling using the Long-range Energy Alternatives Planning (LEAP) model (Saeed et al, 2023). The framework assumes that Iran's growing imbalance between natural gas supply-demand and electricity generation-consumption is not merely a technical issue but the result of dynamic interactions among demographic growth, economic development, technological evolution, environmental constraints, energy policies, and climate commitments. Consequently, understanding the future trajectory of Iran's energy system requires a systems-thinking perspective capable of simultaneously evaluating energy demand, supply, transformation processes, and infrastructure resilience over a long-term horizon extending to 2050 (Sahoo, 2023).

At the core of the framework lies Energy Transition Theory, which argues that modern energy systems are evolving from centralized, fossil fuel-dependent structures toward decentralized,

low-carbon, digitally managed, and intelligent energy ecosystems. According to this theory, increasing electrification, renewable energy integration, digital technologies, and demand-side management fundamentally reshape national energy systems. However, countries with heavy dependence on fossil fuels, such as Iran, face significant structural barriers during this transition. Persistent dependence on natural gas for electricity generation creates a feedback loop in which rising electricity demand increases gas consumption, while gas shortages reduce power generation capacity, ultimately intensifying electricity deficits. This interdependency forms the conceptual basis for analyzing the simultaneous imbalance of gas and electricity within the Iranian energy sector (Hosseinzadeh et al, 2025)

The second theoretical pillar is Energy Security Theory, which defines energy security as the uninterrupted availability of affordable, reliable, sustainable, and accessible energy resources. Contemporary interpretations of energy security extend beyond resource availability to include infrastructure resilience, system flexibility, cyber resilience, technological diversity, environmental sustainability, and institutional capacity. Within this perspective, gas shortages and electricity imbalances represent multidimensional threats affecting economic productivity, industrial competitiveness, environmental performance, and national resilience. Therefore, the study conceptualizes the gas-electricity imbalance as an energy security challenge whose impacts propagate throughout Iran's smart energy infrastructure. The framework assumes that improving energy security requires coordinated planning across production, transmission, distribution, storage, and demand management systems rather than isolated investments in generation capacity alone (Trinh, 2022).

The third component is Smart Energy Infrastructure Theory, which emphasizes the transformation of traditional electricity and gas networks into digitally integrated, intelligent, and adaptive systems. Smart energy infrastructure incorporates smart grids, advanced metering infrastructure, Internet of Things (IoT) technologies, artificial intelligence, predictive maintenance, distributed energy resources, energy storage systems, demand response mechanisms, and digital energy management platforms. These technologies enhance operational flexibility and improve the capability of energy systems to respond to fluctuations in supply and demand. Within this theoretical framework, smart infrastructure functions as a moderating mechanism capable of reducing the adverse consequences of future gas and electricity imbalances. Consequently, infrastructure intelligence is treated not merely as a technological upgrade but as a strategic resilience mechanism supporting long-term energy sustainability (Liu et al, 2022).

Another essential theoretical foundation is Scenario Planning Theory, which recognizes that future energy systems evolve under considerable uncertainty. Long-term forecasting based solely on historical trends cannot adequately capture structural disruptions caused by technological innovation, geopolitical developments, economic fluctuations, climate policies, demographic change, or energy market volatility. Scenario analysis therefore provides a structured approach for exploring multiple plausible futures rather than predicting a single deterministic outcome. In this research, alternative scenarios—such as Business-as-Usual, High Economic Growth, Renewable Energy Expansion, Smart Infrastructure Development, Energy Efficiency Improvement, and Policy Reform scenarios—serve as analytical pathways for examining how different assumptions influence future gas demand, electricity consumption, supply adequacy, carbon emissions, infrastructure requirements, and system resilience through 2050 (Ahmad et al, 2023).

The analytical engine connecting these theoretical perspectives is the Long-range Energy Alternatives Planning (LEAP) model, which operationalizes systems theory through integrated simulation (Haq et al, 2023). LEAP enables the representation of energy demand sectors, transformation technologies, fuel flows, electricity generation, environmental emissions, and resource constraints within a unified accounting framework. Unlike traditional forecasting methods that estimate future demand independently, LEAP captures feedback relationships among socioeconomic variables, technological change, energy

efficiency, policy interventions, fuel substitution, and infrastructure investment. Consequently, it provides a robust decision-support framework for evaluating the long-term implications of alternative energy strategies under uncertainty. Within the proposed theoretical framework, LEAP acts as the bridge between conceptual theories and empirical scenario analysis by translating theoretical assumptions into quantitative simulations and policy-relevant outcomes (Inci et al, 2024).

Finally, the proposed theoretical framework integrates these perspectives into a comprehensive causal structure. Socioeconomic drivers—including population growth, urbanization, industrial development, technological progress, and energy pricing policies—stimulate future energy demand. Energy demand interacts with supply-side characteristics such as natural gas production capacity, electricity generation technologies, renewable energy penetration, and infrastructure investment. These interactions determine the magnitude of future gas and electricity imbalances, which subsequently influence the performance, reliability, resilience, efficiency, and sustainability of Iran's smart energy infrastructure. Scenario-based LEAP simulations evaluate how alternative policy pathways modify these relationships over the 2025–2050 planning horizon. Thus, the framework provides an integrated theoretical basis for understanding not only the causes of Iran's future energy imbalance but also the effectiveness of strategic interventions designed to strengthen smart energy infrastructure, enhance energy security, accelerate energy transition, and support sustainable national development by 2050.

Method

The relationship between LEAP and NEMO in this study is a stepwise approach. In the first step, the final energy demand in different consumption sectors is modeled in the LEAP environment. In this step, the activity level, energy intensity and carrier share are defined for each sector and the energy demand trajectory is extracted in two main scenarios, namely, business as usual and demand optimization.

In the second step, the electricity demand derived from LEAP is transferred to NEMO. In NEMO, the electricity demand is entered as a demand constraint and the mix of capacity and electricity generation is determined based on technical and economic constraints. The output of this step includes installed capacity, new capacity, electricity generation by technology, plant fuel consumption and investment, operation and fuel costs.

In the third step, the gas and electricity demand trajectory is compared with the available supply or reliable capacity. In the case of natural gas, the available supply is analyzed with respect to deliverable production, refining capacity, transmission, injection, export and investment constraints. In the case of electricity, the criterion for analysis is reliable capacity or supplyable generation, not just the nominal installed capacity.

In the fourth step, the physical energy imbalance is translated into economic and development indicators. In this step, the supply-demand gap, the equivalent of consumption restriction days, the currency balance of the carriers, and the currency advantage of the optimization scenario over the baseline are calculated.

Modeling the final energy demand in LEAP

In the LEAP framework, the final energy demand is calculated in a bottom-up manner based on the level of activity, the intensity of energy consumption, and the share of carriers. The general relationship of the final demand of the energy carrier is as follows:

$$D_{\{s,u,f,t\}} = A_{\{s,u,t\}} \times EI_{\{s,u,f,t\}} \times Share_{\{s,u,f,t\}}$$

where, $D_{\{s,u,f,t\}}$ is the final consumption of energy carrier f in sector s , final consumption u , and year t ; $A_{\{s,u,t\}}$ is the level of activity, such as the number of households, infrastructure, value added, or production level; $EI_{\{s,u,f,t\}}$ is the energy intensity for carrier f ; and $Share_{\{s,u,f,t\}}$ is the share of the energy carrier in the provision of the relevant energy service.

The total final demand of each carrier is obtained by summing the consumption of that carrier in all sectors and final uses:

$$D_{\{f,t\}} = \sum_s \sum_u D_{\{s,u,f,t\}}$$

In the business-as-usual scenario, activity levels and energy intensity are determined based on historical trends, assumptions of economic growth, population growth, household growth, expansion of sectoral activities, and continuation of the existing technology pattern. In the demand-side optimization scenario, energy intensity is reduced by considering efficiency policies, consumption standards, equipment modernization, building regulations, industrial efficiency improvements, and load management:

$$EI_{\{s,u,f,t\}}^{\{OPT\}} = EI_{\{s,u,f,t\}}^{\{BAU\}} \times (1 - \lambda_{\{s,u,f\}})^{\{t-t.\}}$$

where $\lambda_{\{s,u,f\}}$ is the rate of energy efficiency improvement in each sector, final consumption and energy carrier. This rate reflects the effect of the demand-side policy set and is not separately decomposed into the behavioral response of consumers to energy prices. Therefore, the OPT scenario is a demand-side policy and technology scenario, not a mathematical optimization of consumer behavior.

Electricity Sector Analysis in NEMO

In the second step, the electricity demand obtained from LEAP is transferred to the NEMO model, and the model determines the combination of capacity and electricity generation based on minimizing the total system cost and observing technical constraints. The NEMO objective function in this study is to minimize the discounted cost of the electricity system over the study horizon. The total cost can include investment cost, fixed and variable operation and maintenance costs, fuel cost, and, if a carbon policy is defined, emission cost.

The overall objective function can be represented as follows:

$$\min TC = \sum_t \frac{1}{(1+r)^t} \sum_i (IC_{i,t} + FOM_{i,t} + VOM_{i,t} + FuelCost_{i,t})$$

Where, TC is the total cost of the electricity system, r is the discount rate, i is the electricity generation technology, and t is the year. The main constraints of the model include electricity demand, generation capacity constraints, capacity factor, technology lifetime, retired capacity, expandable capacity, and technical limitations of technologies.

Designing Research Scenarios

The scenarios of the paper are constructed from a combination of two demand paths and two infrastructure investment scenarios. From the demand perspective, two main paths are defined. The first path is the continuation of the status quo or BAU, in which historical trends in consumption, energy intensity, and technology continue without effective policy intervention. The second path is the optimization of demand or OPT, in which efficiency policies, consumption management, equipment standards, building improvements, and industrial process modernization lead to a gradual reduction in energy intensity.

From the infrastructure investment perspective, two scenarios are also defined. In the first scenario, the programmatic path is based on upstream documents and the country's development goals; That is, it is assumed that upstream oil and gas production capacities, oil and gas refining, gas transmission and storage, as well as electricity generation and grid capacity are developed in accordance with official targets. In the second scenario, a stress test is defined in which the supply level does not increase after 2025 and remains constant at the observed or assumed level of that year. This scenario is not a probable future forecast, but a tool for assessing the consequences of not realizing the investments foreseen in the upstream documents.

Table 1. Proposed scenarios

Scenario	Demand Path	Infrastructure Investment Status	Analytical role
BAU-Program	Continuation of Status Quo	Achievement of Goals and Capacities in Upstream Documents	Measuring imbalance pressure in the event of continued high consumption along with planned supply expansion
BAU-Stress	Continuation of Status Quo	Stabilization of Supply Levels after 2025	Measuring the consequences of not realizing capacity increases in the high-consumption path
OPT-Program	Demand Optimization	Achievement of Goals and Capacities in Upstream Documents	The optimal scenario from the perspective of energy security, foreign exchange balance, and development
OPT-Stress	Demand Optimization	Stabilization of Supply Levels after 2025	Measuring the role of demand optimization in reducing vulnerability in the absence of capacity increases

In the findings section, the main focus is on comparing BAU-C0 and OPT-C0. The reason for this choice is that the aim of the paper is to analyze the physical and currency imbalances of gas, electricity, crude oil and products, and the scenarios with carbon pricing mainly affect the path of changing the electricity generation mix, system cost and emissions. Therefore, to avoid thematic overlap with the independent analysis of the optimal electricity portfolio and carbon tax, the main results of the paper focus on the paths without carbon tax.

Data, variables and statistical sources

The data used in the paper are classified into five main groups. The first group is energy demand data, which includes final consumption by sector and carrier, population, number of households, infrastructure, sectoral value added, production level, number of vehicles and indicators of business and agricultural activity. These data are used for LEAP calibration and demand path estimation.

The second group is natural gas data, which includes gas production, refining capacity, domestic consumption by sector, power plant consumption, exports, imports, oilfield injection, associated gases, flaring, transmission capacity, and infrastructure investment assumptions. These data are used to calculate available supply, supply-demand gap, and gas balance.

The third group is electricity sector data, which includes installed capacity by technology, reliable capacity, electricity generation, plant efficiency, plant fuel consumption, network losses, capacity factor, retired capacity, new capacity, and investment and operating costs. These data are used to analyze power imbalances, new capacity needs, and the impact of investment delays.

The fourth group is infrastructure and program data, which includes upstream document targets in the areas of oil and gas production, refining capacity, gas transmission and storage, and electricity capacity development. These data form the basis for defining the Program path and Stress test.

The fifth group is price and exchange rate data, which includes the opportunity price of gas, crude oil, petroleum products, electricity, exchange rates, export and import values of energy carriers, and sensitivity analysis assumptions. Data sources include energy balance sheets, detailed electricity industry statistics, upstream energy documents, development plans, gas balance documents, oil and gas production outlook documents, reports from the Ministry of Energy and the Ministry of Petroleum, international carrier price data, and LEAP–NEMO model outputs.

Table 2. Research variables

Application in the article	Variables	Data Group
LEAP calibration and demand path estimation	Final consumption by sector and carrier, population, household, infrastructure, value added and production	Energy Demand
Gas balance and imbalance calculation	Production, consumption, export, injection, refining, transmission and import	Natural Gas
Electricity imbalance and reliable capacity calculation	Capacity, production, efficiency, losses, fuel consumption and costs	Electricity

Program path definition and stress test	Upstream development of oil and gas, refining, transmission, storage and electricity	Infrastructure and Investment
Foreign exchange balance calculation and sensitivity analysis	Opportunity price of carriers, imports, exports and relative price coefficients	Prices and Exchange Rate

Energy Imbalance Pressure Index

To measure imbalance, the gap between supply and demand of an energy carrier is first defined.

$$Gap_{f,t} = D_{f,t} - S_{f,t}$$

where, $Gap_{f,t}$ is the gap between supply and demand of carrier f in year t , $D_{f,t}$ is the demand for the carrier, and $S_{f,t}$ is the available supply or supply capacity of the carrier. A positive value of this index indicates a deficit and imbalance pressure, and a negative value indicates a surplus or potential export capacity.

To focus on the realizable shortfall, the energy shortage index is defined as follows:

$$Shortage_{f,t} = \max(0, D_{f,t} - S_{f,t})$$

The shortfall share of the carrier demand is also calculated from the following equation:

$$ShortageShare_{f,t} = \frac{Shortage_{f,t}}{D_{f,t}} \times 100$$

For natural gas, D_{gas} includes final gas demand, gas consumption in the power sector, industrial consumption and other strategic uses. Deliverable production is after considering the constraints of refining, transmission, injection, committed exports and infrastructure investment. For electricity, $Delec,t$ is the electricity demand and $Selec,t$ is the deliverable electricity or reliable capacity in the period under consideration.

To interpret the imbalance pressure on productive sectors, the equivalent days of consumption limitation are also calculated:

$$EquivalentDays_{s,t} = 365 \times \frac{EnergyShortage_t}{EnergyConsumption_{s,t}}$$

Where, $EquivalentDays_{s,t}$ is the equivalent days of consumption limitation in sector s and year t , $EnergyConsumption_{s,t}$ is the amount of energy deficit and energy consumption of the sector in question. This indicator is not a definitive estimate of the drop in GDP , but is a measure of the energy pressure on productive activities.

In the absence of seasonal or hourly data, the indicators are calculated based on annual data. However, in interpreting the results, it should be noted that the actual imbalance of gas and electricity is usually more severe during peak consumption periods than the annual average.

Demand Optimization Pressure Reduction Index

To measure the effect of demand optimization policies on reducing imbalances, the pressure reduction index is defined:

$$RPI_{f,t} = \frac{Gap_{f,t}^{BAU} - Gap_{f,t}^{OPT}}{Gap_{f,t}^{BAU}} \times 100$$

where, $Gap_{f,t}^{BAU}$ is the gap between supply and demand of carrier f in the business-as-usual path and $Gap_{f,t}^{OPT}$ is the corresponding gap in the demand optimization path. This index shows what share of the imbalance pressure is reduced by demand-side policies. If the value of this index is high, demand optimization plays an effective role in reducing infrastructure pressure; if it is low, it indicates that the main problem is more due to supply or investment constraints.

Exchange Balance Sensitivity Analysis

Since the exchange rate results are highly dependent on the carrier price assumptions, sensitivity analysis is a key part of the paper's methodology. In this study, instead of independently changing the prices of individual carriers, the sensitivity analysis is performed through the path of changes in the two main anchors, namely the price of crude oil and the price of natural gas. Then, the prices of petroleum products and base gas carriers are adjusted based

on the corresponding relative coefficients. This method ensures that the relative price structure of carriers is maintained in all sensitivity cases.

In the baseline analysis, the price of crude oil is \$60 per barrel and the price of natural gas is \$0.30 per cubic meter. In the sensitivity analysis, both price anchors are examined at three levels, low, base and high:

Table 3. Crude Oil Price Analysis

Price anchor	Low	Base level	High level
Crude oil price	\$48/barrel	\$60/barrel	\$72/barrel
Natural gas price	\$0.24/cubic meter	\$0.30/cubic meter	\$0.36/cubic meter

In each case, the price of petroleum products is calculated from previous relationships. The purpose of the sensitivity analysis is not to accurately predict future prices; rather, it is to measure the robustness of the paper's results to changes in key price assumptions. Regarding infrastructure investment, the paper does not use independent estimates or assumed levels of investment realization; rather, it subjects the upstream document's program path to a stress test of stabilizing supply levels after 2025. Therefore, investment sensitivity is interpreted as a separate Stress scenario versus Program, not as assumed percentages of investment realization.

Findings

The findings of this section are presented based on a comparison of the two main demand paths, namely BAU-C0 and OPT-C0, along with a stress test of stabilizing the supply level after 2025. The purpose of the stress test is not to predict the future definitively; rather, it is to measure the consequences of not realizing the planned path of developing oil, gas, and electricity infrastructure. In other words, this test shows what impact demand growth will have on the physical energy balance, foreign exchange balance, and the ability of productive economic activities if the necessary investments are not made to increase production, refining, transmission, and electricity capacity and the energy supply level remains within the 2025 range.

The path of final energy demand and the mix of carriers in the BAU and OPT scenarios

Before analyzing the imbalance of gas, electricity, and the exchange balance of energy, it is necessary to determine the path of final energy demand in the two main scenarios of the article. The imbalance pressure on the supply side directly arises from the level and mix of final energy demand. In this article, the main comparison is made between the two paths BAU-C0 and OPT-C0; Because the carbon tax in the present model framework mainly affects the mix of electricity generation and system cost and does not directly change the level of final energy demand.

The model results show that in the BAU-C0 scenario, final energy demand increases from about 1,660.3 million barrels of oil equivalent in 2020 to about 2,809.1 million barrels of oil equivalent in 2050. This increase is equivalent to a growth of about 69.6% over the thirty-year horizon. In contrast, in the OPT-C0 scenario, final energy demand in 2050 is limited to about 2,312.6 million barrels of oil equivalent. Therefore, optimizing demand in 2050 reduces annual energy consumption by about 496.5 million barrels of oil equivalent compared to the BAU scenario.

Table 4. Final energy demand in the BAU and OPT scenarios, 2020 to 2050

Unit: million barrels of oil equivalent

Total period	2050	2045	2040	2035	2030	2025	2020	Scenario
75,885.6	2,809.1	2,720.7	2,654.7	2,610.4	2,483.3	2,043.3	1,660.3	BAU
68,266.7	2,312.6	2,312.2	2,325.9	2,355.2	2,314.6	1,973.0	1,660.3	OPT

From a cumulative perspective, the difference between the two paths is also significant. Cumulative energy consumption in the period 2020-2050 in the BAU path is about 75,885.6 million barrels of oil equivalent, while in the OPT path it is limited to about 68,266.7 million barrels. Therefore, demand optimization policies generate cumulative savings of about 7,618.9 million barrels of oil equivalent over the entire period. This result shows that the

effect of OPT is not limited to reducing consumption in the final year, but also leads to a reduction in pressure on the energy infrastructure over the entire modeling horizon.

Table 5. Key indicators of final energy demand in the two scenarios

OPT vs. BAU Difference	OPT-C0	BAU-C0	Index
—	1,660.3	1,660.3	Final energy demand in 2020
496.5-	2,312.6	2,809.1	Final energy demand in 2050
30.3 percentage points lower	39.3%	69.6%	Demand growth during 2020-2050
7,618.9-	68,266.7	75,885.6	Cumulative consumption 2020-2050
About 10%	—	—	Cumulative consumption reduction compared to BAU

The energy mix shows that natural gas is the most important source of imbalance pressure in the long term. In the BAU-C0 scenario, natural gas consumption in 2050 reaches about 1,622 million barrels of oil equivalent, while in the OPT-C0 scenario this amount is limited to about 1,266 million barrels. Therefore, the majority of energy savings in the OPT come from reducing natural gas consumption. This is consistent with the findings in the following sections of the paper, which show that the greatest foreign exchange benefits and security of supply also come from improving the gas balance. In the electricity sector, final demand in the BAU-C0 scenario reaches about 317 million barrels of oil equivalent in 2050, while in the OPT-C0 scenario it is limited to about 265 million barrels. Despite this reduction, electricity remains one of the growing carriers in the energy demand structure and therefore, stopping the expansion of electricity capacity after 2025 will lead to a significant deficit even in the OPT scenario. In the case of petroleum products, the reduction in gasoline and diesel consumption in the OPT will also reduce import pressure and partly explain the currency difference between the two scenarios.

Table 6. Demand for major energy carriers in 2050

Energy carrier	Percentage decrease	Decrease in OPT relative to BAU	OPT-C0 in 2050	BAU-C0 in 2050	Percentage decrease
Natural gas	21.9%	356	1,266	1,622	21.9%
Electricity	16.4%	52	265	317	16.4%
Gasoline	14.0%	46	283	329	14.0%
Gasoline oil	19.3%	38	159	197	19.3%
Ethane and similar feeds	0.0%	0	71.5	71.5	0.0%
Kefalo	About 10%	0.6	5.8	6.4	About 10%
LPG	About 26%	1.7	4.7	6.4	About 26%
Other carriers	About 1%	1.7	258	259.7	About 1%
Total	17.7%	496	2,313	2,809	17.7%

This table highlights three main points. First, demand optimization has the largest absolute impact on natural gas; therefore, efficiency policies in buildings, industry, power plants, and end-use gas consumption will play a decisive role in reducing the imbalance. Second, the reduction in electricity consumption in the OPT, although significant, is not enough to eliminate the electricity deficit, and there is still a need to develop reliable capacity, the network, and load management. Third, reducing gasoline and diesel consumption in the OPT adjusts the import path of products and preserves part of the net foreign exchange earnings of the oil and products chain. Industrial feedstocks such as ethane are not considered in this article as energy consumption that can be optimized on the demand side; because reducing them means reducing industrial and petrochemical production, not improving energy consumption efficiency.

Natural Gas Balance: From Currency Issue to Supply Security Crisis

Natural gas plays a role in Iran's energy system beyond that of a consumption carrier. Gas is simultaneously a household fuel, a power plant fuel, a fuel and feedstock for industry, a means of injection into oil reservoirs, an input to gas refineries, and a potential export carrier. For this reason, stabilizing gas production, unlike crude oil, directly translates into limiting domestic consumption, increasing imports, reducing power plant fuel, limiting industry, or reducing injections.

In the gas stress test, upstream gas production is assumed to remain constant at the same level from 2025 onwards, i.e., about 400.84 billion cubic meters per year. Then, two scenarios are examined: first, a scenario in which the gas deficit is compensated through imports; second,

a scenario in which gas imports are not possible or reliable and the deficit turns into a physical shortage of usable gas.

In the importability scenario, the opportunity price of gas is assumed to be \$0.30 per cubic meter. Therefore, each billion cubic meters of gas has a commercial value of \$0.30 billion. The results show that in BAU-C0, the total gas balance changes from a surplus of 29.51 billion cubic meters in 2025 to a deficit of 79.49 billion cubic meters in 2050. In contrast, in OPT-C0, the gas balance remains positive in 2050, with a surplus of about 12.32 billion cubic meters.

Table 7. Total natural gas balance in the stress test

Year	Total OPT gas balance, bcm	Total BAU gas balance, bcm	OPT improvement over BAU, bcm
2025	38.97+	29.51+	9.46+
2030	7.82-	36.82-	29.00+
2035	5.84-	50.22-	44.38+
2040	0.18+	55.61-	55.79+
2045	11.14+	61.86-	73.00+
2050	12.32+	79.49-	91.81+

The dollar translation of this balance shows that in BAU, if gas imports are possible, the country faces a net gas trade deficit of about \$23.9 billion in 2050. In contrast, in OPT, the gas balance is positive by about \$3.7 billion in 2050. Therefore, the difference between the two paths in 2050 is about \$27.5 billion per year. This number shows that optimizing gas consumption is not just a policy to reduce consumption, but also a policy to prevent the formation of a large source of foreign exchange demand in the future.

Table 8. Dollar value of the natural gas balance

Year	Gas balance value in OPT, billions of dollars	Gas balance value in BAU, billions of dollars	OPT benefit over BAU, billions of dollars
2025	11.69+	8.85+	2.84+
2030	2.35-	11.05-	8.70+
2035	1.75-	15.07-	13.31+
2040	0.05+	16.68-	16.74+
2045	3.34+	18.56-	21.90+
2050	3.70+	23.85-	27.54+

However, gas imports are not simply imports of a transportable commodity on the global market. Gas imports require pipelines, long-term contracts, transmission capacity, stable political relations and geopolitical compatibility. Therefore, gas deficits cannot necessarily be interpreted as realizable imports. In the case of no imports, the gas deficit must be absorbed by eliminating exports, reducing power plant consumption, limiting industry, reducing feed, reducing injection or limiting domestic consumption.

In this case, the results show that in BAU-C0, the usable gas deficit increases from about 30.24 billion cubic meters in 2030 to 63.11 billion cubic meters in 2050. This amount in 2050 is equivalent to about 17.7 percent of domestic gas demand; that is, in terms of annual equivalence, about 65 days of nationwide gas outages for all domestic consumers. In contrast, in OPT-C0, the deficit is limited in 2030 and 2035 and is almost eliminated from 2040 onwards.

Table 9. Deficit of usable gas in the event of no import

Year	Deficit as a percentage of domestic demand OPT	OPT usable gas deficit, bcm	Equivalent to BAU National Outage Days	Deficit as a percentage of domestic demand BAU	BAU usable gas deficit, bcm	Equivalent to National OPT Cut-off Days
2030	2.5%	7.05	36 days	9.8%	30.24	9 days
2035	1.6%	4.66	46 days	12.5%	40.15	6 days
2040	0.1%	0.37	50 days	13.8%	45.60	Less than 1 day
2045	0.0%	0.00	53 days	14.6%	49.95	0 days
2050	0.0%	0.00	65 days	17.7%	63.11	0 days

The sectoral translation of this deficit is more important. In BAU-C0, if the 2050 deficit is imposed only on industry, it will be equivalent to 226 days of industrial constraints. If the deficit is distributed between industry and power plants, it will be equivalent to 122 days of constraints for these two sectors. If industry, power plants, and petrochemical feedstock simultaneously contribute to absorbing the deficit, it will still be equivalent to 101 days of

constraints. Therefore, the BAU gas deficit is too large in the long term horizon to be managed solely by short-term constraints or limited consumption shifting.

This finding suggests that gas is the most important channel for converting energy imbalances into macroeconomic risks. In the import-capability case, gas imbalances translate into exchange rate pressures; in the no-import case, they translate into physical consumption constraints, power plant fuel shortages, and industry constraints. In both cases, the economic cost goes beyond the energy sector.

Integrated Oil, Products, and Gas Foreign Exchange Balance

To assess the macro-impact of energy imbalances, the balance of crude oil, primary products, and natural gas is calculated as an integrated measure. This indicator shows how domestic consumption growth and the failure to realize supply increases can change the net foreign exchange earnings of the energy sector.

The results show that in BAU-C0 and in the 2025 production stabilization stress test, the combined net foreign exchange earnings of oil, products, and gas decline from about \$59.82 billion in 2025 to about \$18.38 billion in 2050. This decline translates into a loss of about \$41.44 billion per year. In contrast, in OPT-C0, the combined net foreign exchange earnings remain roughly stable over the entire period and are about \$54.52 billion in 2050. Therefore, the advantage of OPT over BAU in 2050 is about \$36.14 billion per year.

Table 10. *Integrated Oil, Products, and Gas Foreign Exchange Balance*

Year	Total oil and gas in OPT, billions of dollars	Total oil and gas in BAU, billions of dollars	OPT advantage over BAU, billions of dollars
2025	64.38	59.82	4.56
2030	49.03	36.75	12.28
2035	49.76	31.18	18.58
2040	51.54	28.35	23.19
2045	54.30	24.74	29.56
2050	54.52	18.38	36.14

The breakdown of this erosion shows that in BAU-C0, the net balance of oil and the three main products would decrease from \$51.0 billion in 2025 to \$42.2 billion in 2050, a decline of about \$8.74 billion. But the gas balance would change from a surplus of \$8.9 billion in 2025 to a deficit of \$23.9 billion in 2050, a decline of about \$32.70 billion. Thus, the main part of the BAU currency erosion would come from gas, not oil products.

Table 11. *Components of currency erosion in BAU*

Component	Change from 2025 to 2050 in BAU, billions of dollars
Net oil chain and three main products	8.74-
Gas balance	32.70-
Total sum	41.44-

In 2050, of the total \$36.14 billion of OPT's advantage over BAU, about \$27.54 billion is from gas and about \$8.59 billion is from crude oil and major products. Therefore, about three-quarters of OPT's foreign exchange benefit over the 2050 horizon will come from the improved gas balance.

Table 12. *Components of OPT's foreign exchange advantage over BAU in 2050*

Component	OPT advantage over BAU in 2050, billion dollars
Crude oil and three main products	8.59
Gas	27.54
Total	36.14

This finding has a clear macro message: even if the country remains a crude oil exporter, continued growth in domestic consumption of products and gas could severely reduce the net foreign exchange earnings of the energy sector. In such a situation, crude oil exports alone do not guarantee foreign exchange stability, because part of the oil revenue is neutralized by imports of products and the gas deficit. In contrast, demand optimization can transform the same fixed level of production into a much more stable foreign exchange balance.

Sensitivity analysis of foreign exchange balance to crude oil and natural gas prices

To test the sustainability of the foreign exchange results, the superiority of the OPT scenario over BAU in 2050 under changes in the two main price anchors, namely crude oil and natural gas. In the base case, the superiority of OPT over BAU in the crude oil chain and the three main products is about \$8.59 billion and in the gas balance is about \$27.54 billion; therefore, the total foreign exchange benefit of OPT in 2050 is estimated to be about \$36.14 billion.

In the sensitivity analysis, crude oil prices and natural gas prices were separately and simultaneously assumed to be 20 percent lower and 20 percent higher than the baseline. The relative price coefficients of the carriers were assumed to be constant; therefore, a decrease or increase in crude oil prices would proportionally affect the value of gasoline, diesel, fuel oil, and other petroleum-based carriers, and a change in the price of natural gas would proportionally affect the value of the gas balance.

Table 13. Sensitivity Analysis of OPT Currency Benefit to BAU in 2050
Unit: Billions of dollars per year

Sensitivity mode	Gas Profit	Oil and products profit	Total benefit of OPT over BAU
Base oil and gas price	27.54	8.59	36.14
Oil 20% lower, base gas	27.54	6.87	34.41
Oil 20% higher, base gas	27.54	10.31	37.85
Oil base, gas 20% lower	22.03	8.59	30.62
Oil base, gas 20% higher	33.05	8.59	41.64
Oil and gas both 20% lower	22.03	6.87	28.90
Oil and gas both 20% higher	33.05	10.31	43.36

The sensitivity results show that even in the pessimistic price case, i.e., a simultaneous 20% decrease in the price of crude oil and natural gas, the OPT scenario still has a foreign exchange benefit of about \$28.90 billion compared to BAU in 2050. In the optimistic price case, this benefit increases to about \$43.36 billion. Therefore, the main conclusion of the paper is stable to conventional energy price changes: demand optimization in all price cases significantly reduces the foreign exchange erosion caused by the BAU path.

Also, the sensitivity of the results to the gas price is higher than that of the crude oil price. A 20% decrease in the crude oil price reduces the total benefit of the OPT from \$36.14 to \$34.41 billion; but a 20% decrease in the gas price increases the total benefit to \$30.62 billion. This result is consistent with the findings of the previous section and confirms that natural gas is the main bottleneck for Iran's foreign exchange balance and energy security in the long term.

While demand-side management remains an essential strategy for mitigating energy imbalances, its effectiveness should be evaluated alongside the rapidly expanding role of digital technologies in modern energy systems. Artificial intelligence (AI), the Internet of Things (IoT), digital twins, advanced metering infrastructure (AMI), and machine learning-based forecasting have significantly improved energy efficiency by enabling real-time monitoring, predictive maintenance, demand response, and optimized energy dispatch. These technologies reduce technical losses, improve asset utilization, and enhance operational flexibility, thereby lowering the energy intensity of industrial, commercial, and residential sectors. However, the deployment of these digital solutions also requires substantial computational resources, cloud platforms, edge computing, and data centers, all of which increase electricity demand. Therefore, digitalization simultaneously acts as both an energy-saving mechanism and a new source of electricity consumption, creating a complex interaction that should be explicitly incorporated into long-term energy planning.

From a policy perspective, this dual effect suggests that future energy strategies should move beyond conventional demand management toward an integrated framework that combines digital innovation with sustainable energy development. Investments in AI-powered energy management systems, smart grids, intelligent building automation, and predictive analytics can substantially improve overall system efficiency, but these gains must be accompanied by parallel investments in renewable energy generation, energy storage technologies, flexible grid infrastructure, and low-carbon electricity supply. Otherwise, the rapid expansion of digital infrastructure—including hyperscale data centers, AI computing clusters, blockchain applications, and industrial digital platforms—may offset efficiency gains through increased electricity consumption, commonly referred to as the digital energy rebound effect. Consequently, scenario-based analyses should explicitly account for both the

energy-saving potential and the additional electricity demand associated with digital transformation to provide a more balanced and realistic assessment of future energy system dynamics

The economic benefits generated by reducing gas and electricity imbalances extend beyond improvements in fiscal performance and trade balances; they also create the financial capacity required for large-scale investment in digital infrastructure. In particular, higher foreign exchange earnings and reduced energy-related subsidies can be strategically redirected toward capital-intensive digital assets such as hyperscale data centers, AI computing infrastructure, smart grids, advanced metering systems, cloud platforms, cybersecurity frameworks, and high-speed communication networks. These investments are essential for supporting digital transformation across industrial, governmental, and commercial sectors. In this context, the economic gains estimated under the optimized scenarios should not be interpreted merely as macroeconomic improvements but as enabling resources that finance the modernization of critical digital infrastructure and strengthen the technological competitiveness of the national economy.

Accordingly, this study positions energy optimization as a foundational driver of digital transformation rather than an isolated objective of energy policy. The LEAP-based scenario analysis demonstrates that improvements in energy efficiency and resource allocation enhance fiscal resilience, which in turn expands the government and private sectors' ability to invest in emerging digital technologies, including artificial intelligence, digital twins, Industrial Internet of Things (IIoT), immersive platforms, and smart urban systems. Consequently, the discussion should emphasize that achieving a resilient digital economy—and, ultimately, enabling metaverse-related applications—depends on a secure, reliable, and intelligently managed energy system. This integrated perspective establishes a direct conceptual pathway from energy system optimization to digital infrastructure development, highlighting that sustainable digital transformation cannot be achieved without parallel investments in both advanced energy infrastructure and next-generation digital technologies.

Discussion

The findings of this study show that the gas and electricity imbalance in Iran is not just a technical issue in the energy sector, but is gradually becoming a macro-economic, currency and infrastructure challenge. This result is in line with the “energy security” perspective proposed by Cherp and Jewell (2014). They argue that energy security is not limited to supply adequacy, but also includes the ability to maintain economic and social performance in the face of energy disruptions. In the modern era, this performance is increasingly tied to the digital realm, where virtual collaboration and remote work rely on an uninterrupted power supply. Accordingly, the results of the present study show that the continuation of the current trend of energy consumption in Iran could lead to a decrease in export capacity, a drop in foreign exchange earnings and an increase in production constraints; a situation that affects various dimensions of energy security. Such economic constraints directly hinder the nation's capacity to invest in the hardware and software ecosystems necessary for a robust Metaverse.

The results of the BAU-C0 scenario showed that the growth of domestic demand gradually depreciates part of the export capacity of oil and petroleum products. This finding is consistent with the results of Stern's (2021) study on countries with hydrocarbon resources. He shows that in economies that rely on energy exports, rapid growth in domestic consumption can undermine export advantages and lead to a decrease in foreign exchange earnings. The results of the present study are also consistent with the analysis of BP Energy Outlook (2024) from an energy economics perspective, which emphasizes the role of energy efficiency and demand management in maintaining the export advantage of oil and gas producing countries. From a digital transformation standpoint, losing this export advantage means fewer resources for developing smart city infrastructures and virtual commerce platforms.

One of the most important findings of the present study is the pivotal role of natural gas in the future of Iran's energy economy. The results showed that if gas production capacity is stabilized at the level of 2025, the gap between supply and demand will gradually increase and will become a significant deficit by 2050. This result is consistent with the findings of Faryadras et al. (2025), who, in their scenario-based study on the future of Iran's energy, showed that continuing the current trend of consumption and investment could face the country with a structural gas imbalance. However, the present study goes a step further and, in addition to estimating the physical gas deficit, also calculates its foreign exchange implications. According to the results of this study, the difference of about 27.5 billion between the demand optimization scenario and the business-as-usual scenario in 2050 shows that gas consumption management is not only an energy policy, but also an economic and currency policy. This 27.5 billion between the demand optimization scenario and the business-as-usual scenario in 2050 shows that gas consumption management is not only an energy policy, but also an economic and currency policy. This 27.5 billion represents a potential "digital dividend" that could be redirected toward AI-driven energy management and virtual reality training simulations.

In the international literature, several studies have emphasized the importance of demand management along with supply development. For example, Grubler et al. (2018) in a report by the International Institute for Applied Systems Analysis (IIASA) showed that increasing energy efficiency can significantly reduce the need for investment in new energy production capacities. The findings of the present study also confirm this. The results of the OPT-C0 scenario showed that modifying the consumption pattern and reducing energy intensity can eliminate a large part of the gas imbalance and improve the country's energy balance. This indicates that demand management policies—facilitated by IoT and smart energy monitoring—can act as a new energy source.

In the electricity sector, the results of the present study are consistent with the findings of international studies on the relationship between demand growth and electricity supply security. The International Energy Agency (IEA, 2024) report shows that the increase in electricity consumption due to economic growth, digitalization of the economy and the development of smart infrastructure requires extensive investment in generation capacity and transmission networks. The present study also found that stopping the development of generation capacity after 2025 could lead to a significant electricity deficit by 2050. This is a critical finding for the Metaverse, as high-fidelity virtual environments and real-time AR applications demand significant localized and cloud-based computational power. This result is also consistent with the findings of Khorramfar et al. (2022), who emphasize the interdependence of the electricity and gas sectors and the need for integrated planning of these two sectors.

From a methodological perspective, the findings of this study are in line with studies that have used the LEAP model for long-term energy planning. Heaps (2024) believes that the most important advantage of LEAP is the ability to analyze different scenarios and examine policy implications over long-term horizons. In this study, LEAP essentially serves as a "Digital Twin" of the Iranian energy system, allowing for the simulation of virtual policy interventions before physical implementation. Studies conducted in Iran have also mainly used LEAP to analyze energy consumption and pollutant emissions (Ataei et al., 2015; Masoomi et al., 2020). The main difference between the present study and these studies is that, instead of focusing solely on consumption or emissions, it focuses on the economic and currency consequences of energy imbalances and their relationship to the reliability of the smart energy infrastructure that supports digital transformation.

Another important result of this study is the emphasis on the complementarity of supply development and demand management policies. This finding is consistent with the approach proposed in the World Energy Outlook 2024, which states that achieving sustainable energy security requires combining investment in new energy capacities with efficiency and

consumption management policies (IEA, 2024). The results of the present study show that even if new production capacities are developed, the lack of control over domestic consumption can eliminate a major part of the economic benefits of investments. On the other hand, energy saving without infrastructure development will not be able to completely eliminate the imbalance.

Overall, the findings of this study indicate that the main bottleneck of Iran's future energy system will be concentrated in the natural gas and electricity sectors. Continuing the current consumption trend could lead to a sharp decline in export capacity and an increase in production constraints, which would ultimately destabilize the virtual economy and the Metaverse's physical foundation. In contrast, a combination of demand management, energy efficiency improvements—driven by AI and digital transformation—and development of energy production infrastructure could play a decisive role in maintaining energy security and enhancing the resilience of Iran's smart energy infrastructure by 2050.

Conclusion

This study demonstrates that Iran's gas and electricity imbalance should no longer be viewed solely as an energy supply-demand mismatch but as a strategic constraint on the country's transition toward an AI-enabled, data-driven, and digitally integrated economy. In the era of artificial intelligence, cloud computing, digital twins, the Industrial Internet of Things (IIoT), and autonomous energy management systems, energy has evolved from a conventional production input into the fundamental infrastructure that powers intelligent technologies. Consequently, persistent energy imbalances undermine not only national energy security but also the deployment of AI ecosystems, high-performance computing facilities, hyperscale data centers, smart manufacturing, and next-generation digital public services. By integrating scenario analysis with the LEAP–NEMO modeling framework, this research demonstrates that maintaining the Business-as-Usual (BAU-C0) trajectory gradually weakens the economic and technological foundations required for building a resilient, AI-powered society.

The simulation results reveal that under the BAU-C0 scenario, increasing gas and electricity deficits progressively erode foreign exchange earnings and reduce the country's capacity to finance strategic digital transformation initiatives. By 2050, the oil and petroleum products sector exhibits an approximately \$8.6 billion lower trade balance than the optimized pathway, while the natural gas sector—the backbone of electricity generation and the primary energy source supporting AI data centers, cloud infrastructure, and intelligent industrial systems—faces a cumulative trade deficit of approximately \$23.9 billion. In contrast, the optimized scenario generates an estimated \$27.5 billion economic advantage, representing not merely additional fiscal resources but the investment capital necessary for scaling artificial intelligence applications, expanding digital infrastructure, deploying smart grids, implementing predictive maintenance platforms, developing digital twins of critical energy assets, and accelerating the adoption of intelligent energy management systems. Without these financial resources, the projected physical gas shortage—equivalent to approximately 122 days of industrial restrictions—would significantly delay AI adoption across strategic sectors and undermine the long-term competitiveness of Iran's digital economy.

The projected electricity imbalance presents an even greater challenge for the future of intelligent infrastructure. The estimated annual electricity deficit of 162.6 million MWh, representing nearly 30% of total electricity demand by 2050, threatens the operational reliability of AI-enabled energy systems and digitally connected infrastructure. As artificial intelligence becomes increasingly embedded in electricity dispatch, predictive analytics, autonomous grid control, cybersecurity, smart transportation, healthcare platforms, industrial automation, and urban digital ecosystems, uninterrupted electricity supply becomes a prerequisite for algorithmic decision-making and real-time system optimization.

Under such conditions, even relatively short-duration power interruptions can cascade through interconnected digital networks, disrupting machine learning operations, cloud services, edge computing architectures, and critical cyber-physical systems. Although demand-side optimization reduces the projected electricity deficit by approximately 76.9 million MWh, the findings indicate that efficiency improvements alone are insufficient. Sustainable digital transformation requires simultaneous investments in renewable energy integration, large-scale energy storage technologies, AI-based demand response systems, intelligent transmission and distribution networks, advanced forecasting algorithms, and resilient smart energy infrastructure capable of supporting the computational demands of future artificial intelligence applications.

Overall, the results suggest that energy transition and digital transformation are inseparable strategic processes. Future investments in artificial intelligence, smart industries, digital government, and intelligent urban systems will be economically viable only if supported by a secure, flexible, and digitally managed energy system. Therefore, national energy planning should move beyond traditional supply expansion toward an integrated strategy that combines AI-driven energy optimization, smart infrastructure development, renewable energy deployment, digital grid modernization, and adaptive scenario-based policymaking. Such an integrated approach will strengthen Iran's energy resilience while providing the technological and financial foundation necessary for achieving sustainable economic growth and maintaining competitiveness in the emerging AI-driven global economy

The main message of this article is that infrastructure investment and demand management are complementary pillars of digital and energy governance. Based on these conclusions, the following strategic orientations are proposed:

1. **Prioritizing Upstream Investment for Digital Reliability:** Investment in gas production and storage is essential to maintain the stable energy supply required for high-availability digital infrastructures and the virtualized economy.
2. **Redesigning the Electricity Sector as a Smart Grid:** Capacity expansion must integrate smart demand management and flexible generation to support the fluctuating needs of a digitalized society.
3. **Strategic Gas Demand Management:** Improving building standards and industrial efficiency should be viewed as a way to free up resources for the high-value digital service sector.
4. **Upgrading Electricity Management via Digital Tools:** Transitioning from advice-based saving to IoT-enabled smart meters, time-based tariffs, and load-response contracts to enhance network stability.
5. **Establishing a Financial Mechanism for the Energy-Digital Nexus:** Using funds from energy savings to finance the renovation of equipment and the deployment of Energy Service Companies (ESCOs) that utilize digital twins for efficiency.
6. **Linking Energy Policy to Digital and Industrial Policy:** Energy allocation should favor energy-efficient, high-value-added industries that contribute to the digital ecosystem, ensuring that energy security remains a cornerstone of industrial development.
7. **Transitioning from Emergency Management to Structural Digital Adjustment:** Policy must move beyond short-term shutdowns toward long-term digital energy governance, where infrastructure development and smart efficiency measures are integrated into a single strategic framework.

In conclusion, for Iran to successfully navigate the path toward 2050 and embrace the opportunities of the Metaverse and digital transformation, it must first resolve the structural imbalances in its energy system. Without a resilient and smart energy foundation, the virtual and digital aspirations of the country will remain physically constrained.

Declaration of Competing Interest

The author declares that he has no competing financial interests or known personal relationships that would influence the report presented in this article.

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