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Interfuel Substitution in the Industrial Sector in Saudi Arabia

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Abstract

The Kingdom of Saudi Arabia has taken many decisive steps toward a more sustainable future, in line with its Vision 2030, including the use of clean energy, offsetting of emissions, and protection of the environment. In this context, Saudi Arabia has set an ambitious target to reduce its carbon emissions by 278 mtpa by 2030. The objective of this study is to investigate the possibility of interfuel substitution in Saudi Arabia's industrial sector and to identify the role of substituting fossil fuel with carbon-neutral fuel, such as electricity, in meeting the CO_2 emissions target. A ridge regression method is used to estimate the parameters of the translog production function for the period 1990–2020. The results reveal that output elasticities for natural gas, electricity, and oil are increasing over the estimated period, reflecting continued technological progress and energy efficiency in the industrial sector in Saudi Arabia. Moreover, the results show that all energy inputs are substitutes and that the estimated elasticities of substitution are constant over time. These results highlight the potential of Saudi Arabia's industrial sector in switching from GHG-emitting fuels such as oil to cleaner energy sources without compromising production. However, the potential for electrification is not the same in all industries. Fossil fuels could be replaced with clean energy sources in industries that depend on low- and medium-temperature heat.

Therefore, these results highlight the importance of renewable energy policies. Electrification reduces the degrees of industrial greenhouse gas emissions and domestic oil consumption in the industrial sector in Saudi Arabia only if sufficient renewable generation capacity is added to meet the industry's electricity demand. In addition, models for predicting future energy demand in the industrial sector can use the elasticities of substitution between the fuels identified in this study to become more reliable.

Keywords: Industry value added; Interfuel substitution, Ridge regression; Autometrics

1. Introduction

Based on a variety of export-oriented industries, including the oil and gas industries, the Kingdom of Saudi Arabia has the largest industrial sector in the Middle East/North Africa (MENA) region. Since the launch of Vision 2030, the government of Saudi Arabia has successfully implemented tremendous initiatives and structural reforms, including those providing financial and administrative support to the industrial sector for economic transformation. These initiatives and reforms include well-developed infrastructure, high-quality utilities, a well-developed logistics network, the strengthening of local content, and the establishment of the Saudi Industrial Development Fund (SIDF), which promotes industrialization. Another important initiative has been the National Industrial Development and Logistics Program (NIDLP), which the Saudi Arabian government launched in 2019 to achieve the goal of economic diversification toward sustainable growth by promoting a globally attractive investment environment in the country.

The industrial sector is the largest sector in the Saudi Arabian economy and has played a crucial role not only in strengthening economic growth but also in creating jobs in the country. Saudi Arabia's industrial sector has experienced rapid growth over the past five decades. Industrial value added in Saudi Arabia increased sharply between 1970 and 2021. In 2021, industrial value added (at constant 2015US$) was US$278 billion, 3.5 times the level in the 1970s, and the corresponding growth rates were 5% during the same periods (WDI 2022). However, a fluctuation was observed in the share of the industrial sector in total GDP. The average share of industrial value added in GDP was 68% in the 1970s and decreased to 53.3% in 2019 (WDI 2022)[1].

Total energy consumption in Saudi Arabia's industrial sector grew rapidly at an annual rate of 8.3% from 1990–2019. Natural gas and heavy fuel oil (HFO) are the main fuels consumed by Saudi Arabia's industrial sector. Between 1990 and 2019, the average annual growth rate for natural gas was 10.5%, while those for HFO and electricity were 6.8% and 14.2%, respectively. Based on the economic diversification strategy proposed in Vision 2030, it is likely that Saudi Arabia's industrial sector will continue to grow rapidly for a long time and that energy demand in the industrial sector will also increase to support industrial sector growth. Therefore, as a large energy-consuming sector, the industrial sector has a much stronger incentive to switch to alternative fuels than do other sectors.

An examination of substitution among different energy sources in Saudi Arabia's industrial sector is important for at least two reasons: first, because of the opportunity cost of domestic oil consumption in the industrial sector and, second, from an environmental protection perspective. The reason for this is that the consumption of different types of energy is associated with different emission levels. Substitution between fuels is an important research topic, as governments worldwide seek to implement policies to reduce carbon emissions from certain types of fuels. Due to its unique geographic and climatic location, Saudi Arabia has large potential for solar and wind energy, making the use of renewable energy sources economically attractive in the country. As a result, Saudi Arabia has initiated several projects to diversify its energy resources and improve its energy mix. The Saudi government launched the National Renewable Energy Program (NREP) under Vision 2030, with the goal of maximizing its renewable energy potential. Through the NREP, the Saudi government intends to generate 50% of its electricity from renewable sources by 2030, with the remainder being generated from natural gas. Renewable energy is a crucial component of the country's low-emissions development strategy and addressing of climate change issues and emission reduction targets. Therefore, investigating the possibility of substituting electricity for oil and gas in Saudi Arabia's industrial sector is a worthwhile research topic. Reducing the dependence on oil in the industrial sector in favor of electricity generated through renewable sources has important implications for economic growth, oil exports, and the environment in Saudi Arabia.

2. Literature Review

Increasing concerns regarding climate change have led economists to explore various ways in which the industry can meet stringent carbon emissions standards. Substitution among different fuels is seen as promising because industries that consume large amounts of energy are thought to have more incentive than are commercial or residential consumers to switch to other forms of energy when relative fuel prices change (Steinbuks 2012). For this reason, the elasticities of substitution between different fuels have become the focus of energy economists and policymakers. It is argued that understanding substitution between fuels is not only important for outlining the impacts of scarce energy inputs but also critical for evaluating sustainability options. The literature on energy demand dates back to the 20th century, beginning with the work of Houthakker (1951). In addition, researchers from around the world have conducted several studies in the field of energy economics over the past 50 years to determine substitutability among factors and fuels and have provided fairly extensive empirical evidence. Many authors have studied the interfactor elasticity of substitution between factors such as energy, capital, and labor. Earlier studies include those by Griffin and Gregory (1976) and Pindyck (1979), showing a positive elasticity of substitution between capital and energy using a translog cost function, with their estimates being close to each other. Griffin and Gregory (1976) used time-series manufacturing data for the period 1947–71, while Pindyck (1979) used industrial sector data for developed economies. Moreover, Pindyck (1979) estimated that a doubling of energy prices could lead to an increase in world capital demand of approximately 2% to 8% in the long run. In contrast, for time-series data, there is also evidence of complementarity between capital and energy (Fuss 1977; Prywes 1986). Lin and Xie (2014) used translog cost and production functions to investigate how energy, capital, and labor could be substituted in the Chinese transportation sector. According to the results of the above study, high elasticities of substitution between capital and energy and between labor and energy in the Chinese transportation sector exist. Similarly, Smyth et al. (2012) used log-linear translog production and cost functions to study interfuel substitution among natural gas, electricity, oil, and coal in China's steel and iron industries and found that there are more opportunities to switch between coal and natural gas and between coal and electricity than there are between coal and oil.

Another significant result of substitution among fuels in the transportation sector was derived by Xie and Hawkes (2015) using log-linear translog production and cost functions. While their estimates demonstrate the degree of substitutability of all energy inputs, the higher degree of substitutability of oil and natural gas is reported compared to other energy input combinations. In addition, some studies have used a normalized quadratic (NQ) cost function to estimate the elasticities of substitution between different fuels. For example, Serletis et al. (2009) used the NQ cost function and found that high-income economies have greater potential for substitution between fuels in the industrial and transportation sectors compared to middle- and low-income economies. Similarly, Serletis et al. (2010) used the NQ cost function to examine the likelihood of interfuel substitution and energy demand in different sectors (residential, commercial, industrial, and electricity generation) in the United States. Serletis et al. (2011) also examined short- and long-run interfuel substitution for Organisation for Economic Co-operation and Development (OECD) and non-OECD countries using the NQ cost function. In general, the elasticities of interfuel substitution are found to be much larger in the long run than in the short run.

In contrast, Jadidzadeh and Serletis (2016) used the locally flexible normalized (NQ) expenditure function for Canada's residential sector and the NQ cost function to study energy demand in the industrial and commercial sectors, respectively. The above authors estimated a positive and significant degree of sectoral interfuel substitution. According to their results, a limited degree of substitution exists between natural gas and electricity, but in most cases, a significant degree of substitution exists between light fuel oil and both electricity and natural gas. Using the NQ model, Hossain and Serletis (2017) examined the substitution of biofuels in the transportation sector in the United States for the period 1990–2017 and found a significant but limited degree of substitution between biofuel natural gas and biofuel oil. Moreover, Shankar and Pachauri (1987) not only estimated the degree of substitution between factors and fuels but also examined the potential for substitution between fuels in terms of industrial energy demand in India. In the above study, coal and oil were found to be maximally substitutable in many industries, especially in the steel and iron industries, and in general, fuel parameters were low, indicating a low degree of substitution or complementarity potential between fuels. Coal and electricity were also found to be substitutable, but to a lesser extent. Smyth et al. (2011) also examined the potential for substitution between factors and fuels in China's steel sector. Using the translog production function in conjunction with a ridge regression approach, the above authors found that capital and energy and labor and energy are substitutable. Energy and labor have lower substitutability potential than do energy and capital. In addition, there appears to be strong evidence that coal is a substitute for other fuels at the national level but is consistently a mild-to-strong substitute for electricity. However, the results show that the values of the elasticities of substitution for other fuels, such as natural gas, petroleum, and electricity, are generally less than one, highlighting the limited possibility of substituting one form of energy for another form. Wesseh et al. (2013) used a translog cost and production function technique to investigate the possibility of substitution between fuels and factors such as labor, capital, electricity, and petroleum in Liberia. Due to possible multicollinearity in the data, the ridge regression approach is used to estimate the model parameters. The above authors showed that in Liberia's industrial production, electricity can be substituted for petroleum. Since there are more incentives to invest in labor than in capital, the possibility of substitution between labor and energy was shown to be relatively higher than that between energy and capital. Similarly, Adeyemo et al. (2007) estimated the substitution possibilities between factor inputs and fuels (such as gas, coal, and electricity) caused by changes in the relative prices of inputs and fuels for the Nigerian economy. The translog cost function was estimated for nine major industries over the period 1970–2001, with the results showing that oil and coal and oil and gas are substitutes rather than complements in most industries.

In addition, Ma et al. (2009) used the translog cost function to simulate energy demand and evaluate the effects of factor demand, technological change, and substitutability between components and fuels in China. The results indicate that there are an enormous number of opportunities to substitute energy for labor, with only three regions identifying the possibility of substituting energy for capital. There is a lower elasticity of substitution between energy and labor than there is between energy and capital. The "budget effect" and the introduction of energy-intensive technologies appear to be the main factors behind the variation in the degrees of energy intensity. Khalid et al. (2021) estimated interfactor and interfuel substitution for Pakistan, assuming a log-linear transcendental logarithmic production function and using data from 1980–2017. The results clearly show that capital and labor are positively and significantly associated with petroleum, but each energy and nonenergy input is found to be substitutable. Starting with the seminal work of Pindyck (1979), many studies have attempted to quantify the elasticities of substitution between fuels. However, there is little consensus on the values of these elasticities of substitution. A review of the literature suggests that estimates of elasticities of substitution from time-series data are generally smaller, estimates from panel data are in the middle range, and cross-sectional estimates are largest (Stern 2012). Therefore, it can be argued that the elasticities of substitution between fuels depend on the type of data (i.e., time-series, panel, or cross-sectional data), the estimation technique, and the choice of variables and country. Nonetheless, Stern (2012) asserted that there is a need for less biased and more precise long-run estimates of elasticities of substitution. Despite the importance of interfuel substitution, Saudi Arabia has received little or no attention in the empirical literature. Therefore, this study attempts to fill this gap in the literature and provides reliable estimates of interfuel substitution elasticities for clean energy policy in Saudi Arabia.

3. Methodology and Data

Elasticities of substitution have been determined using various empirical methods. However, among these empirical methods, the translog production function is the most attractive method for estimating the elasticity of substitution in the energy industry because it is flexible and easy to use. To estimate the demand elasticities of energy inputs, the translog production function has generally been used in the energy economics literature (e.g., Khalid et al. 2021; Lin and Wesseh 2013; Smyth et al. 2012; Xie and Hawkes 2015).

This study is based on a log-linear translog production function, i.e., a second-order Taylor series approximation, to investigate the degree of substitution among electricity, oil, and gas in the industrial sector in Saudi Arabia between 1990 and 2019. The general form of the translog production function that defines the relationship between inputs and outputs is as follows:

$$lnY_t = \alpha_0 + \sum_i \alpha_i lnZ_i + \frac{1}{2}\sum_i \sum_J \alpha_{ij} Z_i Z_j \quad (1)$$

where ln represents the natural log, Y denotes value added in the industrial sector, α_0 is the intercept, and Z_i and Z_j are inputs i and j, respectively. Furthermore, α_i and α_{ij} are the parameters that can be determined by technology. The important notion is that the translog production function, which relates industrial value added to energy inputs (electricity, oil, and natural gas), labor, and capital, is twice differentiable.

The translog function form does not necessarily require assumptions such as perfect substitution or perfect competition among production factors (Pavelescu 2011). The quadratic terms in the translog functional form deal with the nonlinear relationships between output and production factors. The aforementioned properties imply that the translog production function is relatively flexible and therefore more convenient for researchers. However, the problem of multicollinearity between variables on the right-hand side of the equation may arise because the translog form contains cross-products of various input variables and the squared terms of the independent variables.

The twice-differentiable translog production function can be written as follows:

$$\begin{aligned} \ln Y_t = {} & \mu + \alpha_k lnK_t + \alpha_l lnL_t + \alpha_g lnG_t + \alpha_e lnE_t + \alpha_o lnO_t + \\ & + \alpha_{ge} lnG_t lnE_t + \alpha_{g0} lnG_t lnO_t + \alpha_{e0} lnE_t lnO_t \\ & + \alpha_{gg}(lnG_t)^2 + \alpha_{ee}(lnE_t)^2 + \alpha_{oo}(lnO_t)^2 \end{aligned} \quad (2)$$

where Y denotes the industrial output and K_t and L_t are the capital and labor used in the production process, respectively. Furthermore, G_t, E_t, and O_t are the natural gas, electricity, and oil used in the production process, respectively.

The linearly homogeneous production function that is described by the strictly positive marginal productivities of all production factors can be expressed as presented below. The output elasticity of the ith input from equation (2) can be obtained as follows:

$$\varepsilon_{it} \frac{\partial Y}{\partial Z_i}\frac{Z_i}{Y} = \frac{\partial lnY}{\partial lnZ_i} = \alpha_i + \sum_i \alpha_{ij} \ln Z_j \quad (3)$$

Thus, the elasticity of substitution between two energy inputs I and j can be calculated as follows:

$$\sigma_{ij} = \frac{\%\Delta\left(Z_{it}/Z_{jt}\right)}{\%\Delta\left(P_{jt}/P_{it}\right)} \quad (4)$$

where Z_i and Z_j are inputs i and j, respectively, P_i and P_j are the prices of the inputs, and t is the time subscript. The output elasticities and elasticities of substitution are expected to vary across the sample period because they are functions of the level of energy consumption per period. For simplicity, we remove subscript t from the elasticity of substitution formula. According to marginal productivity theory, the prices of production factors will be equal to their degrees of marginal productivity.

$$\sigma_{ij} = \frac{\%\Delta\left(Z_i / Z_j\right)}{\%\Delta\left(MP_j / MP_i\right)} = \left(\frac{d\frac{Z_i}{Z_j}}{d\frac{MP_j}{MP_i}}\right)\left(\frac{\frac{MP_j}{MP_i}}{\frac{Z_i}{Z_j}}\right) \quad (5)$$

From Equation (5), we derive the final formula for the elasticity of substitution between energy inputs i and j as follows:

$$\sigma_{ij} = \left[1 + \frac{-\alpha_{ij} + \left(\varepsilon_i / \varepsilon_j\right)\alpha_{jj}}{-\varepsilon_i + \varepsilon_j}\right]^{-1} \quad (6)$$

The detailed and full derivation of the elasticity of substitution formula is provided in Appendix A.

Ridge Regression

The translog form of Equation (2) contains the squared terms of the independent variables and the cross-products of numerous input variables, which could lead to a problem of multicollinearity between the variables on the right-hand side of the equation. The consequences of multicollinearity in the regression mode include incorrect estimates of the regression coefficients, inflated standard errors of the regression coefficients, deflationary partial t tests for the regression coefficients, nonsignificant p values, and reduced model predictability (Jim 2017; Kennedy 2003*)*. To address the multicollinearity problem, Hoerl and Kennard (1970) suggested that the potential instability of the ordinary least squares (OLS) estimator,

$$\hat{\beta}_{OLS} = (X'X)^{-1} X'Y, \quad (7)$$

could be ameliorated by adding a small constant value, λ, to the diagonal entries of matrix $X'X$ before taking its inverse. The result is the following ridge regression estimators:

$$\hat{\beta}_{ridge} = (X'X + \lambda I_p)^{-1} X'Y \quad (8)$$

Parameters βs are subject to a specific kind of constraint in ridge regression. βs are chosen in the ridge regression to reduce the penalized sum of squares as follows:

$$\sum_{i=1}^{n}\left(y_i - \sum_{j=1}^{p} x_{ij}\beta_{j)}\right)^2 + \lambda\sum_{j=1}^{p}\beta_j^2 \quad (9)$$

The ridge regression places the constraint on βs in the parameters of the linear model. Therefore, in the regression model, instead of minimizing the residual sum of squares, we also have a penalty term on βs . This penalty term is λ times the squared term of vector β. This finding implies that the optimization function is penalized if β_j takes a large value. To ensure that the ridge regression estimates are accurate approximations of the true population values, bias is included in the ridge regression model. The issue of multicollinearity in linear regression, which frequently arises in models with many parameters, can be solved via ridge regression estimation. In return for a tolerable degree of bias, the approach generally increases the efficiency of parameter estimation problems (see, for example, Gruber 2017; Hilt and Seegrist 1977; Kennedy 2003). The main advantage of ridge regression is that it solves the problem of multicollinearity by adding a small value to the diagonal of the quantity expressed as a correlation. In this scenario, the ridge estimator outperforms the OLS estimator in terms of stability and variance (Lin and Wesseh 2013).

Therefore, the elasticities of output and elasticities of substitution among electricity, oil, and natural gas fuels are calculated using the ridge estimation method for the industrial sector in Saudi Arabia for the period 1990–2020.

4. Data

Gross value added (GVA) in the manufacturing sector

Data on nominal GVA in the manufacturing sector (in millions SAR) are from Saudi Central Bank's (2022) annual statistics. The nominal series of GVA is deflated by the price level (i.e., the CPI deflator, 2010 = 100) to convert it to a real value.

Capital

Increasing capital stock is one of several crucial factors of economic growth and industrialization. Capital stock in an economy is strongly associated with the possibilities of changing the scale of production technologies. Therefore, capital stock is considered one of the most important determinants of growth, along with other inputs. Capital stock is not directly observed and, instead, has to be computed using the usual perpetual inventory method as follows:

$$K_t = (1-\delta)K_{t-1} + I_t$$

The three components for calculating the time series of capital stock (K) are gross investment data, the depreciation rate, and the initial value for the capital stock. The initial value of capital stock is usually calculated by reference to neoclassical growth theory, which states that capital stock grows at the same rate as does the output in the steady state (Berlemann and Wesselhoeft 2014). This result is suggested by the following formula:

$$g_Y = g_K = \frac{I_t}{K_{t-1}} - \delta \Rightarrow K_{t-1} = \frac{I_t}{g_Y + \delta}$$

where g_Y and g_K are the growth rates of output and capital stock, respectively. To avoid making the calculation dependent on investment in a given year, when the economy may not be in equilibrium due to investment shocks, following Harberger (1978), a three-year average, instead of a single-year average, is employed. Thus,

$$K_0 = \frac{1}{3}\sum_{t=0}^{2}\left(\frac{I_t}{g_Y + \delta}\right)$$

Investment in manufacturing is used to calculate the capital stock of manufacturing. Following Erumban et al. (2012), a depreciation rate of 6.5% is used in the calculation of the capital stock of the manufacturing sector in Saudi Arabia. Data are obtained from the Oxford Economics Global Economic Modeling Database.

Labor

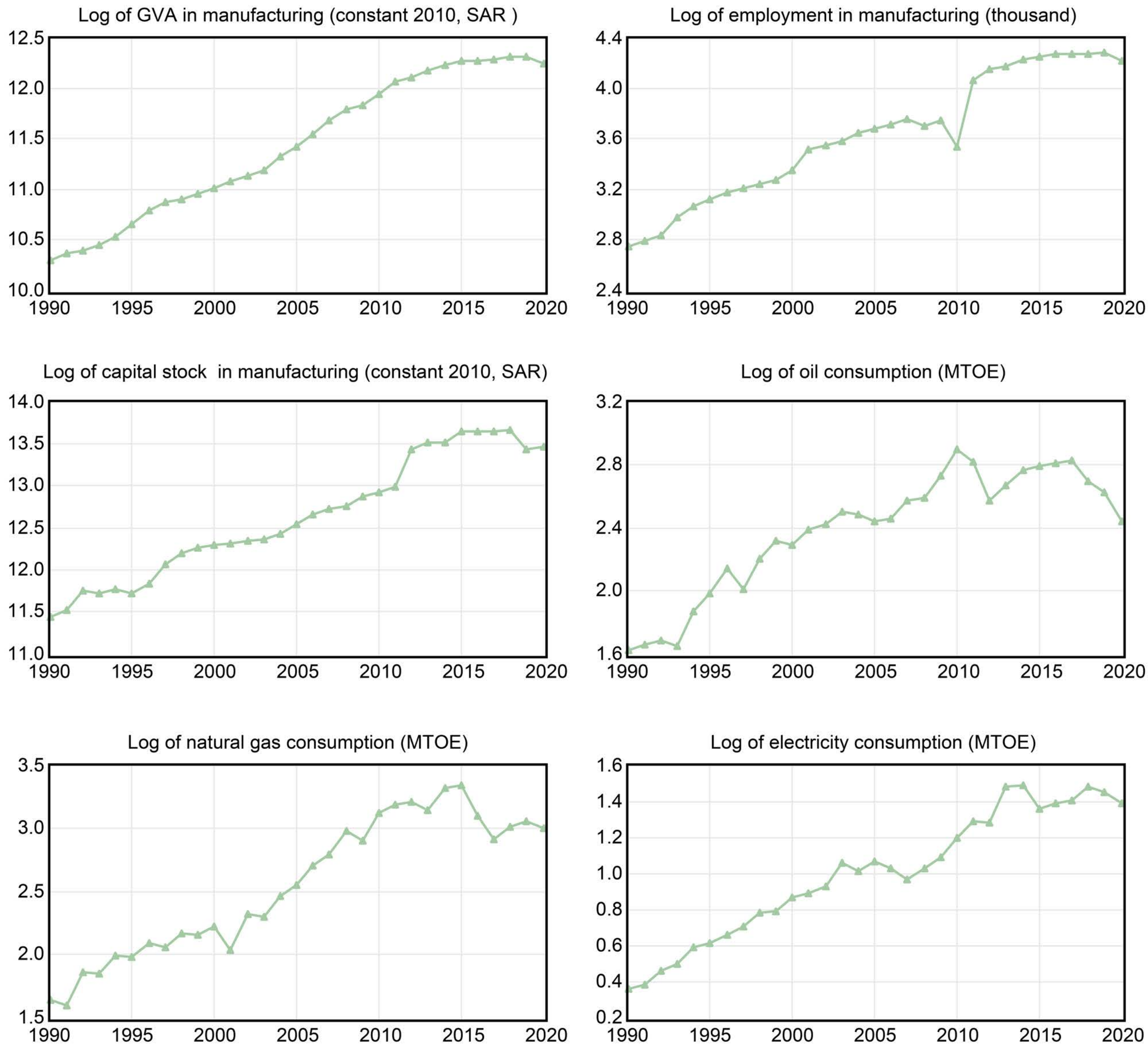
Labor is another crucial factor of economic growth. The labor factor affects industrial growth in two ways: first, by promoting exogenous economic growth by increasing the size of the labor force and, second, by triggering endogenous economic growth in the form of an efficient labor force. The flow of labor across industries, especially from the low-productivity agricultural sector to the high-manufacturing sector, is an important mechanism for economic growth. For this study, manufacturing employment data are taken from the Saudi Arabia General Authority for Statistics.

Energy component

The International Energy Agency (IEA) reports the elaborated level of energy consumption (natural gas, electricity, and oil) for the industrial sector in Saudi Arabia. The component of energy data is available in kilotons of oil equivalent (KTOE) from the IEA's (2023) world energy balance sheet[2]. Figure 1 plots the log level of the variables over the study period.

4. Data

Figure 1. Graph of variables, 1990–2020



5. Results and Discussion

To detect multicollinearity among the explanatory variables included in the regression analysis, correlation coefficients are calculated before proceeding with the empirical analysis. In statistics, the correlation coefficient is a measure of the degree of linear dependence between two variables. Table 1 presents the results of the correlation analysis and shows that all correlation coefficients are greater than 0.90. There is a possibility that the high degree of correlation between explanatory variables is due to some common factor rather than these variables having any meaningful economic relationship. In such a situation, the possibility of spurious relationships in regression analyses exist. To address this issue, we apply the augmented Dickey–Fuller (ADF) unit root and cointegration test, and the results are reported in Appendix B. According to the findings of the ADF and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) unit root tests, all variables are nonstationary at level and stationary at first difference. A cointegration test, also known as the residual-based cointegration test (see Ericsson and MacKinnon 2002), is used to evaluate whether the variables have a long-term relationship. The cointegration test result shows that the estimated test statistic of -5.113 is greater than the critical value in absolute terms at a 1% significance level, showing that the variables are cointegrated.

The correlation results not only show that there is strong multicollinearity between the explanatory variables but also suggest that the ridge regression procedure used in this study is a more appropriate econometric approach compared to other approaches. However, choosing the appropriate lambda value (λ) is the key hurdle in ridge regression analysis. Thus, Hoerl and Kennard (1970) proposed a graphical approach to determine the appropriate lambda (λ) value. In their approach, the ridge regression coefficients are plotted against different values of λ; the appropriate lambda value is the smallest possible value that produces the least amount of bias, and above this value of λ, the regression coefficients appear to remain constant. Based on the ridge trace presented in Figure 1, we choose 0.40 as the value of the ridge parameter because the ridge regression coefficients appear to have stabilized at approximately this value. Different values of the ridge parameter ranging from 0.25 to 0.40 are used for sensitivity analysis, confirming that the estimated ridge coefficients are not sensitive to the value of the ridge parameter.

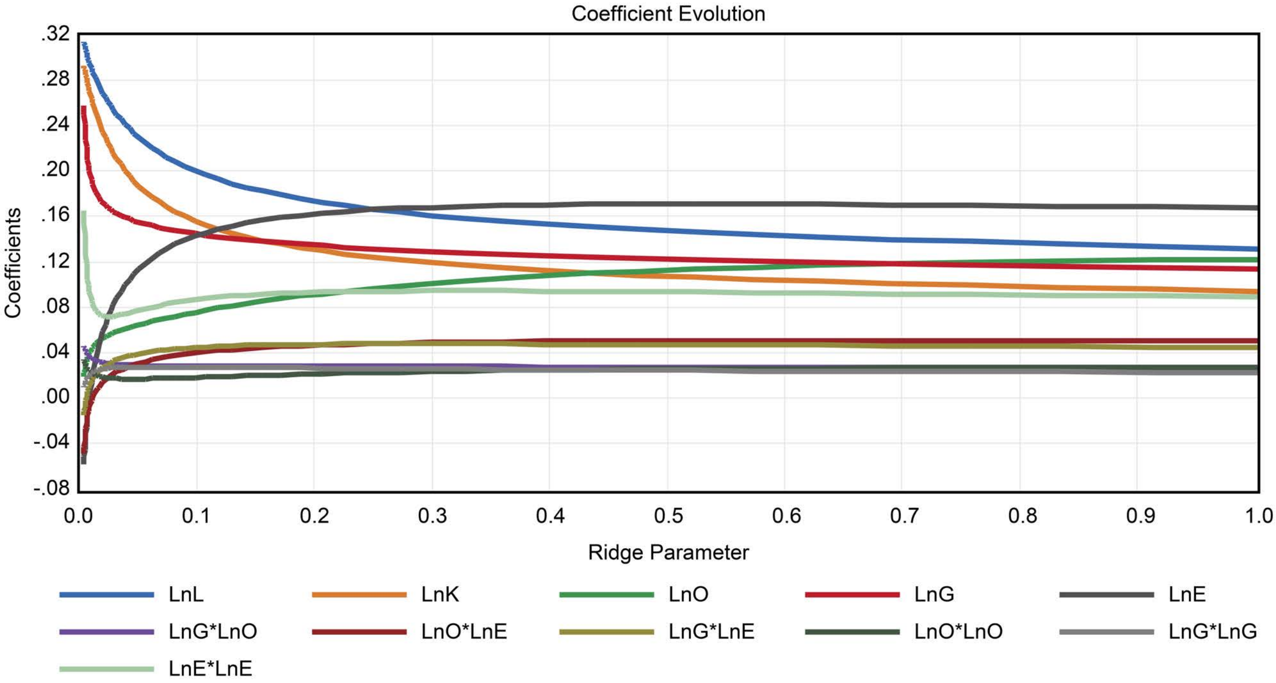
Table 1. Correlation analysis

Variable	Labor	Capital	Natural Gas	Oil	Electricity
Labor	---				
Capital	0.977				
	(24.76)	---			
Natural Gas	0.929	0.945	---		
	(13.53)	(15.56)			
Oil	0.885	0.879	0.910	---	
	(13.53)	(9.95)	(11.84)		
Electricity	0.980	0.975	0.939	0.916	---
	(26.61)	(23.56)	(14.80)	(12.37)	

Figures in parentheses indicate t-statistics.

5. Results and Discussion

Figure 2. Ridge trace of the coefficient estimates of the ridge regression



Estimation Procedure

In early 2016, the government of Saudi Arabia launched its ambitious energy price reform plan to achieve its economic transformation objective. The first wave of energy price reform was implemented on January 1, 2016, resulting in substantial increases in fuel and electricity prices for both industry and households. The second wave was implemented on January 1, 2018, with the introduction of a 5% value-added tax (VAT) on all goods and services. In the first wave of this energy price reform, the prices of natural gas, ethane, electricity, HFO, and crude oil for industry were significantly increased. For example, the price of HFO increased from $2.08/barrel to $3.80/barrel, an increase of nearly 83%. Similarly, natural gas and ethane prices increased from $0.75/barrel to $1.25/barrel and from $0.75/barrel to $1.75/barrel, respectively; the equivalent increases were 67% for natural gas and 133% for ethane (Alarenan et al. 2020). These initiatives represent a significant policy shift and underscore the government's commitment to achieving its economic transformation goals. The reform achieved the desired impact on energy demand in the industrial sector in Saudi Arabia. The demand for natural gas, electricity, and oil in the industrial sector declined after 2015; however, it is difficult to solely attribute this decline to the abovementioned price increases (see Figure 1).

As a result, we expect outliers and structural breaks in Saudi Arabia's industrial production and energy demand data due to the internal policy shift in the country, and to detect these breaks, we employ an Autometrics approach. Ignoring the structural breaks in the data can lead to a potentially misspecified empirical model and misleading policy implications (see, for example, Castle et al. 2021, 2011). The Autometrics algorithm is implemented in the econometrics software OxMetrics 9, which performs automatic model selection using the general to specific (Gets) methodology (Doornik 2009). An Autometrics approach allows the automatic model selection to include impulse indicator saturation (IIS) for outliers, step indicator saturation (SIS) for location shifts, trend indicator saturation (TIS) for trend breaks, and designated indicator saturation (DIS) for specific shapes in the regression model, in addition to the theoretical variables in the general unrestricted model (GUM) framework. Under the Autometrics estimation approach, the dummies for 1996, 2010, and 2017 are chosen to be TIS.

In the second step, we incorporate these dummy variables into the ridge regression estimation, the results of which are reported in Table 2. The output elasticities of energy inputs are computed by using ridge regression parameters, the results of which are reported in Table 3. The estimation results show that the output elasticities for natural gas, oil, and electricity are all positive and significant. The estimated elasticities for all energy inputs exhibit an increasing trend over the estimated period. The increasing trends of the output elasticities of natural gas, electricity, and oil over the estimated period are indicative of the continuous technological progress and energy efficiency in Saudi Arabia's industrial sector. Furthermore, the output elasticity of electricity is relatively higher than those of the other energy types, followed by the elasticities of natural gas and oil.

The interfuel substitution elasticities for each energy input are calculated using the output elasticities reported in Table 3 and are shown in Table 4. The values of the cross-input elasticities are positive, indicating that all energy input pairs considered in the study are substitutes. The elasticity of substitution is the elasticity of the ratio of two inputs to a production function with respect to the difference in their marginal products

Table 2. Ridge regression estimation results

Variable	Coefficient	t-Statistic
LnL	0.120	9.003
LnK	0.091	10.343
lnG	0.077	6.500
lnO	0.104	6.771
lnE	0.130	4.192
lnG ∗ *lnO*	0.023	8.997
lnG ∗ *lnE*	0.040	8.468
lnO ∗ *lnE*	0.039	12.33
lnG ∗ *lnG*	0.019	6.247
lnO ∗ *lnO*	0.021	17.08
lnE ∗ *lnE*	0.077	8.912
Constant	8.755	16.59
*TI*1996	0.002	4.575
*TI*2010	0.008	7.242
*TI*2017	0.008	6.756
R^2	0.989	
Ridge parameter	0.40	

and thus measures the curvature of an isoquant and consequently the degree of substitutability between inputs. This finding indicates the possibility of substituting one energy input for another energy input.

Our findings for the industrial sector in Saudi Arabia are consistent with the previous findings of Serletis et al. (2009) for Japan, Italy, and Poland. The above authors found strong degrees of substitutability between oil and natural gas and between electricity

Table 3. Output elasticities of energy input in the industrial sector in Saudi Arabia

Year	Elasticity of natural gas	Elasticity of oil	Elasticity of electricity
1990	0.225	0.189	0.314
1991	0.225	0.190	0.316
1992	0.240	0.200	0.340
1993	0.240	0.200	0.344
1994	0.255	0.215	0.372
1995	0.258	0.220	0.380
1996	0.269	0.231	0.399
1997	0.266	0.226	0.398
1998	0.278	0.239	0.422
1999	0.280	0.243	0.427
2000	0.286	0.247	0.441
2001	0.280	0.247	0.440
2002	0.295	0.257	0.459
2003	0.301	0.264	0.481
2004	0.306	0.266	0.480
2005	0.311	0.268	0.491
2006	0.316	0.271	0.492
2007	0.320	0.274	0.490
2008	0.331	0.282	0.507
2009	0.333	0.288	0.520
2010	0.351	0.303	0.552
2011	0.356	0.305	0.565
2012	0.350	0.296	0.554
2013	0.357	0.306	0.586
2014	0.368	0.314	0.599
2015	0.364	0.311	0.580
2016	0.355	0.307	0.576
2017	0.349	0.304	0.572
2018	0.353	0.304	0.583
2019	0.352	0.301	0.576
2020	0.343	0.291	0.559
Average	0.307	0.263	0.478

and natural gas for the industrial sector in Japan. Similarly, they found a strong degree of substitutability between oil and natural gas in the industrial sector in Italy and a mild degree of substitutability between oil and natural gas in the industrial sector in Poland. Similar conclusions were reached by Smyth et al. (2012) for China's iron and steel sector and by Lin and Wesseh (2013) for China's chemical sector.

Table 4. Elasticities of substitution for various energy inputs in the industrial sector in Saudi Arabia

Year	Oil vs. natural gas	Natural gas vs. electricity	Oil vs. electricity
1990	1.157	0.848	0.949
1991	1.159	0.856	0.951
1992	1.144	0.869	0.961
1993	1.144	0.878	0.966
1994	1.137	0.898	0.971
1995	1.138	0.904	0.970
1996	1.134	0.913	0.972
1997	1.134	0.917	0.977
1998	1.130	0.928	0.979
1999	1.132	0.930	0.978
2000	1.128	0.937	0.983
2001	1.137	0.944	0.982
2002	1.124	0.942	0.984
2003	1.125	0.954	0.988
2004	1.119	0.948	0.987
2005	1.115	0.951	0.989
2006	1.111	0.945	0.988
2007	1.110	0.940	0.984
2008	1.104	0.942	0.986
2009	1.107	0.949	0.988
2010	1.101	0.955	0.989
2011	1.098	0.959	0.993
2012	1.097	0.957	0.994
2013	1.097	0.968	0.998
2014	1.094	0.967	0.997
2015	1.094	0.960	0.994
2016	1.100	0.965	0.995
2017	1.104	0.968	0.995
2018	1.100	0.970	0.998
2019	1.099	0.968	0.998
2020	1.100	0.965	0.998
Average	1.118	0.935	0.983

5. Results and Discussion

Our estimated substitution elasticity for all energy inputs is close to unity, which means that Saudi Arabia's industrial sector has the option to switch from greenhouse gas-emitting fuels to cleaner energy sources without running the risk of output losses. In other words, switching from oil to electricity in the industrial sector would not only increase the likelihood of an increased amount of oil exports from Saudi Arabia but also improve the quality of the environment by replacing fossil fuels with carbon-neutral energy sources such as electricity. Our results are consistent with previous results in the literature for other countries. However, the potentials for electrification are not the same across industries. Fossil fuels could be replaced by clean energy sources in industries that depend on low- and medium-temperature heat. According to Roelofsen et al. (2020), existing technology could replace nearly half of the fuels used in the industrial sector with electricity. The industrial sector, for which energy is needed to produce heat for industrial processes operating at temperatures up to 1,000 degrees Celsius, could be electrified using available technology (Roelofsen et al. 2020). However, in some cases, renewable energy cannot be integrated quickly enough to provide the massive amount of energy needed for industry. The main exception is the use of fuels to generate very-high-temperature heat (over 1,000 degrees Celsius), which is needed for the cement and virgin steel production industries.

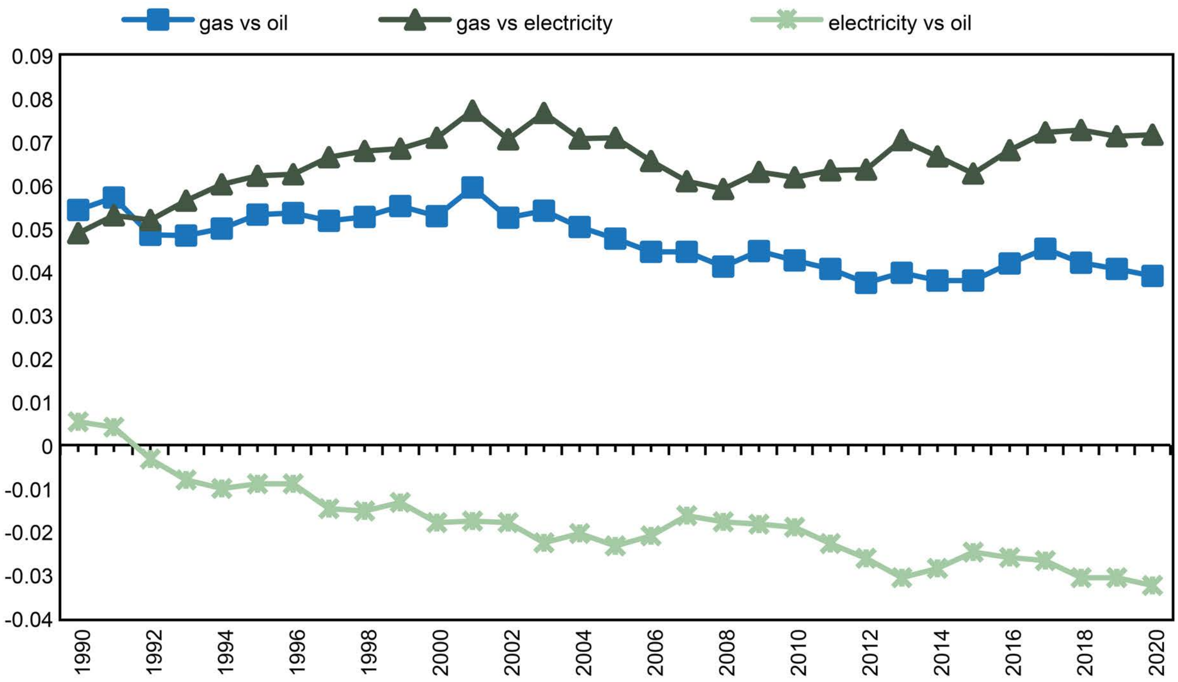
In the following section, relative differences in the technical progress of oil, natural gas, and electricity are calculated. For this purpose, the estimated output elasticities of energy inputs and coefficients from Equation (4) are combined with the translog production function of the Saudi Arabian industrial sector. The specific function used for the calculation is as follows:

$$RD_{ij} = \left(\alpha_i / \varepsilon_i \right) - \left(\alpha_j / \varepsilon_j \right)$$

where RD_{ij} represents the difference between the technical progress of inputs i and j, α_i and α_j are the estimated parameters from Equation (3), and ε_i and ε_j indicate the output elasticity of inputs i and j, respectively. A positive value of RD_{ij} is a direct indication that the state of technical progress for input i is faster than that of input j. A negative value of RD_{ij}, however, means that the state of technical progress for input j is faster than that of input i. If $RD_{ij} = 0$, then this implies equality in technical progress for both inputs.

The results of this analysis are presented in Figure 2 and show that there is only a modest difference in the relative technical progress of all inputs. The relative differences in technical progress between natural gas and oil and between natural gas and electricity are positive and slightly above zero. Thus, technical progress in terms of natural gas is modestly faster than are those in terms of oil and electricity. The values of RD_{ij} for electricity and oil are similar and negative, which implies that technical progress in terms of oil is faster than is that in terms of electricity.

Figure 3. Differences in the degrees of technical progress in terms of different energy inputs



6. Conclusions

In this paper, a translog production function model is used to study the elasticities of interfuel substitution among natural gas, oil, and electricity in the industrial sector in Saudi Arabia. A ridge regression procedure is used to estimate the parameters of the function. The estimation results show that all energy inputs are substitutes and that the estimated elasticities of substitution are constant over time. Since electricity is substitutable for oil and gas, for example, the Saudi government can encourage the industrial sector to use more electricity and less oil through subsidies or more competitive electricity pricing. These results highlight the potential for the Saudi industrial sector to switch from GHG-emitting fuels, such as oil, to cleaner energy sources without risking losses of output. However, the potentials for electrification are not the same across industries. Fossil fuels could be replaced with clean energy sources in industries that depend on low- and medium-temperature heat.

The findings of this study have important policy implications for Saudi Arabia, particularly considering its commitment to reducing carbon emissions. The ambitious goal set by the Saudi government is to reduce annual greenhouse gas emissions by 278 million tons annually by increasing the use of clean energy[3]. The Kingdom of Saudi Arabia, as a major energy producer, is committed to making a good contribution to the global fight against climate change. The Saudi industrial sector can play an important role in achieving the ambitious target of reduced carbon emissions. The electrification of the industrial sector can be a useful strategy through which to achieve the GHG emissions reduction targets. Electrification is an economically attractive strategy because of the declining cost of renewable energy, rapid technological advances, and significant potential for reduced carbon emissions. Electrical equipment is more energy efficient than is conventional equipment and has lower maintenance costs (Roelofsen et al. 2020). Switching from oil to electricity in the industrial sector would not only increase the likelihood of a rise in the amount of oil exports but also limit any unintended negative environmental effects on the Saudi Arabian economy. However, electrification reduces the amount of industrial greenhouse gas emissions and increases the amount of oil exports of Saudi Arabia only if sufficient renewable generation capacity is added to meet electricity demand in the industry.

Since energy inputs are found to be substitutes, Saudi Arabia's government may benefit from policies that encourage the greater use of alternative energy sources. As electricity is substitutable for oil, for example, the Saudi government can encourage the industrial sector to use more electricity and less oil through subsidies or more competitive electricity pricing for the industrial sector. In this regard, it is crucial for the government to concentrate on boosting installed renewable electricity generation capacity. Switching from one energy source to another could result in increased capital expenditure for new machines and manufacturing equipment because transitioning from one energy source to another involves a certain amount of technological change. Thus, the government may need to design a policy framework through which to reduce the capital expenses associated with energy switching. Moreover, models for predicting future energy demand in the industrial sector can use the elasticities of substitution between fuels identified in this study to become more reliable.

Endnotes

[1] https://data.worldbank.org/indicator/NV.IND.TOTL.ZS?locations=SA.

[2] http://webstore.iea.org/.

[3] https://www.greeninitiatives.gov.sa/about-sgi/sgi-targets/reducing-emissions/reduce-carbon-emissions/.

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Appendix

Appendix A

From Equation (2), we can derive the output elasticities of natural gas, electricity, and oil by taking the derivative of Equation (2) with respect to the respective energy inputs. The output elasticity for natural gas is as follows:

$$\varepsilon_g = \frac{dY/y}{dG/G} = \frac{dlnY_t}{dlnG_t} = \alpha_g + \alpha_{ge} lnE_t + \alpha_{go} lnO_t + \alpha_{gg} lnG_t \tag{A1}$$

The output elasticity for electricity is as follows:

$$\varepsilon_e = \frac{dY/Y}{dE/E} = \frac{dlnY_t}{dlnE_t} = \alpha_e + \alpha_{ge} lnG_t + \alpha_{eo} lnO_t + \alpha_{ee} lnE_t \tag{A2}$$

The output elasticity for oil is as follows:

$$\varepsilon_o = \frac{dY/Y}{dO/O} = \frac{dlnY_t}{dlnO_t} = \alpha_o + \alpha_{go} lnG_t + \alpha_{eo} lnE_t + \alpha_{oo} lnO_t \tag{A3}$$

Thus, the elasticity of substitution between natural gas and electricity (σ_{ge}) can be calculated as follows:

$$\sigma_{ge} = \frac{\%\Delta\left(G_t/E_t\right)}{\%\Delta\left(MP_{et}/MP_{et}\right)} \tag{A4}$$

Equation (A4) can be written as follows:

$$\sigma_{ge} = \frac{d\left[G/E\right]}{\left[G/E\right]}\left[\frac{d\left[MP_e/MP_g\right]}{MP_e/MP_g}\right]^{-1} = \frac{d\left[G/E\right]}{d\left[MP_e/MP_g\right]}\frac{MP_e/MP_g}{G/E} \tag{A5}$$

For simplicity, we remove subscript t from the elasticity of substitution formula. The MP_e-to-MP_g ratio are given by the following:

$$\frac{MP_e}{MP_g} = \frac{\partial Y/\partial E}{\partial Y/\partial G} = \frac{\varepsilon_e}{\varepsilon_g}\frac{G}{E} \tag{A6}$$

Appendix

Further, σ_{ge} can be decomposed by substituting Equation (A6) into Equation (A5) as follows:

$$\sigma_{ge} = \frac{d\left[G/E\right]}{d\left[MP_e/MP_g\right]}\frac{\varepsilon_e}{\varepsilon_g} = \frac{\varepsilon_e}{\varepsilon_g}\left[\frac{d\left[MP_e/MP_g\right]}{d\left[G/E\right]}\right]^{-1} = \frac{\varepsilon_e}{\varepsilon_g}\left[\frac{d\left[\varepsilon_e/\varepsilon_g \; G/E\right]}{d\left[G/E\right]}\right]^{-1} \tag{A7}$$

$$\left[\frac{d\left[\varepsilon_e/\varepsilon_g \; G/E\right]}{d\left[G/E\right]}\right] = \frac{\varepsilon_e}{\varepsilon_g} + \frac{G}{E}\left[\frac{d\left[\varepsilon_e/\varepsilon_g\right]}{d\left[G/E\right]}\right] \tag{A8}$$

$$d\left[\frac{\varepsilon_e}{\varepsilon_g}\right] = -\frac{\varepsilon_e}{\varepsilon_g^2}d\varepsilon_g + \frac{1}{\varepsilon_g}d\varepsilon_e$$

$$d\left[G/E\right] = -\frac{G}{E^2}dE + \frac{1}{E}dG$$

$$\left[\frac{d\left[\varepsilon_e/\varepsilon_g\right]}{d\left[G/E\right]}\right] = \frac{-\left(\varepsilon_e/\varepsilon_g^2\right)d\varepsilon_g + \left(1/\varepsilon_g\right)d\varepsilon_e}{-\left(G/E^2\right)dE + \left(1/E\right)dG} \tag{A9}$$

$$\left[\frac{d\left[\varepsilon_e/\varepsilon_g\right]}{d\left[G/E\right]}\right] = \frac{-\left(\varepsilon_e/\varepsilon_g^2\right)d\varepsilon_g/dE + \left(1/\varepsilon_g\right)d\varepsilon_e/dE}{-\left(G/E^2\right) + \left(1/E\right)dG/dE} \tag{A10}$$

By substituting Equation (A10) into Equation (A8), we have the following:

$$\left[\frac{d\left[\varepsilon_e/\varepsilon_g \; G/E\right]}{d\left[G/E\right]}\right] = \frac{\varepsilon_e}{\varepsilon_g} + \frac{G}{E}\left[\frac{-\left(\varepsilon_e/\varepsilon_g^2\right)d\varepsilon_g/dE + \left(1/\varepsilon_g\right)d\varepsilon_e/dE}{-\left(G/E^2\right) + \left(1/E\right)dG/dE}\right]$$

$$\left[\frac{d\left[\varepsilon_e/\varepsilon_g \; G/E\right]}{d\left[G/E\right]}\right] = \frac{\varepsilon_e}{\varepsilon_g} + \frac{\varepsilon_e}{\varepsilon_g}\left[\frac{-\left(1/\varepsilon_g\right)\alpha_{ge}/E + \left(1/\varepsilon_e\right)\alpha_{ee}/E}{-\left(1/E\right) + \left(1/G\right)dG/dE}\right]$$

$$\left[\frac{d\left[\frac{\varepsilon_e}{\varepsilon_g}\frac{G}{E}\right]}{d\left[\frac{G}{E}\right]}\right]=\frac{\varepsilon_e}{\varepsilon_g}+\frac{\varepsilon_e}{\varepsilon_g}\left[\frac{-\alpha_{ge}+\left(\frac{\varepsilon_g}{\varepsilon_e}\right)\alpha_{ee}}{-\varepsilon_g+\varepsilon_g\left(\frac{E}{G}\right)\frac{dG}{dE}}\right] \tag{A11}$$

By substituting Equation (A11) into Equation (A8), we have the following:

$$\sigma_{ge}=\frac{\varepsilon_e}{\varepsilon_g}\left[\frac{\varepsilon_e}{\varepsilon_g}+\frac{\varepsilon_e}{\varepsilon_g}\left[\frac{-\alpha_{ge}+\left(\frac{\varepsilon_g}{\varepsilon_e}\right)\alpha_{ee}}{-\varepsilon_g+\varepsilon_e}\right]\right]^{-1} \tag{A12}$$

where $\varepsilon_e=\varepsilon_g\left(\frac{E}{G}\right)\frac{dG}{dE}$.

The final elasticity of substitution between natural gas and electricity is as follows:

$$\sigma_{ge}=\left[1+\frac{-\alpha_{ge}+\left(\frac{\varepsilon_g}{\varepsilon_e}\right)\alpha_{ee}}{-\varepsilon_g+\varepsilon_e}\right]^{-1} \tag{A13}$$

The elasticities of substitution between oil and natural gas (σ_{og}) and between oil and electricity (σ_{oe}) can be calculated in a similar fashion as follows:

$$\sigma_{og}=\left[1+\frac{-\alpha_{og}+\left(\frac{\varepsilon_o}{\varepsilon_g}\right)\alpha_{gg}}{-\varepsilon_o+\varepsilon_g}\right]^{-1} \tag{A14}$$

$$\sigma_{oe}=\left[1+\frac{-\alpha_{oe}+\left(\frac{\varepsilon_o}{\varepsilon_e}\right)\alpha_{ee}}{-\varepsilon_o+\varepsilon_e}\right]^{-1} \tag{A15}$$

Appendix B

Table B.1. ADF unit root test

Variable	Level			First difference	
	t-Stat	C	C&T	t-Stat	C
$LnGVA_t$	-1.697	x		-1.918	x
LnL_t	-2.925		x	-6.730*	x
LnK_t	-1.312	x		-4.800*	x
LnO_t	-2.169	x		-4.362*	x
LnG_t	-1.529	x		-6.770*	x
LnE_t	-1.939		x	-5.438*	x
$LnO_t * LnG_t$	-1.767	x		-4.637*	x
$LnO_t * LnE_t$	-1.630	x		-4.904*	x
$LnG_t * LnE_t$	-1.174	x		-4.855*	x
$LnO_t * LnO_t$	-1.937	x		-4.173*	x
$LnG_t * LnG_t$	-1.292			-5.942*	x
$LnE_t * LnE_t$	-2.625		x	-5.439*	x
$LnGVA_t^{\&}$	0.713*			0.290	
t_{URT}	-5.113*				

Notes: The maximum lag order is set to two, and the optimal lag order (k) is selected based on the Schwarz criterion. *** indicates the rejection of the null hypothesis of a unit root at the 1% significance level. & indicates that the KPSS test is used for unit root tests. * indicates the rejection of the null hypothesis of stationarity at a 1% significance level. The critical values for the KPSS test are taken from Kwiatkowski, Phillips, Schmidt, and Shin (1992, Table 1). Note that the final UR test equation can take one of three options of the deterministic regressors: intercept (C), intercept and trend (C&T), or none of these. x indicates that the corresponding option is selected in the final UR test equation based on the significance of the deterministic regressors. t_{URT} denotes the unit root test for the residual.

Notes

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About the Project

This study is part of the KGEMM Policy and Research Studies.

The KGEMM Policy and Research Studies project produces policy and applied research studies that can provide Saudi Arabian decision-makers with a better understanding of domestic and international macroeconomic-energy relationships. The project mainly employs KGEMM, an energy-sector augmented general equilibrium macro-econometric model, as well as partial equilibrium frameworks.

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