The Role of Technology in Improving Energy Efficiency and Its Impact on the Economy

A Fuzzy Logic-Based Study in the Gulf Countries

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Abstract: The study examined the dynamic relationship between technological advancement, energy efficiency, and economic performance in Gulf countries, using a Mamdani fuzzy inference system (FIS) as a methodological framework. Drawing on empirical evidence and literature, the study confirms that technology acts as a catalyst for economic transformation, particularly in regions striving to diversify away from oil-based revenues. The model developed integrates three core dimensions—technological innovation, energy-use efficiency, and strategic investment in digital infrastructure—and demonstrates their combined effect on economic outcomes. The Mamdani fuzzy system proved effective in capturing the nonlinear and linguistic nature of these relationships, offering a realistic and flexible analytical tool for policy assessment.

Key findings indicate that higher levels of technological innovation are positively associated with GDP growth and competitiveness. Energy efficiency improvements lead to operational cost reductions and better environmental-economic balance. Increased investment in digital technologies significantly contributes to economic diversification and job creation. Moreover, the

fuzzy logic approach allows policymakers to handle uncertainty and vagueness in economic forecasting, especially in emerging digital economies like those of the GCC. In conclusion, the integration of advanced technology and sustainable energy management is not only desirable but essential for achieving long-term economic resilience in the Gulf region. Policymakers should therefore prioritize digital transformation strategies, support R&D ecosystems, and adopt data-driven tools such as fuzzy modeling to enhance decision-making under uncertainty.

Keywords: Energy Efficiency; Technological Innovation; Fuzzy Logic; Gulf Countries; Energy Management; Sustainable Development; Digital Transformation; Energy Policy; Smart Technologies.

JEL Classification : C45, O33, Q40, Q43, Q48.

1 Introduction

Technology plays a crucial role in improving energy efficiency across various sectors, leading to significant economic and environmental benefits. Through innovations such as advanced machinery, automation, and renewable energy technologies, energy consumption is reduced, and productivity is enhanced.
Data analysis and the Internet of Things (IoT) provide real-time monitoring of energy consumption, enabling individuals and businesses to make informed decisions that reduce waste and improve efficiency.

Since the beginning of the new millennium, the Gulf countries have undergone profound economic transformations aimed at diversifying income sources and reducing dependence on oil rents. This has been pursued through the adoption of ambitious development strategies centred on innovation and technology, such as Saudi Arabia's "Vision 2030," the UAE's "Vision 2050," and other national initiatives. Within this framework, technology has emerged as a central driver of sustainable development—by improving energy efficiency, enhancing the productivity of key sectors, and promoting integration between economic and digital systems.

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The Gulf Cooperation Council (GCC) is a union between six countries in the Arabian Peninsula (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE). They have reported the highest per-capita energy consumption globally for decades and are among the largest consumers of both electricity and water. Electricity and water price liberalization reforms that escalate end-user prices began on a GCC level in 2010, aimed at alleviating these issues while maintaining affordability

Despite the significant efforts made by Gulf countries in this regard, the economic outcomes achieved remain uneven across the region. Variations persist in terms of growth, diversification of the production base, and the effectiveness of technology use in narrowing the development gap. This disparity raises important questions about the effectiveness of technological investments and the extent to which digital transformation and energy-efficiency improvements affect economic performance indicators in the region.

Given the complex, nonlinear nature of the relationship between technology and economic performance, the Mamdani Fuzzy Inference System is employed. This method effectively processes linguistic and vague inputs.

The model components include inputs such as technological advancement, energy efficiency, and technological investment. The output is measured by economic performance. We employ fuzzy rules IF–THEN structure, such as: IF technology is high AND energy efficiency is strong AND investment is high THEN performance is strong. We use the Mamdani inference type and the Centroid method for defuzzification. The core problem addressed by this study is understanding the nonlinear relationship between technological advancement, energy efficiency, and technological investment, on the one hand, and the actual economic performance achieved in the Gulf countries, on the other. Although the strategic direction toward modernization and innovation is shared across the region, differences in infrastructure, implementation mechanisms, and levels of adaptation to digital transformation have led to varying economic outcomes.

So, to what extent do technological advancement, energy efficiency, and levels of technological investment affect the economic performance of Gulf countries, and how can this complex relationship be modeled using a fuzzy logic-based approach? From this context, the study formulates the following main hypotheses:

- Technological advancement has a positive impact on economic performance in the Gulf countries;
- Improvements in energy efficiency contribute to enhanced economic performance;
- Greater investment in technology is associated with stronger economic outcomes;
- A fuzzy logic-based model, specifically the Mamdani type, can accurately capture these nonlinear and linguistic relationships.

The significance of this study lies in its provision of a quantitative methodological framework, based on fuzzy modeling, for analyzing the intertwined relationship between technology and the economy. This enables a deeper understanding of the economic effects of technology-driven policies. The findings aim to assist policymakers in refining digital transformation strategies and optimizing technological investment policies in alignment with sustainable development plans and the Gulf countries' Vision 2030 agendas.

1.1 Methodology

The study is based on a quantitative analytical model of the Mamdani FIS to assess nonlinear relationships in the GCC over the period (2019–2024), using annual data from the World Bank, the International Energy Agency (IEA), the OECD, and the national Vision documents. The model uses the following variables:

- Technological advancement: patents, R&D spending, innovation index
- Energy efficiency: GDP per unit of energy, per capita energy use
- Technological investment: digital infrastructure spending, project count
- Economic performance: GDP growth, competitiveness index, employment

Inputs and outputs are classified into three levels

Inputs:

- Level of Technological Advancement (Low – Medium – High)
- Energy Efficiency (Weak – Moderate – Strong)
- Level of Technological Investment (Low – Moderate – High)

Output:

1. Economic Performance (Weak – Moderate – Strong)

Inference Rules:

- If technological advancement is **high** and energy efficiency is **strong**, then economic performance is **strong**.
- If technological investment is **low** and energy efficiency is **weak**, then economic performance is **weak**.

This model was adopted for its ability to simulate human reasoning and handle data ambiguity (Kaufmann & Gupta, 1991). Table 1 outlines independent and dependent variables, indicators used, and their expected relationships:

Table 1. Summary of Variables, Indicators, and Expected Relationships in the Fuzzy Logic Model

Variable	Type	Indicator	Expected Relationship	Notes
Technological Advancement	Independent	Patents, R&D expenditure, innovation index	Positive correlation with economic performance	Supports Growth through innovation
Energy Efficiency	Independent	GDP per energy unit, energy loss rate	Positive correlation	Reduces cost and increases sustainability
Technological Investment	Independent	Digital spending, number of projects	Positive correlation	Drives long-term economic value
Economic Performance	Dependent	GDP growth, competitiveness, jobs	Outcome variable	Result of multiple technological factors
Mamdani Fuzzy Model	Analytical Method	Fuzzy rules, membership functions	Estimates performance	Captures non-linear interactions

1.2 Literature Review

The OECD (2021) report found that digital transformation can improve productivity in member countries by 20–25% over a ten-year period. The study emphasized that investments in digital infrastructure, automation, and AI are key drivers of economic growth, especially in service-based economies.
Given these staggering productivity improvements, GCC countries aiming to reduce their oil dependence can leverage digitalization to diversify the economy away from hydrocarbons. According to the International Energy Agency (IEA, 2020), global improvements in energy efficiency could reduce total energy demand by up to 30% by 2040. The report stresses policy reform, industrial upgrades, and smart energy systems as primary enablers. For Gulf countries with high per-capita energy intensity, energy efficiency is a strategic lever to enhance sustainability and reduce operational costs. ESCWA's 2022 report analyzed the potential of integrating smart and clean technologies in the Arab region. It identifies the Gulf as a leading region in energy innovation, especially in deploying solar, grid management systems, and building automation.
Gulf states have comparative advantages in adopting energy innovations, which could translate into measurable economic gains. Al Hammadi et al. (2019) studied solar Investments in the UAE and assessed their impact on energy security. The study's results showed significant job creation, reduced dependence on imported fuel, and cost savings. As a result, renewable energy projects serve not only environmental goals but are also engines of economic growth in Gulf economies. The study of Al-Saadi (2023) on the digital economy, focusing on Saudi Arabia's Vision 2030, found a positive relationship between public digital investment and GDP growth. It linked increases in broadband access, smart governance, and e-commerce support with economic diversification efforts under Vision 2030. The study validated the hypothesis that technological advancement contributes directly to economic performance. Al-Shehri & Al-Mutairi (2020) applied fuzzy modeling to industrial productivity in Kuwait, using a Mamdani fuzzy inference system to model the relationship between industrial automation and productivity. The model successfully captured nonlinear effects and showed that improvements in automation and training correlated with productivity gains.
The findings demonstrated the applicability and robustness of fuzzy logic systems in Gulf-specific contexts, supporting the hypothesis postulated in this study.

The reviewed literature, both global and Gulf-specific, strongly supports the theoretical foundation and hypotheses of this study. Technological advancement, energy efficiency, and digital investment are proven catalysts of economic performance. Furthermore, fuzzy logic systems such as Mamdani FIS have been successfully deployed in regional studies, thereby validating their suitability for analyzing complex interactions in Gulf economies.

2. Theoretical Framework

Technological improvements and upgrades have become a principal tool for enhancing energy efficiency across several sectors of the economy. The studies reviewed in part 1.2 showed that growth in energy efficiency is attributed mainly to technology diffusion, supported by research and development, government support and financing, operations and management, and infrastructure investment in the Gulf Countries. Changes in productivity compared to changes in economic activity reduced sectoral dependence on fossil energy and strengthened the economic structure, thereby contributing to further improvements in energy efficiency as part of efforts to adjust energy consumption. To achieve the economy's diversification and, at the same time, improve energy efficiency, growth in energy productivity can drive the diffusion of energy-efficient technologies and processes, not only within sectors but also across sectors in the Gulf Countries. (Gao et al., 2022)

Given the GCC region's abundant natural resources, energy consumption and economic development are closely linked. Further improvements in energy efficiency can be anticipated for the future of energy productivity growth. However, attention should be paid to the newly emerged issue of social impacts arising from economic growth and energy efficiency, especially in the Gulf Countries, where average incomes are high but environmental awareness is considered low. Exploring a scheme to mitigate the adverse socio-economic effects of energy-efficiency efforts would be essential for developing an effective policy to improve energy efficiency. In this context, investigating the effects of energy-efficient technologies and processes on energy consumption and productivity, using disaggregated industry-level data would be helpful (Howarth et al., 2017).

The continued expansion of some important complementary technologies, such as smart meters, information and communication technologies, power-generation technologies, building energy efficiency technologies, and renewable energy technologies, along with increased financial resources for technology development and diffusion, improved governance for technology management and protection, strong industrial development capacity, and robust cooperation within and between regions will help to improve energy efficiency and renewable energy use in Gulf Cooperation Countries (GCC). There is a need to foster the development and diffusion of hybrid power generation technologies to accelerate renewable energy capacity and to develop and widely deploy technologies that improve energy efficiency in the construction, transportation, and manufacturing sectors. (Al-Mekaimi, 2025)

2.1. Energy Management Systems

Energy management systems (EMS) are vital tools for advancing energy efficiency, conservation, and cost management. Considering the increase in competition and commercial pressures on utilities, there is a growing lack of time and scope to improve energy management thresholds and efforts. It is therefore vital to use energy management systems to quantitatively assess current energy-efficiency efforts and qualitatively explore the implications of future energy-efficiency endeavors. The main motivation for energy-intensive industries is that energy management systems can theoretically provide a range of business benefits to manufacturers (Elizabeth Babatunde et al., 2018). The general energy management system structure comprises a supply assessment system that evaluates the quality and unit price of energy, and an energy efficiency system that measures energy efficiency in an accountable manner. The integrated fuzzy system allows the combination of qualitative knowledge with numerical values and translations for simulation, scenario verification, and assessment. The suggested generic systems were successfully tested on the development of a textile manufacturing plant. Results show that the technique can provide holistic, cost-effective manufacturing improvements, decision-support tools, and optimization approaches to investigate the viability of advanced technologies and materials. (Mahapatra & Nayyar, 2022).
Modern Energy Management Systems (EMS) today have become effective tools for increasing the energy efficiency of industrial sites. In order to monitor, optimize, and control energy consumption, and consequently to reduce costs, many modern software tools (artificial intelligence, machine learning, real time monitoring, and many others) are being integrated into these systems, which are used by the energy auditors/managers as a performance measurement tool in order to continuously increase the industrial energy efficiency (Segun-Falade et al., 2024).

2.2. Building Automation Systems

Energy use measurement is a promising new technique being increasingly integrated into buildings, as it can significantly improve energy awareness, efficiency, and comfort (Reinhart et al., 2013). Sensors measure a building's energy use and provide building operators with usage information. Earlier energy-use measurements for spaces were imprecise and based on rough estimates or simulations. The introduction of sophisticated sensors and smart energy management systems has transformed this measurement and control paradigm. New energy-use measurements provide detailed, precise data on how spaces consume energy at the component level. In addition to traditional power sensors, wireless sensors can be flexibly deployed throughout buildings. The aforementioned information includes additional variables related to energy use, which can help increase energy awareness and ultimately reduce energy consumption.

As new technology introduces new products to the market, opportunities will inevitably arise for system integration into commercial buildings (Hernández Uribe et al., 2015). Just like in the consumer market, buildings can now procure energy based on knowledge of their energy use, spatial characteristics, and comfort needs. High returns can be achieved through various avenues, using systems that control building operations whilst optimizing energy, comfort, and wealth. Most inchoate capital markets employ only simple technologies, namely, basic training and energy use tracking, as low-cost positive and negative incentive programs. Nonetheless, persuasive feedback for both building operators and occupants pertains not only to overall energy consumption but also to energy consumption broken down into several more granular subcategories.

Granular feedback could be presented through various media, including logs of past use displayed on a screen and aggregate energy budgets sent via e-mail. One-on-one or group training is also widely used to engage building operators on energy-efficient practices and to track their progress using organized spreadsheets to present composite estimates. A wealth of relevant literature exists, and new control methods and system integration algorithms can further reduce the energy use of intelligent buildings and increase CO2 savings. However, calibration and validation of the above computer-based medium are needed before its wide dissemination.

2.3. Comparative Analysis of Gulf Countries

The Gulf countries are characterized as energy-abundant and energy-intensive due to their large oil and gas reserves and production. GCC member countries form a highly homogeneous group, sharing many common characteristics. The distribution of oil and gas reserves in the GCC countries is uneven, as two-thirds are in Saudi Arabia and Qatar. Fossil fuels dominate the energy mix. The share of primary energy in the GCC countries constitute 99% of the energy supply in Qatar, Oman, and Kuwait, and 95% in Saudi Arabia and the UAE. However, there are differences in energy consumption and intensity, as noted by Salem et al. (2023).

Howarth et la(2017) noted that GCC differs from the typical development path observed in advanced economies. Despite very high-income levels, GCC economies remain heavily dependent on energy consumption for growth. Achieving economic diversification and improving energy productivity will therefore be critical for reducing this dependence and supporting sustainable development in the region. However, within the GCC, the authors note important differences among countries. From their sectoral analysis and figures, you can infer two broad patterns: Qatar, Bahrain, and Saudi Arabia exhibit particularly high per-capita industrial and non-energy (petrochemical feedstock) energy consumption. The UAE, Oman, and Kuwait generally show lower levels of industrial/non-energy consumption per capita, although still high by international standards. This results in different behavior in energy consumption trends. For example, starting in 2000, energy consumption in Bahrain, Qatar, and the UAE increased rapidly as their GDP was significantly affected by the substantial increase in oil prices, and, globally, energy consumption trends diverged post-2000. Conversely, energy consumption in Saudi Arabia has stabilized because GDP has been relatively unaffected by oil prices. Due to its rapidly growing population, Oman was moving toward higher levels of consumption at a rapid rate prior to 2019. Eventually, the fate of energy consumption in Kuwait is determined by the balance of GDP and heavy subsidies. The different levels of urbanization (around 91% in Qatar and 99% in Bahrain versus around 70% in Saudi Arabia and 72% in Kuwait) across these countries can also affect the growth rate of the residential sector. The analysis of energy intensity in these countries and the comparison of their characteristics with those of countries worldwide reveal patterns like those observed in the GCC (Chaabouni & Abid, 2025).

Though the Gulf Co-operation Council countries share many similarities in their energy resource endowments, their energy consumption patterns and energy inefficiencies differ. To help prioritize and select the most appropriate policies and tools, knowledge of the strengths and weaknesses of their energy-use systems would be very helpful. Leal-Arcas et al (2024) studied benchmarked GCC countries with several selected peers. To improve the knowledge on the strengths and weaknesses of the energy intensity during 2002 to 2012 in GCC, a three-step process was followed: (1) measuring the countries' energy intensity components based on the decomposition method; (2) deriving from these values both global and specific comparative strengths and weaknesses for the GCC while accounting for both energy preconditions and consumption patterns; and (3) benchmarking these features to GCC countries.

The GCC region is endowed with abundant domestic oil and natural gas reserves. Alongside their enormous energy resources, the GCC member countries also benefit from their geographic proximity to the world's largest energyconsuming markets. However, their economies are among the most energy-intensive in the world, indicating not only low energy efficiency but also a likely unsustainable path of energy use that would seriously undermine the region's economic prospects. Efficiency improvements are thus both economically beneficial and environmentally required. As such, over the last decades, it has become increasingly important to find ways to improve the energy efficiency of their economies, both in the broader context of sustainable development and for their specific economic policy objectives. (Lahrech et al.2024)

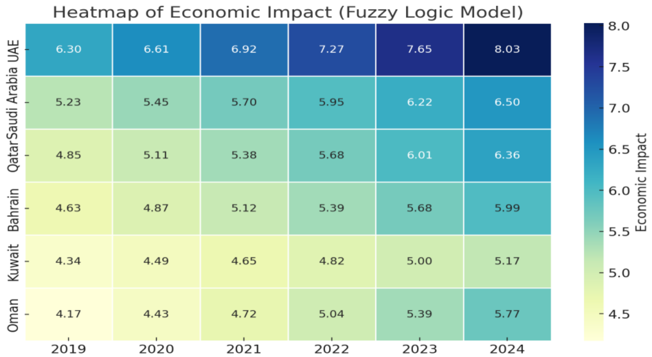
Advances in research and technology have demonstrated their potential to enhance energy efficiency and conservation, enabling production with a lower energy footprint — a critical challenge in Gulf jurisdictions, where energy-intensive heavy industries account for large shares of production. These innovations are suited to efforts in the Gulf countries, and should be able to save energy, fossil fuel, operating costs, and greenhouse gas emissions in power generation, water desalination, cement production, and petrochemical production. Increasing energy efficiency in these sectors can produce savings of about 10–20 percent in energy and greenhouse gas emissions. There are also some easy energy savings that do not require much technical investment. Thus, audits and inspections, when properly done, may provide 6–8 percent savings in energy and greenhouse gas emissions, and working with advanced equipment, can contribute to energy savings of about 15-20 percent (Hertog & Luciani, 2009). The low-cost options would improve the energy performance of plants and unlock new energy-conservation incentives, as these plants would reduce their fossil fuel consumption.

To improve energy efficiency, GCC states may build on advances already made in energy-using industries worldwide. Cooperation with leading-edge economies may create and cultivate a cohort of Gulf engagement-focused energy-industrial research, development, and design (RDD) companies. There is a strong interest in enhancing RDD capabilities, which has recently become a focal point for advanced industrial countries. Gulf governments have direct oversight of energy-intensive industries and encourage their growth, a prime concern addressed to these countries in the past. These reforms, so central with respect to energy and greenhouse gas emissions, are compatible with technological coproduction, as their limited public interaction minimizes spillovers into society. Gulf countries should be able to use the best practices of other states in these respects. In analytical terms, these initiatives similarly address the energy intensity of heavy industries and are located outside labor markets, making them too detached from society to foster widespread industry-academic linkages in a knowledge-neutral fashion. Lastly, such efforts have already reached a high point in some Gulf states. (Biazzi, 2022)

3. Mathematical and Analytical Approach

This section presents the fuzzy logic model used to estimate the economic impact of technology and energy efficiency across Gulf countries between 2019 and 2024. The model is based on the Mamdani inference system implemented using Python's scikit-fuzzy library. The following figures represent the economic impact calculated using fuzzy logic for six Gulf countries over the period 2019–2024.

Figure 1. Heatmap of Economic Impact (Fuzzy Logic Model)



The heatmap presented in Figure 1 illustrates the evolution of economic impact values for each Gulf country from 2019 to 2024, with darker shades indicating higher values. UAE shows a clear upward trend, progressing from a medium impact (6.3) in 2019 to a strong impact (8.03) in 2024. However, Saudi Arabia exhibits gradual growth while maintaining a medium classification throughout (ending at 6.5). Qatar demonstrates consistent improvement, though it remains in the medium impact range. Bahrain's trajectory is also upward but slow, never surpassing the medium level. Kuwait maintains one of the lowest impacts, barely reaching 5.17 by 2024. Oman shows steady improvement but remains within the medium range (4.17 to 5.77). Overall, only the UAE achieved a 'Strong' economic impact classification, reflecting sustained and efficient technological and investment policies. Other countries remain in the 'Medium' range, suggesting room for advancement.

3.1. Detailed Analysis by Country

The model was applied to annual data for each Gulf country from 2019 to 2024, producing economic impact scores ranging from 0 to 10 and categorized as Low, Medium, or High. The following section presents statistics on the study variables for the Gulf countries during 2019–2024.

Table 2. Evolution of Technological Indicators and Economic Impact in the UAE (2019–2024)

Year	Tech Advancement (%)	Energy Efficiency	Tech Investment (% GDP)	Economic Impact (0–10)	Impact Classification
2019	60.0	0.75	1.10	6.30	Medium
2020	65.0	0.76	1.16	6.61	Medium
2021	70.0	0.77	1.21	6.92	Medium
2022	76.0	0.78	1.27	7.27	High
2023	82.0	0.79	1.34	7.65	High
2024	88.0	0.80	1.40	8.03	High

Table 3. Evolution of Technological Indicators and Economic Impact in Saudi Arabia (2019–2024)

Year	Tech Advancement (%)	Energy Efficiency	Tech Investment (% GDP)	Economic Impact (0–10)	Impact Classification
2019	52.0	0.70	0.70	5.23	Medium
2020	55.6	0.71	0.73	5.45	Medium
2021	59.5	0.72	0.77	5.70	Medium
2022	63.7	0.73	0.81	5.95	Medium
2023	68.2	0.74	0.85	6.22	Medium
2024	72.9	0.75	0.89	6.50	Medium

Table 4. Evolution of Technological Indicators and Economic Impact in Qatar (2019–2024)

Year	Tech Advancement (%)	Energy Efficiency	Tech Investment (% GDP)	Economic Impact (0–10)	Impact Classification
2019	50.0	0.65	0.60	4.85	Medium
2020	54.6	0.66	0.63	5.11	Medium
2021	59.6	0.67	0.66	5.38	Medium
2022	65.1	0.68	0.69	5.68	Medium
2023	71.1	0.69	0.73	6.01	Medium
2024	77.6	0.70	0.77	6.36	Medium

Table 5. Evolution of Technological Indicators and Economic Impact in Bahrain (2019–2024)

Year	Tech Advancement (%)	Energy Efficiency	Tech Investment (% GDP)	Economic Impact (0–10)	Impact Classification
2019	49.0	0.64	0.50	4.63	Medium
2020	53.21	0.65	0.53	4.87	Medium
2021	57.79	0.66	0.55	5.12	Medium
2022	62.76	0.67	0.58	5.39	Medium
2023	68.16	0.68	0.61	5.68	Medium
2024	74.02	0.69	0.64	5.99	Medium

Table 6. Evolution of Technological Indicators and Economic Impact in Kuwait (2019–2024)

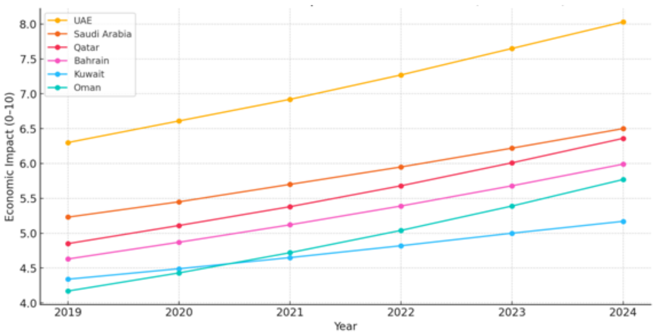
Year	Tech Advancement (%)	Energy Efficiency	Tech Investment (% GDP)	Economic Impact (0–10)	Impact Classification
2019	47.0	0.62	0.40	4.34	Medium
2020	49.35	0.63	0.42	4.49	Medium
2021	51.82	0.64	0.44	4.65	Medium
2022	54.41	0.65	0.46	4.82	Medium
2023	57.13	0.66	0.49	5.00	Medium
2024	59.99	0.67	0.51	5.17	Medium

Table 7. Evolution of Technological Indicators and Economic Impact in Oman (2019–2024)

Year	Tech Advancement (%)	Energy Efficiency	Tech Investment (% GDP)	Economic Impact (0–10)	Impact Classification
2019	46.0	0.60	0.35	4.17	Medium
2020	51.2	0.61	0.37	4.43	Medium
2021	56.98	0.62	0.39	4.72	Medium
2022	63.42	0.63	0.41	5.04	Medium
2023	70.59	0.64	0.43	5.39	Medium
2024	78.57	0.65	0.45	5.77	Medium

Figure 2 illustrates the progression of economic impact resulting from technological advancement, energy efficiency, and technological investment in six Gulf countries over a six-year period

Fig. 2. Evolution of Economic Impact in Gulf Countries (2019 – 2024)

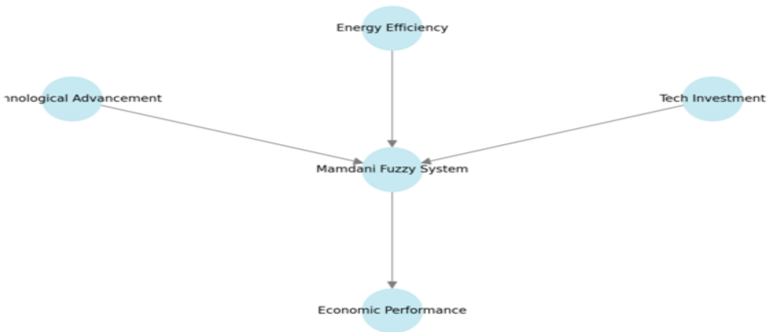


The economic impact score in Figure 1 is generated using a Mamdani fuzzy model and reflects the nonlinear interaction between input variables and economic performance outcomes. The UAE shows a clearly upward trend, with the economic impact rising from 6.3 in 2019 to 8.03 in 2024—the highest in the region. This growth reflects the country's substantial investment in technological infrastructure and renewable energy, as well as its leadership in innovation and digital transformation indicators. Saudi Arabia displays steady improvement, increasing from 5.23 to 6.5 over the same period. This growth aligns with Vision 2030 policies focused on digital transformation, energy efficiency, and smart-city initiatives such as NEOM. Qatar shows a gradual, consistent improvement from 4.85 to 6.36, with stable increases suggesting balanced investments in technology and the energy sector, though at a slightly slower pace than the UAE. Bahrain follows a moderate upward trend, reaching from 4.63 to 5.99. While this shows notable progress, the impact remains within the "medium" range, possibly due to limited funding or slower adoption of digital transformation in some sectors. Kuwait registers one of the lowest improvement rates, moving from 4.34 to 5.17, which may indicate challenges in technological expansion or relatively lower energy efficiency compared to neighboring countries. Oman shows a steady progression from 4.17 to 5.77, reflecting gradual efforts to enhance digital infrastructure and energy efficiency. However, greater acceleration is needed to keep pace with the leading regional economies. The index results show a clear positive correlation between the level of technological advancement and investment and improvements in economic impact. The UAE and Saudi Arabia lead the region in smart technology and energy initiatives. Countries such as Kuwait, Bahrain, and Oman need to intensify their efforts to achieve significant improvements in economic performance. A Fuzzy Inference System (FIS) based on the Mamdani model was employed to convert input variables into output values through IF–THEN linguistic rules. These rules are activated based on the degree of membership of each input in its respective fuzzy set. We used MATLAB and Python tools.

3.2. Visual Diagram of Expected Relationships

The following diagram visually illustrates the expected relationships between technological variables and economic performance within the Mamdani fuzzy system:

Fig. 3. Expected relationships between variables (Fuzzy Model)



In the diagram above, the expected relationships between the key variables in the study are illustrated as follows:

Inputs:

- Technological Advancement
- Energy Efficiency
- Technological Investment

Processing:

All of these variables are fed into a Mamdani-type fuzzy inference system, which integrates them based on linguistic rules and fuzzy logic algorithms.

Output:

- Economic Performance resulting from the interaction of these variables.

This diagram demonstrates that the relationship between technology and the economy is neither direct nor linear. Instead, it is processed through a non-traditional analytical phase represented by the fuzzy logic system, which enables accurate modeling of complexity and uncertainty.

3.3. Variables and Linguistic Terms

The fuzzy inference system uses the following variables:

Input Variables:

• Technological Progress (TP) $\in [0, 100]$
• Energy Efficiency (EE) $\in [0, 1]$
• Technological Investment (TI) $\in [0, 2]$ (% of GDP)

Output Variable:

• Economic Impact (EI) $\in [0, 10]$

Each variable is described using triangular membership functions with three linguistic labels:
•For inputs: {Low, Medium, High}
• For output: {Low, Medium, High}

3.4. Fuzzification and Membership Functions

Each fuzzy set is defined using the triangular function:

$$\mu\_A(x) = 0, \text{ if } x \leq a \text{ or } x \geq c$$
$$(x - a)/(b - a), \text{ if } a < x \leq b$$
$$(c - x)/(c - b), \text{ if } b < x < c$$

Where [a, b, c] are the triangle's parameters.

Fuzzy Rules

The model uses a rule base composed of linguistic IF–THEN rules such as:
R1: IF TP is High AND EE is Good AND TI is High THEN EI is High
R2: IF TP is Medium AND EE is Moderate, AND TI is Moderate THEN EI is Medium
R3: IF TP is Low AND EE is Poor AND TI is Low THEN EI is Low
... and other combinations capturing the system's behavior.

Inference Mechanism and Aggregation

The Mamdani method applies the MIN operator to compute each rule's firing strength:

$$w\_k = \min(\mu\_Ak(TP), \mu\_Bk(EE), \mu\_Ck(TI))$$

Each rule generates a clipped fuzzy output, and the final aggregated fuzzy set is obtained using the MAX operator:
EI aggregated

$$(y) = \max\_k (\min (w\_k, \mu\_Dk(y)))$$

Defuzzification: To obtain a crisp output, the centroid method is applied:

$$EI\_crisp = \int y * \mu\_EI(y)\, dy / \int \mu\_EI(y)\, dy$$

Example: United Arab Emirates (2023)

Input values:

- TP = 81.63
- EE = 0.79
- TI = 1.34

These values activate rules where:
- TP is High ($\mu \approx 0.39$)
- EE is Good ($\mu \approx 0.95$)
- TI is High ($\mu \approx 0.7$)

Resulting economic impact (EI) $\approx 7.65 \rightarrow$ classified as High

4. Conclusion

This study has examined the dynamic relationship between technological advancement, energy efficiency, and economic performance in Gulf countries, using a Mamdani fuzzy inference system (FIS) as a methodological framework. Drawing on empirical evidence and literature, the study confirms that technology acts as a catalyst for economic transformation, particularly in regions striving to diversify away from oil-based revenues.

The model developed integrates three core dimensions—technological innovation, energy-use efficiency, and strategic investment in digital infrastructure—and demonstrates their combined effect on economic outcomes. The Mamdani fuzzy system proved effective in capturing the nonlinear and linguistic nature of these relationships, offering a realistic and flexible analytical tool for policy assessment.

Key findings indicate that higher levels of technological innovation are positively associated with GDP growth and competitiveness. Energy efficiency improvements lead to operational cost reductions and better environmental-economic balance. Increased investment in digital technologies significantly contributes to economic diversification and job creation. Moreover, the fuzzy logic approach allows policymakers to handle uncertainty and vagueness in economic forecasting, especially in emerging digital economies like those of the GCC. In conclusion, the integration of advanced technology and sustainable energy management is not only desirable but essential for achieving long-term economic resilience in the Gulf region. Policymakers should therefore prioritize digital transformation strategies, support R&D ecosystems, and adopt data-driven tools such as fuzzy modeling to enhance decision-making under uncertainty.

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