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DEA-Malmquist Method to Analyse Total-Factor Energy Efficiency for GCC Countries

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Abstract

Objectives: Carbon dioxide emissions are primarily produced as a result of energy consumption, and improving energy efficiency is a critical component in mitigating the effects of climate change. Total energy consumption in the GCC countries is expected to rise from 238.8 million tons in 2000 to 584 million tons in 2023. This study aims to assess the Total-Factor Energy Efficiency (TFEE), which influences energy efficiency in the GCC countries. Three inputs were used—labor, capital stock, and energy consumption—to evaluate energy efficiency in two key sectors: the transportation sector and the electricity sector.

Methods: Data Envelopment Analysis (DEA) and the Malmquist Productivity Index were employed to measure energy efficiency in two models: the first model for the electricity sector, and the second model for the transportation sector in the GCC region.

Results: The findings of the study reveal a general decline in energy efficiency across the GCC countries in both the electricity generation and transportation sectors. In the electricity model, the Total-Factor Energy Efficiency (TFEE) decreased by 3.9%, driven primarily by a 4% drop in technological change, although technical efficiency exhibited a slight improvement of 0.1%. Similarly, in the transportation sector, overall energy efficiency fell by 2.9%, largely due to a 2.8% reduction in technological change, accompanied by a marginal 0.1% decline in technical efficiency growth. Together, these results indicate that deteriorating technological progress is the main factor behind the downward trend in energy efficiency across both sectors.

Conclusion: The findings of this study can help policymakers identify the key variables influencing energy efficiency in GCC countries, enabling them to design more effective strategies for the future.

Keywords: Total-factor energy efficiency (TFEE), GCC countries, electricity generation, transport sector, DEA- Malmquist analysis

طريقة تحليل مغلف البيانات - مالمكويست لتحليل الكفاءة الإجمالية لعامل الطاقة لدول مجلس التعاون الخليجي

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ملخّص

الأهداف: تُنتَج انبعاثات ثاني أكسيد الكربون في الغالب نتيجة استهلاك الطاقة، ويُعدّ تحسين كفاءة الطاقة عنصرًا حاسمًا في التخفيف من آثار التغير المناخي. من المتوقع أن يرتفع إجمالي استهلاك الطاقة في دول مجلس التعاون الخليجي من 238.8 مليون طن في عام 2000 إلى 584 مليون طن في عام 2023. تهدف هذه الدراسة إلى تقييم الكفاءة الإجمالية لعامل الطاقة (TFEE) ، والتي تؤثر على كفاءة الطاقة في دول مجلس التعاون الخليجي. وقد تم استخدام ثلاثة مدخلات: القوى العاملة، ومخزون رأس المال، واستهلاك الطاقة لتقييم كفاءة الطاقة في قطاعين مهمين في هذه الدول، هما: قطاع النقل، وقطاع الكهرباء.

المنهجية: تم استخدام أسلوب تحليل مغلف البيانات ومؤشر مالمكويست لقياس كفاءة الطاقة في نموذجين: النموذج الأول لقطاع الكهرباء، والنموذج الثاني لقطاع النقل في منطقة الخليج.

النتائج: أظهرت نتائج النموذجين أنّ كفاءة الطاقة الأساسية في دول مجلس التعاون الخليجي قد شهدت تراجعًا عامًا. ففي نموذج توليد الكهرباء، انخفض مؤشر الكفاءة الكلي للطاقة (TFEE) بنسبة 3.9%، ويُعزى ذلك بشكل رئيسي إلى تراجع التغير التكنولوجي بنسبة 4%. في المقابل، شهد التغير في الكفاءة التقنية نموًا طفيفًا بنسبة 0.1%. أما في نموذج قطاع النقل، فقد بلغ معدل انخفاض كفاءة الطاقة في القطاع العام 2.9%، نتيجة تراجع التغير التكنولوجي بنسبة 2.8%، مع انخفاض طفيف في نمو الكفاءة التقنية بنسبة 0.1%.

الخلاصة: يمكن أن تسهم نتائج هذه الدراسة في مساعدة صُناع السياسات على تحديد المتغيرات الرئيسية المؤثرة في كفاءة الطاقة في هذه الدول، مما يساعد في رسم استراتيجيات أكثر فاعلية في المستقبل.

الكلمات الدالة: الكفاءة الإجمالية لعامل الطاقة، دول مجلس التعاون الخليجي، توليد الكهرباء، قطاع النقل، تحليل مغلف البيانات - مالمكويست

1. INTRODUCTION

The long-term rapid economic growth in the Gulf Cooperation Council (GCC) countries—Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE)—has occurred over the last few decades. GDP has increased at an average annual rate of 4.8%, while the population has grown by 4.2% (World Bank, 2022). As expected, this has led to increases in energy consumption and thus higher carbon dioxide (CO_2) emissions year by year (see Fig. 3). This means that maintaining fast and steady economic growth can significantly increase CO_2 emissions. Therefore, with increased international concern over climate change, governments face political and economic pressures. The GCC countries share the objective of transitioning their economies to be less dependent on fossil fuels by emphasizing energy efficiency and diversifying their sources of revenue to achieve sustainable development. However, energy consumption in the GCC countries—particularly in the electricity and transportation sectors—indicates a rise in energy intensity. This has raised concerns that GCC countries are not using energy efficiently, an issue examined in this study (see Table 1).

Increasing energy efficiency is the most crucial way to implement any energy program. It is possible to achieve sustainable development with an adequate supply of energy if economic growth and energy efficiency are well balanced (Hu & Wang, 2006). Since energy is necessary for economic growth, sustainable development should be considered when designing energy policy. However, measuring energy efficiency is difficult, and analysts tend to use simple indicators to assess it. Measurement can help analysts quantify the impact of policies such as minimum appliance standards and energy efficiency labeling (Alarenan et al., 2019).

Using a total-factor energy efficiency (TFEE) approach and taking into account important inputs such as labor, capital stock, and energy consumption, this study aims to evaluate energy efficiency in both the transportation and electricity sectors for the Gulf Cooperation Council (GCC) countries between 2000 and 2019. To the best of our knowledge, this paper fills a gap in the energy policy literature by being the first to examine TFEE for the GCC countries using the DEA–Malmquist approach to measure the energy efficiency of these sectors. This analysis will help policymakers in these countries identify the factors that need to be prioritized to enhance energy efficiency and develop effective strategies for sustainable economic development, which in turn can support environmental quality.

The remainder of the paper is organized as follows: Section 2 presents a literature review. Section 3 introduces the methodological framework of the DEA–Malmquist approach and the data. Section 4 presents the econometric results using the Malmquist index technique, along with a discussion. Finally, Section 5 summarizes the paper's conclusion and policy implications.

2. LITERATURE REVIEW

A non-parametric technique was presented by Farrell (1957) to evaluate the efficiency of decision-making units (DMUs). Later, Charnes et al. (1978) introduced the Data Envelopment Analysis (DEA) method for solving such problems under Constant Returns to Scale (CRS) when analyzing situations involving multiple inputs and multiple outputs. Banker et al. (1984) expanded DEA by developing a method to measure productivity changes of a DMU over different time periods using the Malmquist Productivity Index (MPI). Malmquist (1953) initially proposed the MPI, which Caves et al. (1982) later used to quantify changes in total-factor productivity. Additionally, Färe et al. (1992) applied DEA methods to calculate the MPI to evaluate productivity changes over time in Sweden. Their study provides a foundation for applying DEA-based Malmquist indexes in empirical research and offers a robust framework for decomposing productivity growth into two components: technological change and efficiency change.

Following this, DEA analysis was employed in several publications on environmental and energy-related topics. Førsund and Kittelsen (1998) found that technological change contributed to productivity increases in their analysis of the MPI for Norwegian electrical firms between 1983 and 1989. Hu and Wang (2006) introduced the concept of total-factor energy efficiency, evaluating energy efficiency for 29 Chinese districts from 1995 to 2002 using real GDP as the output and four inputs: capital stock, labor, energy consumption, and total sown area of farm crops.

Yang and Pollitt (2007) examined the effects of undesirable outputs using Malmquist TFP indices for panel data in China covering the period 1996–2002. Their results show that there is significant potential to improve efficiency and emissions control in Chinese power plants. Chang and Hu (2010) evaluated the total-factor energy productivity change index (TFEPI) of regions in China from 2000 to 2004, and their results reveal that China’s energy productivity was decreasing by 1.4% per year during the study period. Additionally, Liu et al. (2017) used Data Envelopment Analysis (DEA) and the Malmquist index to assess total-factor energy efficiency (TFEE) in the thermal power industry of China between 2005 and 2014. The findings of their study demonstrated that TFEE was mainly determined by the technical efficiency index (TECH) and the pure efficiency index (PECH).

Wu et al. (2019) used DEA analysis to evaluate the industrial sector's energy and environmental efficiency in China; however, they found low and imbalanced sector efficiency. Chen and Yang (2020) evaluated total-factor energy efficiency (TFEE) for China’s provinces under resource and environmental constraints. Their findings showed that TFEE decreases in a constrained environment. Additionally, under environmental restrictions, Shang et al. (2020) evaluated the total-factor energy efficiency of multiple Chinese regions between 2005 and 2016. The results showed a low level of energy efficiency. Ohene-Asare et al. (2020) evaluated TFEE for the period from 1980 to 2011 using three inputs—capital, labor, and total primary energy consumption—to produce two outputs: real GDP and emissions. They conducted this analysis using DEA for 46 African countries, and their findings demonstrated that beneficial technological advancements contributed to an increase in energy efficiency in African nations. By measuring the rise in energy productivity using the DEA-SBM (Slacks-Based Measure) and Malmquist Productivity Index approach, Tachega et al. (2021) examined energy productivity growth, energy efficiency, and the determinants of energy efficiency in 14 oil-producing nations between 2010 and 2017. The results indicate that the average energy efficiency of the 14 countries included in the study is 98%. Ji and Hoti (2021) analyzed TFEE from the perspective of low-carbon agricultural growth in the 11 cities of the Yangtze River Economic Belt using the Malmquist–Luenberger (ML) index. The empirical findings showed a substantial relationship between agricultural energy efficiency and labor-force literacy. Furthermore, between 2001 and 2020, Wang et al. (2024) employed DEA to determine total-factor energy efficiency (TFEE) for ten major energy-consuming countries (China, the United States, India, Russia, Japan, Canada, Germany, Brazil, Iran, and South Korea) at both national and sectoral levels. Their results demonstrated that energy-efficiency levels varied greatly across the ten nations; Germany and the United States ranked highest, while China and India ranked lowest in terms of TFEE.

Regarding research on the GCC, Ramanathan (2005) used Data Envelopment Analysis to examine energy consumption and carbon dioxide emissions for 17 Middle Eastern and North African nations between 1992 and 1996. The findings demonstrate efficiency differences between nations; for example, Bahrain and Oman were considered efficient, whereas Saudi Arabia, Kuwait, and the UAE were less efficient. According to Howarth et al. (2017), who assessed energy efficiency in the GCC, there is a significant correlation between these nations’ economic growth and energy usage, indicating that the GCC needs to improve its energy efficiency. Furthermore, Alarenan et al. (2019) employed frontier analysis to examine the energy efficiency of the GCC countries in two sectors—residential electricity and road-transport gasoline—between 2004 and 2014. The empirical results demonstrated an improvement in overall energy efficiency in the GCC countries. Almasri and Narayan (2021) evaluated energy efficiency and renewable energy in the GCC and recommended: (1) benefiting from energy-efficiency improvements, and (2) establishing clear and straightforward governmental mechanisms for implementing energy-efficiency measures. Additionally, Almasri and Alshitawi (2022) examined energy efficiency in residential buildings as well as indicators of electricity consumption. They found that the most effective ways to increase energy efficiency in GCC countries are improving air-conditioner efficiency and enhancing wall thermal insulation. Further research has examined energy efficiency in GCC nations individually, using various techniques. According to Alajmi (2021), there exists a long-term relationship between Saudi Arabia's electricity consumption and CO_2 emissions between 1980 and 2017. Moreover, Alajmi (2022) examined the factors affecting Saudi Arabia's GHG emissions across nine sectors, and the results demonstrated that the primary source of rising emissions is the energy effect.

Data Envelopment Analysis and Tobit regression were recently employed by Nikbakht et al. (2023) to evaluate the degree of TFEE in the Persian Gulf nations between 2000 and 2014. They found that none of these nations had perfect energy efficiency. Using the DEA–Malmquist approach, Alajmi (2024) examined the energy efficiency of the Gulf Cooperation Council countries between 2000 and 2019. According to the analysis, the technical progress index is responsible for the decline in energy efficiency in these regions.

3. METHODOLOGY FRAMEWORK

This paper evaluates TFEE using a combined DEA and Malmquist approach following Hu and Wang (2006), Liu et al. (2017), and Alajmi (2024). The Malmquist approach effectively decomposes TFEE into more specific indexes and incorporates multiple input and output variables. This methodology is applied twice in two models: the first model assesses the electricity sector in the Gulf region, and the second model evaluates its transportation sector from 2000 to 2019. These two sectors were selected because they exhibit higher emissions than other sectors, according to IEA statistics (IEA, 2021).

3.1. Research models

Data Envelopment Analysis-Malmquist Productivity Index

In this paper, Data Envelopment Analysis (DEA), introduced by Charnes et al. (1978), is used as a non-parametric method for evaluating the efficiency of decision-making units (DMUs). DEA is the most commonly used method to calculate total factor productivity (TFP) based on the Malmquist Productivity Index (MPI), where productivity or efficiency is measured as weighted output divided by weighted input. The MPI is a suitable method for measuring efficiency using panel data at two different time points, t and $t + 1$, by applying the geometric mean of an efficient frontier shift (Caves et al., 1982). Traditional partial-factor energy efficiency indexes consider only energy as a single input to produce output (GDP), while ignoring other inputs. Total-factor energy efficiency (TFEE) was developed to overcome these limitations (Vlahinić-Dizdarević & Šegota, 2012). The Malmquist total factor productivity index (TFPCH) can be decomposed into two components: technical efficiency change (EFFCH) and technological frontier shift (TECHCH) (Moirangthem & Nag, 2020). The MPI, given by the relative efficiency or ratio of two output distance functions of an entity using the same technology available at time t, is shown in Eq. (1).

$$M^t = \frac{d_i^t(x_{t+1}, y_{t+1})}{d_i^t(x_t, y_t)} \quad (1)$$

Where d stands for the distance function, x stands for the mth inputs of the nth DMU, y is the sth outputs of the nth DMU.

Similarly, MPI at time t + 1 using technology at t + 1 is given as Mt + 1 in Eq. (2)

$$M^{t+1} = \frac{d_i^{t+1}(x_{t+1}, y_{t+1})}{d_i^{t+1}(x_t, y_t)} \quad (2)$$

Then, Färe et al. (1992) suggested that the MPI for two reference points should be calculated as the geometric mean of these two indices. Thus, the functional definition of the DEA–MPI is given in Eq. (3).

$$M_{(x_{t+1}, y_{t+1}, x_t, y_t)}^{t+1} = \left[\frac{d_i^t(x_{t+1}, y_{t+1})}{d_i^t(x_t, y_t)} \times \frac{d_i^{t+1}(x_{t+1}, y_{t+1})}{d_i^{t+1}(x_t, y_t)}\right]^{\frac{1}{2}} \quad (3)$$

MPI can be factorized into technical efficiency change and technology change (Färe et al., 1994). In Eq. (4), the first term on the right side measures productivity due to technical efficiency change, and the second term measures productivity due to technology change. The geometric mean of these productivity ratios is understood as technology change or frontier shift.

$$M_{(x_{t+1}, y_{t+1}, x_t, y_t)}^{t+1} = \left[\frac{d_i^{t+1}(x_{t+1}, y_{t+1})}{d_i^t(x_t, y_t)}\right] \times \left[\frac{d_i^t(x_{t+1}, y_{t+1})}{d_i^{t+1}(x_{t+1}, y_{t+1})} \times \frac{d_i^t(x_t, y_t)}{d_i^{t+1}(x_t, y_t)}\right]^{\frac{1}{2}} \quad (4)$$

When the TFPCH value is greater than 1, energy efficiency has increased (progressed) between the two reference periods (t to t + 1). When the TFPCH value is less than 1, energy efficiency has decreased from period t to t + 1, indicating a regression in efficiency (energy-inefficient). A value equal to 1 indicates efficiency stagnation, meaning no change or effect. To sum up, if MPI values are greater than 1, this implies positive TFP growth, whereas MPI values less than 1 indicate negative TFP growth (Moirangthem & Nag, 2020). The TFEE model was constructed to assess the energy efficiency of the electricity and transport sectors in the GCC countries.

3.2 Data

Färe et al. (1996) improved the Malmquist productivity index to study environmental and energy problems. Thus, this study empirically utilizes a panel dataset of GCC countries to measure the energy efficiency of the electricity and transport sectors for the GCC countries for the period 2000–2019. In the measurement of total-factor energy efficiency, the factors selected to measure the TFEE of these two sectors in GCC countries are three input and two output factors. Thus, in our two models, three production factors (labour force, capital stock, and energy consumption in the electricity and transport sectors) produce two outputs: GDP as a desired output and total CO_2 emissions as an undesired output. The variables in this paper are labour force (million people), obtained from the World Development Indicators (World Bank, 2022); and real GDP (million 2017 US$) and capital stock (million 2017 US$), obtained from the Penn World Tables (Feenstra et al., 2015). CO_2 emissions in million tonnes (Mt) for electricity-generation emissions and transport-related emissions were obtained from the International Energy Agency (IEA, 2021). Data on electricity generation in billion kilowatt-hours (kWh) and energy consumption in the transport sector in millions of barrels per day (Mb/d) were obtained from the U.S. Energy Information Administration (EIA, 2020). Data on energy consumption in the transport sector were gathered by calculating the sum of motor gasoline, jet fuel, and kerosene.

Before presenting the results of the models, we provide an overview of the main variables in the study: energy consumption in both sectors, CO_2 emissions from these two sectors, and GDP during 2000–2019. Table 1 displays a summary of the growth rates for key variables in our model. The electricity-generation data for GCC countries, presented in Fig. 1, generally show a continuously rising trend in energy consumption in this sector during the study period. The volume of electricity generation varies across countries according to economic size and population, but the overall trend is increasing.

Fig. 1 also illustrates these countries' dependence on fossil fuels as the main energy source for electricity generation, which increased on average from 36.43 billion kWh in 2000 to 112.67 billion kWh in 2019.

For energy consumption in the transportation sector (Fig. 2), the same rising pattern is observed over the period 2000–2019, increasing on average from 86.15 Mb/d in 2000 to 231.27 Mb/d in 2019. This reflects the tendency of people in these countries to rely on private cars within cities rather than public transportation. In this sector, the highest energy consumption is observed in Saudi Arabia, followed by the United Arab Emirates and then Qatar, while Bahrain has the lowest consumption. As noted earlier, this is influenced by the size of each country's economy and population.

Table 1. A summary of the average growth rates for key variables of the study from 2000-2019 (%)

GCC countries	Real GDP	electricity generation	Energy consumption of the transport sector	CO_2 emissions electricity generation	CO_2 emissions from transport sector
Saudi Arabia	3.5	234.05	475.9	169.83	105.2
Qatar	9.1	26.25	59.015	202.83	8.1
Kuwait	3.6	51.25	73.37	158.995	11.1
Oman	3.3	20.125	52.005	170.04	7.9
UAE	4.3	84.6	226.55	193.63	28.1
Bahrain	4.5	21.45	25.865	151.485	2.95

Source: World Bank, IEA and EIA

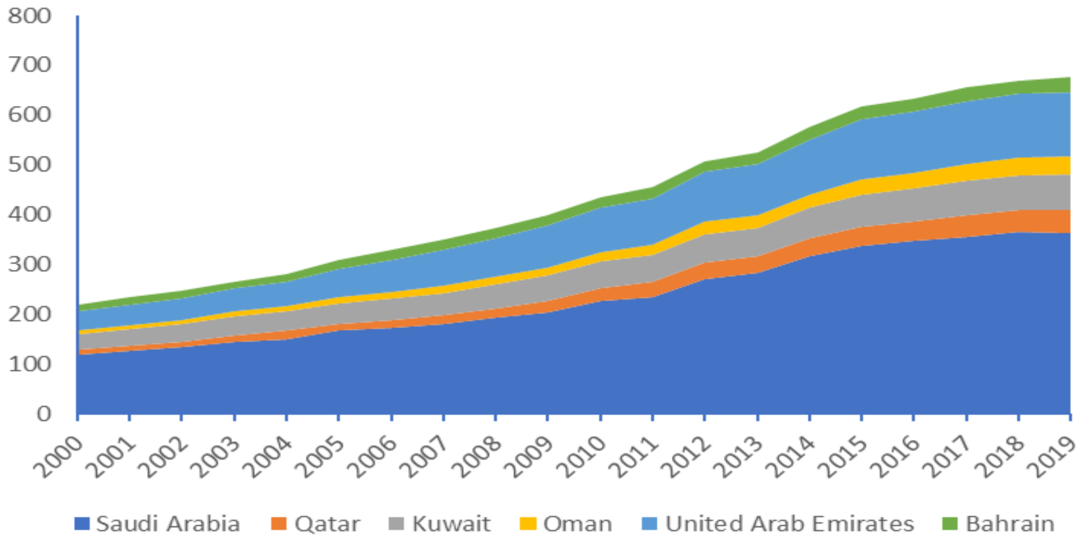
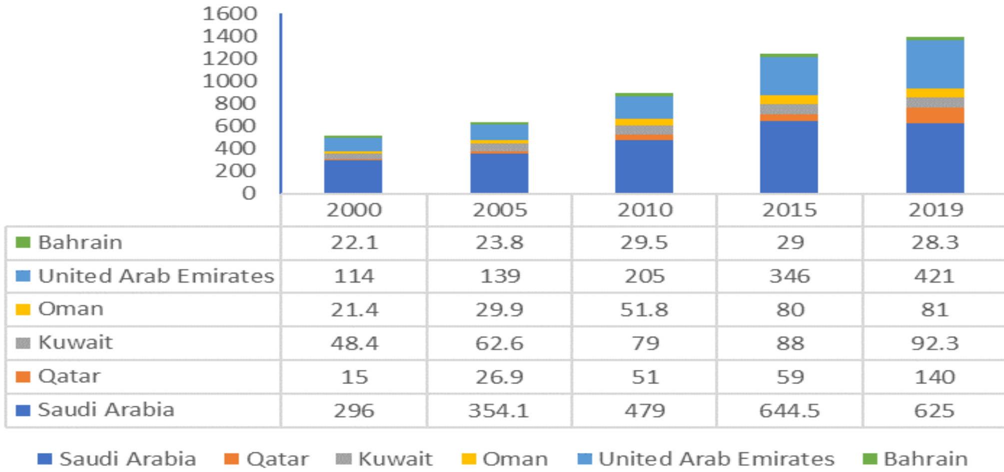


Fig.1. The GCC countries' electricity generation by billion kWh (2000-2019)

Source: Energy Information Administration U.S.



	2000	2005	2010	2015	2019
Bahrain	22.1	23.8	29.5	29	28.3
United Arab Emirates	114	139	205	346	421
Oman	21.4	29.9	51.8	80	81
Kuwait	48.4	62.6	79	88	92.3
Qatar	15	26.9	51	59	140
Saudi Arabia	296	354.1	479	644.5	625

Fig.2. The GCC countries' energy consumption in the transport sector by Mb/d (2000-2019)

Source: Energy Information Administration U.S.

GDP continuously rises during the period from 2000 to 2019 in all GCC countries, reflecting that GDP still relies on oil revenues despite the increasing contribution of non-oil sectors. Fig. 3 shows the total CO_2 emissions of the GCC region caused by electricity generation and energy consumption in the transport sector. CO_2 emissions from electricity generation increased on average from 100 Mt in 2000 to 233.88 Mt in 2019. CO_2 emissions from energy consumption in the transport sector increased on average from 14.83 Mt in 2000 to 36 Mt in 2019. This increase reflects the overall rise in energy consumption in these countries over the sample period. In other words, increasing energy consumption produces more CO_2 emissions, which in turn adversely affects environmental quality. It appears that oil, as the dominant energy source in GCC countries, continues to shape their economies and is likely to remain dominant for a long period. Additionally, increasing population size raises energy demand, which places further pressure on environmental quality.

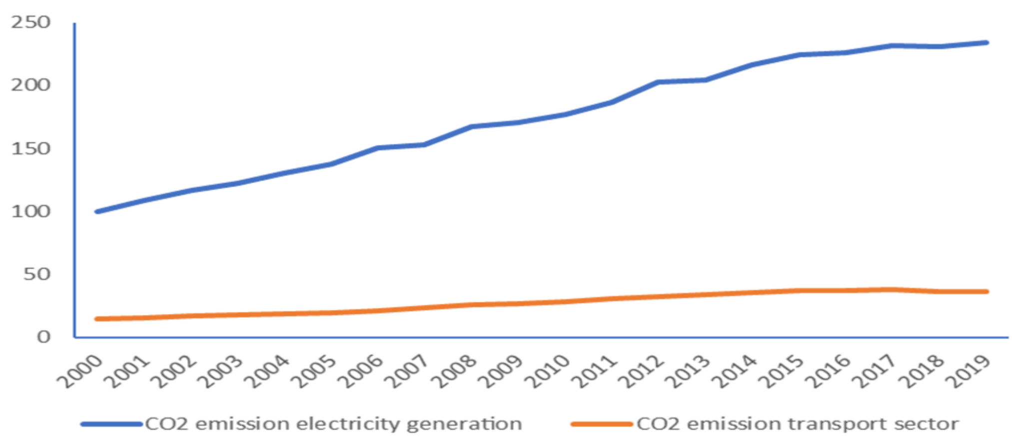


Fig.3. The GCC countries' total CO_2 emissions from electricity generation and transportation sector by Mt (2000-2019)

Source: International Energy Agency

4. EMPIRICAL RESULTS AND DISCUSSION

This study assesses the level of TFEE in GCC countries using two models with two outputs: CO_2 emissions as an undesired output and GDP as a desired output—both oriented by output factors using DEAP software for solving the equations of the DEA models. The factors were incorporated into the CCR and Malmquist index–based DEA model, generating the Malmquist index (TFPCH), technical efficiency change (EFFCH), and technological frontier shift (TECHCH) for the electricity and transport sectors in the GCC countries. The EFFCH, TECHCH, and TFPCH based on the MPI for the electricity and transport sectors in the GCC region are presented in Table 2 and Table 3, respectively, and the average TFEE for both sectors is illustrated in Fig. 4.

Table 2. The GCC countries' TFEEs of electricity generation from 2000-2019

GCC countries	EFFCH	TECHCH	TFPCH
Saudi Arabia	1.001	0.962	0.963
Qatar	1.000	0.962	0.962
Kuwait	1.019	0.953	0.971
Oman	0.998	0.945	0.944
United Arab Emirates	0.987	0.983	0.970
Bahrain	1.000	0.958	0.958
Average	1.001	0.960	0.961

It appears from Table 2 that, over the duration of the study, GCC countries experienced a decline in productivity growth in electricity generation, as indicated by the TFEE value (0.961), which reflects a 3.9% decrease. The main observation from the results is that this decline is driven in part by technological change (TECHCH) over the 20-year period, as shown by the TECHCH value of less than 1 (0.960), representing a 4% reduction. In contrast, technical efficiency change (EFFCH) increased slightly by 0.1%. In other words, the decrease in productivity among GCC countries is largely attributable to the low level of energy-technology innovation. More specifically, EFFCH for Kuwait and Saudi Arabia was greater than 1 on average; for Qatar and Bahrain, EFFCH was stagnant; and for the United Arab Emirates and Oman, it was less than 1. The results of the MPI for energy efficiency in electricity generation for the GCC region indicate a decline in productivity growth (TFPCH), driven primarily by technological change (TECHCH), meaning that energy efficiency shows a relative decline in the electricity sector.

Table 3. The GCC countries' TFEEs in the transportation sector from 2000-2019

GCC countries	EFFCH	TECHCH	TFPCH
Saudi Arabia	1.000	0.985	0.985
Qatar	1.000	0.971	0.971
Kuwait	1.013	0.960	0.973
Oman	0.988	0.955	0.944
United Arab Emirates	0.987	0.988	0.975

GCC countries	EFFCH	TECHCH	TFPCH
Bahrain	1.008	0.972	0.980
Average	0.999	0.972	0.971

Table 3 illustrates that GCC countries experienced a decline in productivity growth in the transport sector during the study period 2000–2019, as shown by the TFEE value (0.971), which indicates a 2.9% decrease. The major observation in the results is that this decline is partly driven by technological change (TECHCH), which regressed to below 1 (0.972), representing a 2.8% reduction, along with a 0.1% decrease in technical efficiency change (EFFCH) (0.999) over the 20 years. In other words, the low level of energy technology innovation contributed substantially to the decreasing productivity of GCC countries. At the country level, EFFCH for Kuwait, Bahrain, and Saudi Arabia exceeded 1 on average; for Qatar and Saudi Arabia, EFFCH was stagnant; while for the United Arab Emirates and Oman, it was below 1.

The results of the MPI for energy efficiency in the transport sector for the GCC region also showed a decline in productivity growth (TFPCH), with the decrease driven by both technological change (TECHCH) and technical efficiency change (EFFCH). Energy efficiency shows a relative decline in development in the transport sector. The findings are consistent with previous research such as Liu et al. (2017), Chen and Yang (2020), Wu et al. (2019), Nikbakht et al. (2023), and Alajmi (2024). By contrast, some studies found that energy efficiency in the GCC region improved, such as Alarenan et al. (2019).

From Fig. 4, average TFEE levels fluctuated over the study period for both sectors. In most years, the energy efficiency value of the transport sector was higher than that of electricity generation. Overall, despite all input and output variables increasing over the sample period, these input levels were not efficiently transformed into outputs.

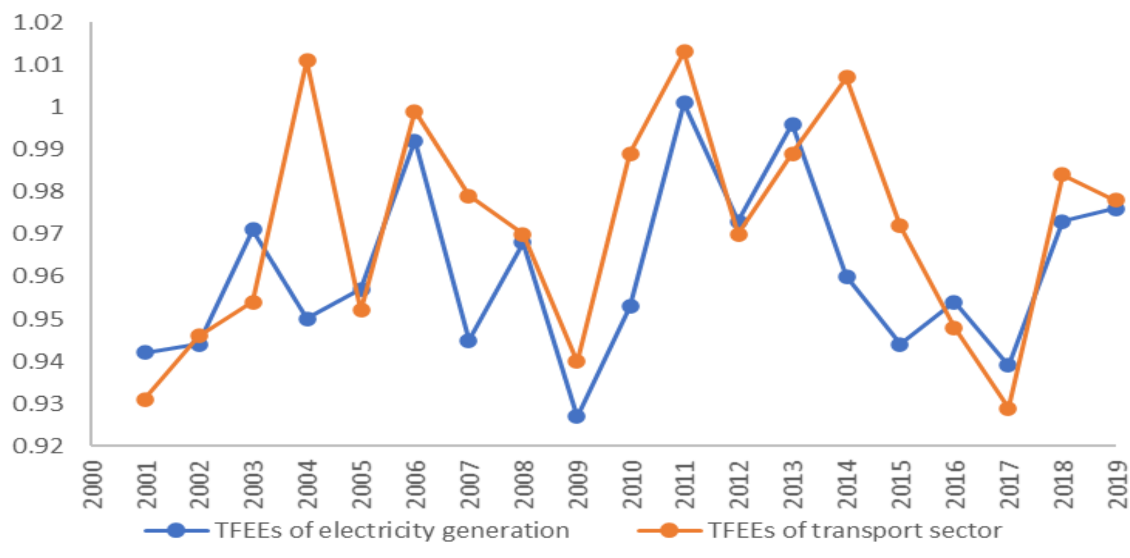


Fig. 4. Presentation of TFEE means for electricity generation and transportation sectors of GCC countries from 2000 to 2019

Estimations for annual TFEEs of the electricity and transport sectors for GCC countries over the sample period are presented in Table 4 and Table 5, respectively. From Table 4, over the 20-year period, the average energy efficiency in the GCC region is less than 1 (0.963), indicating that economic growth in these countries still depends on fossil fuels. The TFPCH of electricity generation for Saudi Arabia and Qatar exceeded 1 in three years, driven by the mutual influence of technical efficiency change (EFFCH) during 2000–2019. Bahrain's productivity exceeded 1 in four years. Kuwait's TFPCH was greater than 1 for seven years, whereas in Oman, TFPCH exceeded 1 for only one year. TFPCH for the United Arab Emirates exceeded 1 for eight years. Overall, based on the MPI analysis, the increase in TFEE in GCC countries was mainly determined by technological change (TECHCH).

Table 4. TFEEs of electricity generation yearly by country (2000–2019)

GCC countries	Saudi Arabia	Qatar	Kuwait	Oman	United Arab Emirates	Bahrain	Average
Year							
2000-2001	0.946	0.924	0.966	0.960	0.939	0.917	0.942
2001-2002	0.932	0.939	1.006	0.919	0.953	0.920	0.945
2002-2003	1.038	0.883	1.139	0.902	1.018	0.877	0.976
2003-2004	1.026	0.888	1.039	0.920	1.010	0.837	0.953
2004-2005	0.974	0.974	1.022	0.836	0.914	1.035	0.959
2005-2006	0.962	1.017	1.001	0.966	0.994	1.015	0.993
2006-2007	0.928	0.957	1.013	0.978	0.878	0.922	0.946
2007-2008	0.945	0.981	0.981	0.923	0.992	0.988	0.968
2008-2009	0.875	0.947	0.927	0.971	0.879	0.968	0.928
2009-2010	0.922	0.984	0.947	0.943	0.959	0.962	0.953
2010-2011	0.999	1.009	1.038	0.958	1.012	0.992	1.001
2011-2012	0.964	0.956	0.996	1.004	1.019	0.902	0.974
2012-2013	0.965	0.994	0.932	0.951	1.052	1.089	0.997
2013-2014	1.005	1.013	0.897	0.996	0.864	0.998	0.962
2014-2015	0.945	0.976	0.896	0.914	0.963	0.972	0.944
2015-2016	0.951	0.943	0.941	0.934	1.014	0.946	0.955
2016-2017	0.967	0.972	0.819	0.984	0.983	0.919	0.941
2017-2018	0.992	0.968	0.963	0.963	1.004	0.952	0.974
2018-2019	0.968	0.969	0.965	0.925	1.006	1.030	0.977
Average	0.963	0.963	0.973	0.945	0.971	0.960	0.963

Table 5 illustrates that over the 20 years from 2000 to 2019, the average energy efficiency of the GCC region was 0.974, implying that the economic growth of the GCC region relies on energy consumption. The TFPCH of energy consumption in the transport sector for Saudi Arabia exceeded 1 in six years and for Qatar in seven years, driven by a regression in technical efficiency change (EFFCH) and technological change (TECHCH) during 2000–2019. Bahrain's productivity exceeded 1 in four years, while Kuwait and the United Arab Emirates exceeded 1 for six years; however, Oman's TFPCH exceeded 1 for only four years. TFPCH for Bahrain reached more than 1 for eight years. Specifically, based on the above analysis, the increase in TFEE in the transportation sector in GCC countries was mainly determined by technological change (TECHCH) and technical efficiency change (EFFCH).

Table 5. TFEEs in the transportation sector yearly by country (2000–2019)

GCC countries	**Saudi Arabia**	**Qatar**	**Kuwait**	**Oman**	**United Arab Emirates**	**Bahrain**	**Average**
Year							
2000-2001	1.001	0.944	0.978	0.882	0.960	0.832	0.933
2001-2002	0.984	0.907	1.005	0.879	1.022	0.886	0.947
2002-2003	1.024	0.872	1.058	0.836	1.006	0.946	0.957
2003-2004	1.006	1.132	1.055	0.995	0.949	0.938	1.013
2004-2005	0.996	0.943	1.026	0.860	0.946	0.950	0.954
2005-2006	0.981	1.021	1.014	0.905	0.970	1.114	1.001
2006-2007	0.993	1.037	1.015	0.969	0.929	0.934	0.980
2007-2008	0.983	0.936	0.986	0.958	0.966	0.993	0.970
2008-2009	0.945	0.963	0.948	0.954	0.913	0.916	0.940
2009-2010	0.955	1.042	0.984	0.949	0.993	1.015	0.990
2010-2011	1.019	0.998	0.986	1.031	1.003	1.040	1.013
2011-2012	1.011	0.882	0.994	1.060	0.965	0.920	0.972
2012-2013	0.961	1.008	0.937	1.001	0.905	1.141	0.992
2013-2014	1.023	1.090	0.897	1.055	0.966	1.025	1.009
2014-2015	0.973	1.079	0.910	0.865	1.000	1.023	0.975
2015-2016	0.953	0.875	0.938	0.893	1.090	1.002	0.959
2016-2017	0.954	0.811	0.825	0.989	1.030	0.986	0.933
2017-2018	0.982	1.096	0.981	0.950	0.999	0.909	0.986
2018-2019	0.977	0.893	0.977	0.945	0.982	1.108	0.980
Average	0.985	0.975	0.974	0.946	0.979	0.983	0.974

To sum up, the TFEE of the electricity generation and transport sector models shows regression (energy-inefficiency) at the average level over the sample period, indicating that the GCC countries' current economic growth is still dominated by energy consumption from fossil fuels. Therefore, in the GCC region, there is a need to develop environmental assessment systems, technical standards, and clean-development plans for energy consumption in these two sectors. Moreover, it is important for environmental protection to employ high-quality, energy-saving equipment (Liu et al., 2017).

TFEE in GCC countries may have been influenced by the economic recession, which caused energy demand to shrink as oil prices collapsed in late 2008 and again from 2014 onward, coinciding with global economic crises. The decreasing TFEE during the period could also be attributed to limited attention given to energy issues at the time. These results imply that GCC countries need greater investment in technology, environmental policy reforms, and regulatory changes to improve energy efficiency. Furthermore, GCC countries have historically provided domestic consumers with energy at low administered prices due to abundant fossil fuels, which led to increased energy consumption levels and reduced energy-efficiency performance (Alarenan et al., 2019). However, a critical step in mitigating CO_2 emissions and protecting the environment in these countries is improving energy efficiency, especially in energy-intensive sectors such as transportation and electricity.

5. CONCLUSION AND POLICY IMPLICATIONS

The TFEE analysis from 2000 to 2019 using the DEA–Malmquist index formed the basis for this empirical study of energy efficiency in two sectors of the GCC countries. Three production factors (labour force, capital stock, and energy consumption) produce a desired output (GDP) and an undesired output (CO_2 emissions) in both models. The MPI results for the electricity model show that the TFEE of electricity generation in the GCC region regressed to a value of 0.961, representing a 3.9% decrease. The main reason for this decline was the technological change (TECHCH) value below 1 (0.960), reflecting a 4% reduction, while technical efficiency change (EFFCH) was slightly above 1, representing an increase of 0.1%. The MPI results for the transport model show that the TFEE of energy consumption in the transport sector also regressed, reaching a value of 0.971—a 2.9% decrease—driven by both technological change (TECHCH) and technical efficiency change (EFFCH). The TECHCH value below 1 (0.972) indicates a 2.8% decrease, while EFFCH fell by 0.1% (0.999) over the 20-year period. Therefore, the GCC region must implement effective strategies to enhance energy efficiency in both sectors.

Long-term efforts by the GCC to improve energy efficiency and strengthen national environmental policies will contribute to mitigating emissions growth in the region. However, the study's findings indicate that GCC countries need to adopt several policy measures: (1) since empirical results show declining energy efficiency in the transportation and electricity sectors, improving energy efficiency should be a top priority for reducing emissions; (2) technology that enhances energy efficiency should be promoted by investing in advanced R&D and boosting technological innovation in the energy sector; (3) the use of high-quality, energy-saving, and environmentally protective equipment and devices should be prioritized; (4) the rising GDP trend from 2000 to 2019 is driven largely by the oil sector, indicating that the GCC region is highly dependent on oil production—thus, accelerating national strategies to diversify the income base is essential, especially given the strong relationship between GDP and domestic energy consumption in these countries (Howarth et al., 2017); (5) transitioning to a green economy can promote sustainable economic growth by raising environmental standards and energy efficiency; (6) human capital development and foreign investment significantly improve energy efficiency by enhancing technological innovation (Yao et al., 2021); and (7) energy efficiency is strongly influenced by changes in industrial structure, foreign direct investment, GDP per capita, and the structure of energy consumption (Wang et al., 2024), making these areas important targets for policy action.

At present, only a limited number of energy-efficiency policies have been implemented in the GCC countries, but policymakers have been exploring a range of potential measures—for example, thermal insulation regulations, energy-efficiency labelling, and minimum energy-efficiency standards (Alarenan et al., 2019). Consequently, there is considerable potential for improving energy efficiency across these six countries in the future. In sum, further environmental improvements can be strategically planned and implemented based on the findings of this research.

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