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Modeling Industrial Energy Demand in Saudi Arabia and Understanding Its Drivers

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Key Points

Between 1986 and 2016, industrial energy consumption in Saudi Arabia increased tenfold, making industry one of the Kingdom's largest end-use sectors. We modeled Saudi industrial energy demand using a structural time series model and found that:

Industrial energy demand in Saudi Arabia is both price and income inelastic, with estimated long-run elasticities of -0.34 and 0.60, respectively. Accordingly, industrial companies in Saudi Arabia appear to be more responsive to changes in energy prices compared with households (estimated price elasticities for households from previous studies range from -0.1 to -0.2).

The activity effect (i.e., the growth in industrial output) and the structure effect (i.e., the shift toward energy-intensive manufacturing) were the primary drivers of industrial energy consumption growth in Saudi Arabia.

Significant energy efficiency improvements were observed in the industrial sector from 2010 onwards, leading to cumulative energy savings of around 7 million tonnes of oil equivalent (Mtoe) between 2010 and 2016.

Saudi Arabia's energy price reforms of 2016 had a significant impact on that year's growth in industrial energy consumption. The analysis revealed that higher industrial fuel prices reduced the sector's consumption in 2016 by around 3 Mtoe, holding all else fixed. This is equivalent to a 6.9% decrease.

Policymakers could build on the energy price reforms and energy efficiency measures to help mitigate the growth rate of domestic industrial energy consumption over the coming years.

Summary

In 2016 Saudi Arabia's industrial (or manufacturing) sector accounted for 30.3% of total final energy consumption (IEA 2018a). When non-energy use (mainly feedstock for the petrochemical subsector) is included, the industrial sector's share of total final energy consumption rises to over 50%.

Despite its importance, we found no published econometric studies on aggregate industrial energy demand in Saudi Arabia. This paper is, to the best of our knowledge, the first to model aggregate industrial energy demand in Saudi Arabia econometrically and to quantify the contributions of its growth drivers.

Industrial energy demand in Saudi Arabia was modeled using a structural time series model, which revealed long-run price and income elasticities of -0.34 and 0.60, respectively. The long-run income elasticity suggests that Saudi industrial energy consumption will continue to grow over the coming decades as economic activity expands.
The long-run price elasticity, however, suggests the potential for mitigating this growth through increased energy prices. The price elasticity also demonstrates that industrial companies are more responsive than households to changes in energy prices (estimated price elasticities for households from previous studies range from -0.1 to -0.2).

The estimated econometric model also showed that Saudi Arabia could increase its industrial energy productivity substantially by moving away from energy-intensive manufacturing. The structural elasticity shows that a 10 percentage point shift away from energy-intensive exports, for example, could reduce industrial energy consumption by as much as 6.7%, holding all else fixed. We therefore expect Saudi Arabia to shift toward higher value-added manufacturing over the coming decades to help mitigate the growth in its industrial energy demand.

We applied a decomposition analysis to the estimated econometric model to quantify the drivers of the growth in industrial energy consumption in Saudi Arabia over the past several decades. The decomposition results showed that the activity effect was the primary driver. Additionally, the shift toward energy-intensive manufacturing exerted upward pressure on industrial energy consumption throughout the study period. In contrast, the efficiency effect exerted downward pressure from 2010 onwards, helping to mitigate some of the growth in industrial energy consumption. Finally, the decomposition analysis revealed that energy prices, which had not changed significantly prior to 2016, played a limited role.

On December 29, 2015, Saudi Arabia implemented the first stage of its energy price reform, with economic implications for households and companies across all sectors of the economy. The energy price reform program aims to raise domestic energy prices toward international benchmarks, which will not only raise government revenues but will also stimulate productivity and encourage investments that can help Saudi Arabia diversify its energy mix. The decomposition analysis showed that higher industrial energy prices in 2016 reduced the sector's energy consumption by 6.9% in that year, equivalent to energy savings of around 3 million tonnes of oil equivalent (Mtoe). Further gradual price reform for industrial fuels should continue over the coming years and is expected to mitigate the growth of industrial energy consumption in the Kingdom.

Although we quantify the impact of higher energy prices on consumption, this does not show the possible impact higher prices could have on competitiveness. Saudi Arabia's relatively low energy prices have steered domestic industries toward the production and export of energy-intensive goods, an area where they appear to hold a comparative

advantage. Higher energy prices would likely weaken this advantage, but they may also drive domestic industries toward the production and export of higher value-added goods, such as the petrochemical industry, which already appears to be moving in this direction.

Since higher domestic energy prices lift government revenues, a subsidy scheme (or similar program) that promotes industrial energy efficiency could be introduced to lessen the negative impact of higher energy prices on competitiveness. In fact, the decomposition analysis in this study revealed that improvements in energy efficiency from 2010 onwards delivered cumulative energy savings of around 7 Mtoe. Energy efficiency thus carries the potential to mitigate the rapid growth in industrial energy consumption while supporting industrial companies' competitiveness.

In summary, the econometric results revealed the relationships between prices, income, economic structure, efficiency, and energy consumption in the Saudi industrial sector, while the decomposition results showed the drivers of the growth in industrial energy consumption. The results also highlight how energy efficiency has been a key factor in mitigating the rapid growth of industrial energy consumption over the last decade. Furthermore, in 2016, higher energy prices helped to significantly reduce consumption in that year. This shows that policymakers could build on the current policy of energy price reform and energy efficiency measures to help mitigate the growth of industrial energy consumption, increase economic efficiency, and maintain industrial sector competitiveness.

Introduction

In Saudi Arabia, according to the International Energy Agency (IEA) (2018a) the industrial (or manufacturing) sector accounted for 30.3% of total final energy consumption in 2016. When non-energy use (mainly feedstock for the petrochemical subsector) is included, the industrial sector's share of total final energy consumption rises to over 50%.

Saudi Arabia's industrial sector has grown rapidly over the last several decades. Industrial value added grew from 29 billion 2010 Saudi riyals (SAR) in 1986 to 213 billion SAR in 2016, according to the Saudi Arabian Monetary Authority (SAMA) (2018). This translates into a real average annual growth rate of 7%, highlighting the pace of development in Saudi Arabia's industrial base. During this period, industrial energy consumption grew at an even faster rate of almost 8%.

The abundance of oil and natural gas in Saudi Arabia has allowed the government to provide energy to the industrial sector at relatively low administered prices. These low energy prices appear to have influenced both the levels of energy efficiency in Saudi industry and its structure. The Heckscher-Ohlin theorem of specialization states that a country will specialize in the export of commodities that are produced with the factor of production that it possesses in abundance (Heckscher 1919; Ohlin 1933). According to this theorem, Saudi Arabia's specialization in energy-intensive exports would thus be a natural outcome of its fossil fuel endowments.

A deep understanding of industrial energy demand and its determinants is necessary for developing economic plans. However, as noted by Greening et al. (2007), the industrial sector is "one of the hardest end-uses to analyze, model, and forecast" (Greening et al. 2007, 599). Their paper highlights different methods used by researchers to model industrial energy demand, such as decomposition analysis, econometric modeling, top-down models, and bottom-up or engineering models.

Econometric modeling of industrial energy demand offers several advantages. It allows for a wide range of econometric techniques, the identification and quantification of causal linkages between variables, and produces outputs (estimated elasticities) often used as inputs in other models, such as bottom-up and top-down models (Greening et al. 2007). Econometric models can also be used to forecast, helping policymakers predict the evolution of industrial energy demand, central to the development of economic policy.

Despite the importance of econometric modeling of energy demand, we found no econometric studies published on aggregate industrial energy demand in Saudi Arabia and very few studies on the Middle East. With no published energy elasticities in the literature, this is a gap that this paper aims to fill. As noted previously, this gap likely stems from the difficulties associated with modeling industry, and in the case of Saudi Arabia, the limited availability of energy-related data. Furthermore, we found no published studies that quantified the drivers of industrial energy demand growth in Saudi Arabia, often done using decomposition analysis. We are also, to the best of our knowledge, the first to apply a decomposition analysis to the Saudi industrial sector.

Methods

Econometric modeling of industrial energy demand

Aggregate industrial energy demand is modeled as a function of the real average energy price; gross value added; a factor that captures how specialized Saudi Arabia is in energy-intensive exports, which we call the structural factor; and an underlying energy demand trend (UEDT), which captures exogenous factors such as energy efficiency:

$$E_t = f\,(GVA_t, P_t, SF_t, UEDT_t) \quad (1)$$

where:

E_t= Aggregate manufacturing energy consumption;
GVA_t= Real gross value added by the manufacturing sector;
P_t= Real weighted average energy price;
SF_t= Structural factor;
$UEDT_t$= Underlying energy demand trend.

The subscript t denotes the year.

The structural time series model (STSM) is used to model industrial energy demand econometrically. The study period is 1986-2016, and a two-year lag is used. More details on the econometric method can be found in Appendix A.

Decomposition of the estimated energy demand equation

The goal of decomposition analysis is to decompose the change in energy consumption between an end year and a base year into factors that we refer to as drivers (see Textbox 1 for more details).

Textbox 1: Understanding Decomposition Analysis

There are different types of decomposition analysis, such as additive and multiplicative decomposition. Additive decomposition decomposes a change in a variable between an end year and a base year into a sum of factors (often referred to as drivers). This paper uses additive decomposition analysis to decompose the change in energy consumption between an end year and a base year (denoted by ΔE) into five drivers: activity, price, structure, UEDT, and error term effects.

$$\Delta E = activity\ effect + price\ effect + structure\ effect + UEDT\ effect + error\ term\ effect$$

The activity effect represents how changes in output between an end year and base year affected the change in energy consumption. Similarly, the price and structure effects represent the impact of changes in prices and economic structure, respectively. The UEDT effect captures the impact of changes in energy efficiency (in addition to other factors), but also the impact of exogenous breaks, known as interventions. For example, the UEDT incorporates an intervention in 1990 to account for the break in the energy consumption data obtained from the IEA (2018a). Such interventions can be isolated from the UEDT, allowing it to largely reflect changes in energy efficiency. This then yields the following decomposition equation:

$$\Delta E = \textit{activity effect} + \textit{price effect} + \textit{structure effect} + \textit{efficiency effect} + \textit{interventions effect} + \textit{error term effect}$$

The error term effect reflects the fact that there is always a small error between the estimated or predicted value of energy consumption from the model and its actual value.

By decomposing the change in 'fitted' energy consumption, the error term can be eliminated. Fitted energy consumption is defined as the level of energy consumption estimated by the model, which, for models that fit the data very well, is often almost equal to actual energy consumption. By decomposing the change in fitted energy consumption (denoted by $\Delta\hat{E}$), the error term effect can be eliminated, leading to the following equation:

$$\Delta \hat{E} = \textit{activity effect} + \textit{price effect} + \textit{structure effect} + \textit{efficiency effect} + \textit{interventions effect}$$

Data

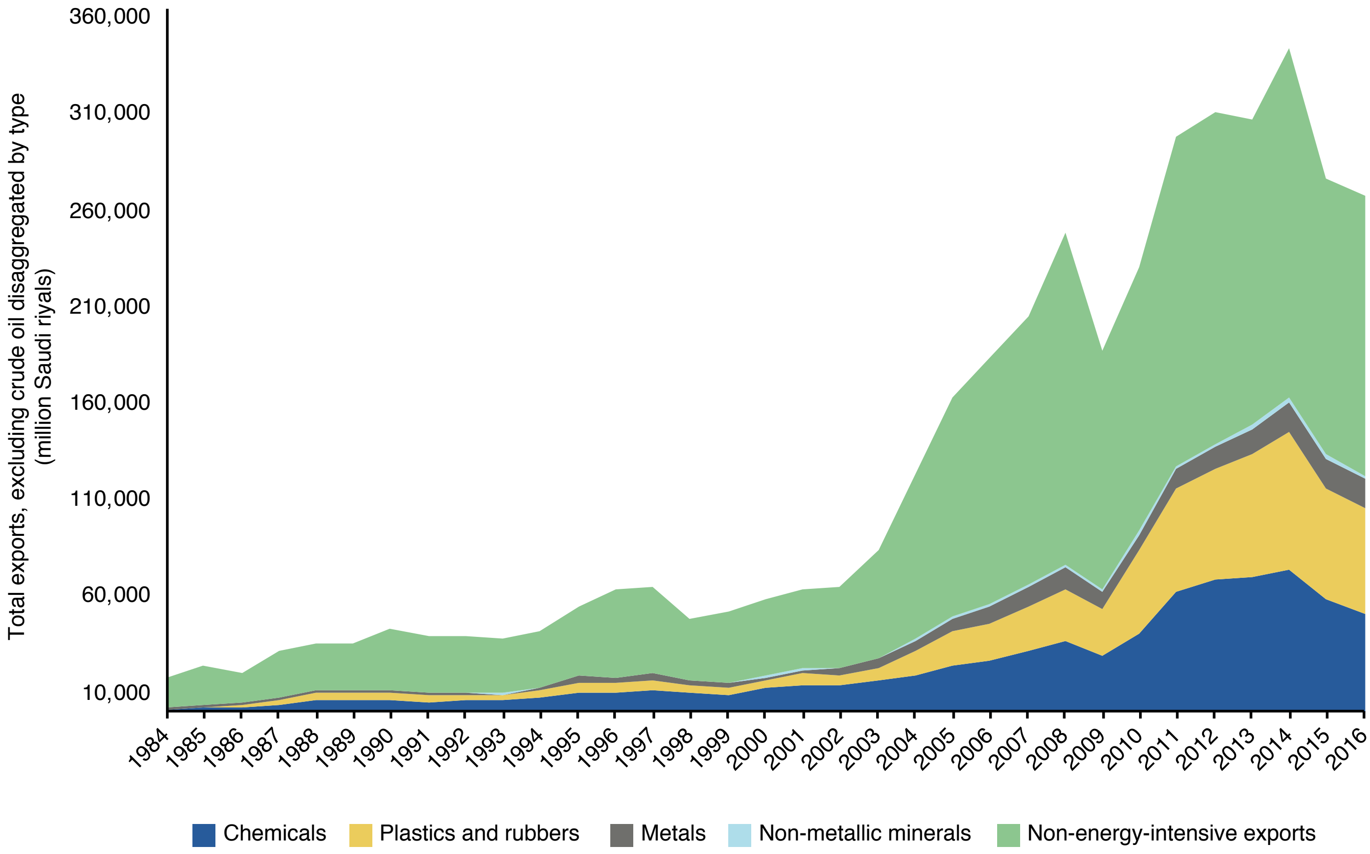
The data required to conduct this analysis include the structural factor (a variable that reflects how specialized Saudi Arabia is in energy-intensive exports), real industrial energy prices, industrial value added (a variable that reflects manufacturing activity), and industrial energy consumption.

Saudi Arabia has undergone rapid industrial development over the last several decades, becoming a major exporter of oil and many non-oil products. Between 1986 and 2016, total exports of non-oil products grew from 20 billion SAR to more than 260 billion SAR. The abundance of oil and natural gas in Saudi Arabia has allowed the government to provide energy to the industrial sector at relatively low administered prices, influencing the structure of Saudi exports. Figure 1 shows the evolution of total exports, excluding crude oil, between 1986 and 2016, highlighting the fast expansion in the export of energy-intensive goods. We include a variable, which we call the structural factor, to capture the degree of specialization in energy-intensive manufacturing. This factor was calculated by taking the share of chemical, plastic and rubber, metal, and non-metallic mineral exports in total exports (excluding crude oil), all of which were obtained from CEIC Data (2018).

Energy prices in Saudi Arabia are set at relatively low administered levels and can remain fixed for long periods. These prices can only change through royal decrees and often change simultaneously. For this study, the price of energy consumed by industry was calculated using a weighted average of fuel prices, in which the weights represented the share of industrial consumption by fuel. The weighted average energy price was then deflated using the sector's deflator, obtained from Saudi Arabia's General Authority for Statistics (GaStat) (2018). The fuels used in Saudi Arabia's industrial sector include crude oil, diesel, heavy fuel oil, and natural gas, in addition to electricity and other refined oil products. The prices of these fuels were all obtained from Saudi Aramco (2018).

We use manufacturing value added as a measure of the manufacturing sector's economic activity. Although manufacturing output and value added are highly correlated, the two are different. Gross output captures the total revenues obtained from selling

Figure 1. Saudi exports by commodity type.



Source: CEIC.

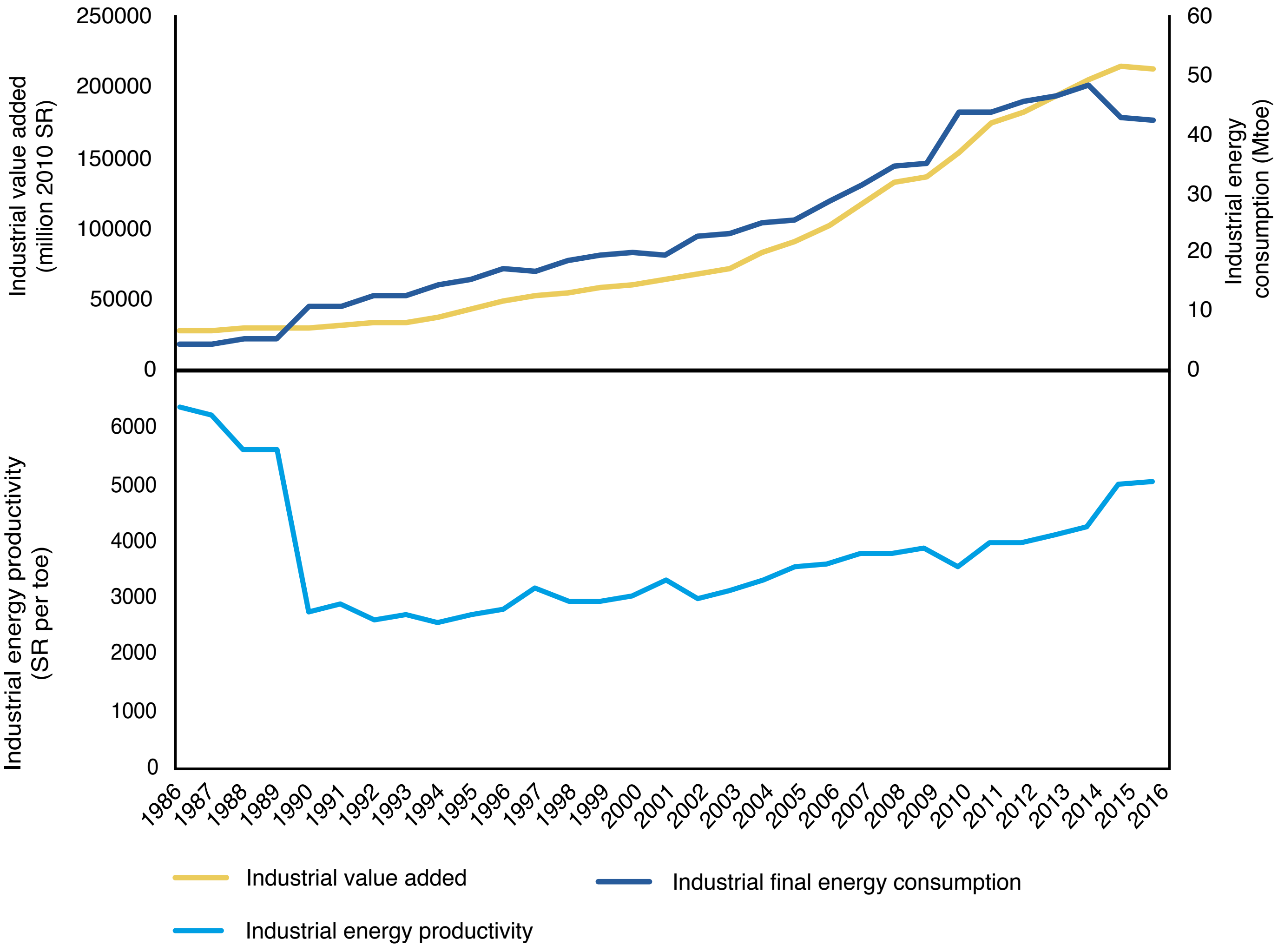
manufactured goods, while value added is defined as gross output minus intermediate consumption. While there is limited data on output, the data on manufacturing value added is readily available. The data show that over the last few decades, Saudi manufacturing value added grew from 28.3 billion 2010 SAR in 1986 to 213.4 billion SAR in 2016 (SAMA 2018).

During this same period, aggregate industrial energy consumption grew from 4.4 million tonnes of oil equivalent (Mtoe) to 42.3 Mtoe. Figure 2 illustrates the evolution of industrial energy consumption, value added, and energy productivity (the ratio of the latter two) between 1986 and 2016, highlighting the rapid pace of development.

Time series data on subsectoral energy consumption do not (yet) exist. The same holds true for subsectoral manufacturing value added. Thus, energy demand cannot currently be modeled for industrial subsectors nor disaggregated by fuel type. Nevertheless, estimating elasticities for subsectors of Saudi industry by fuel type will likely be an important area of research in the future as the data becomes available.

Figure 2 suggests that there may be an issue with the IEA's energy consumption data prior to 1990, which is likely a specification issue from the data source. According to the IEA's (2018b) country note on Saudi Arabia: "New data became available in 2015 allowing the estimation of natural

Figure 2. The evolution of industrial energy consumption (Mtoe), gross value added (million 2010 SAR), and energy productivity (2010 SAR per toe).



Sources: IEA, SAMA, and KAPSARC analysis.

gas consumption as a feedstock in ammonia and methanol manufacture from 1990 to 2013. The remaining natural gas consumption has been allocated to the non-specified industry sector. Breaks in time series may occur between 1989 and 1990 for this reason." This is a further reason for adopting the STSM approach since such an issue can be resolved using level or slope interventions and, not surprisingly, the preferred estimated econometric model includes a level intervention for 1990.

Results and Discussion

Econometric results

Following the estimation strategy outlined in the Methods section, the preferred estimated energy demand equation was obtained for the period 1986-2016. Table 1 shows the estimated coefficients. More information on the estimated econometric equation can be found in Appendix B.

Given that energy consumption, income, and price enter the estimated equation in natural logarithms, the associated estimated coefficients can be interpreted as elasticities. An income elasticity of 0.60 implies that if manufacturing value added increased by 10%, energy consumption would increase by 6.0%. Similarly, a price elasticity of -0.34 implies that if energy prices increased by 10%, energy consumption would decrease by 3.4%.

The estimated model reveals that industrial energy demand is somewhat income inelastic, with a long-run elasticity of 0.60. Additionally, demand is revealed to be price inelastic, both in the short and long run. The short-run price elasticity is found to be -0.18, which reflects the response of companies to a price change in the same year. The long-run price elasticity is found to be -0.34, which reflects the net response of companies to a price change over a two-year period. Comparing our long-run price elasticity for industry (-0.34) in Saudi Arabia with the price elasticity for residential electricity (-0.16) from Atalla and Hunt (2016) and the price elasticity for gasoline (-0.09 to -0.15) from Atalla et al. (2018) demonstrates that industrial energy demand is considerably more price elastic. In other words, companies are more responsive than households to price changes.

The estimated model also reveals that economic structure has a significant impact on energy demand, with a long-run elasticity of 0.67. This coefficient is not interpreted as an elasticity since the structural factor does not enter the equation in logarithms. Instead, the long-run coefficient (0.67) may be interpreted as follows: a 10 percentage point increase in the structural factor, which is a ratio between 0 and 1, yields a 6.7% increase in industrial energy demand. This underscores the large impact a change in economic structure can have on industrial energy demand.

Table 1. Estimated coefficients from the preferred econometric model.

Variable	Short-run coefficient	Long-run coefficient
Income	0.60	0.60
Price	-0.18	-0.34
Structure	N/A	0.67

Source: KAPSARC.

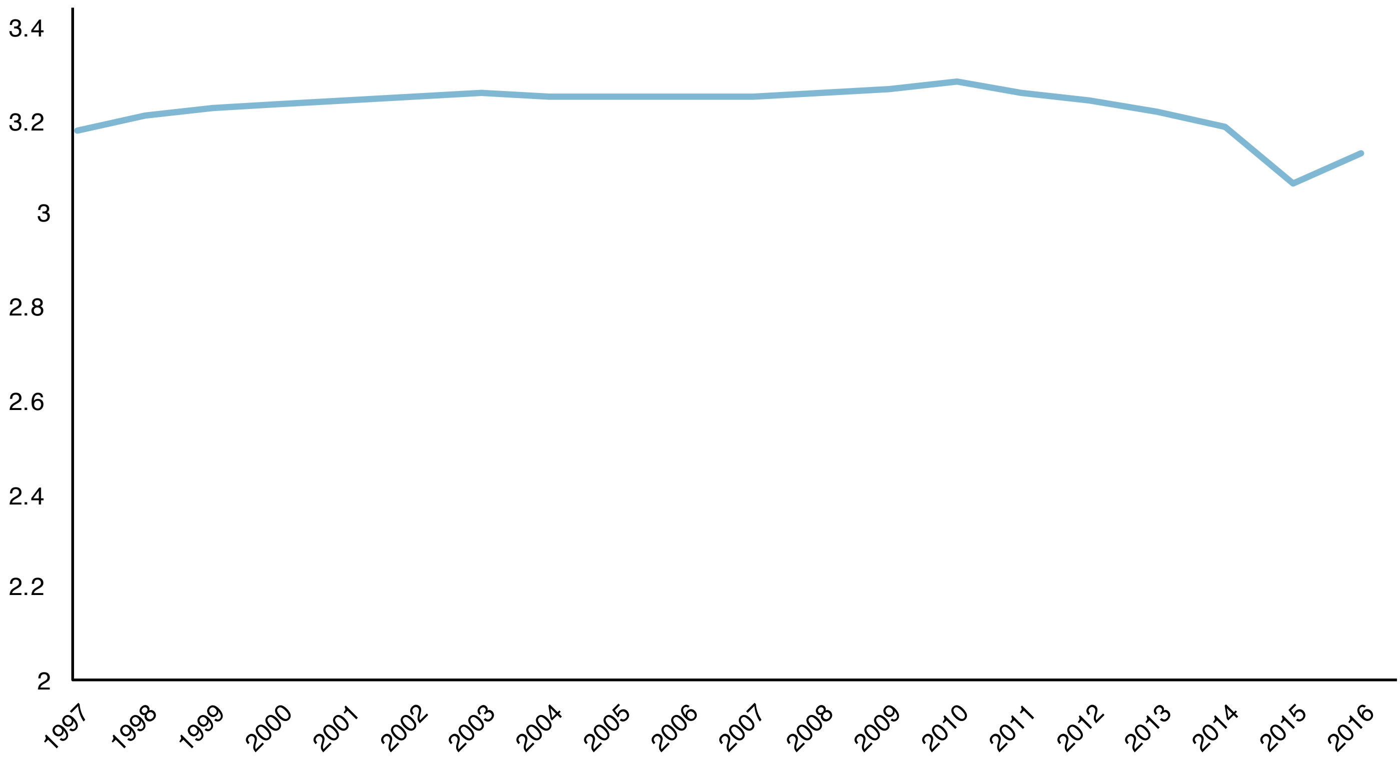
Figure 3 shows the estimated UEDT for the preferred model. In many econometric studies of industrial energy demand, the UEDT captures changes in energy efficiency and economic structure, two variables that are exogenous in most models. However, because we made the effect of economic structure endogenous through the inclusion of the structural factor as an independent variable in the model, the UEDT should largely reflect changes in energy efficiency. Figure 3 shows that until 2010 the UEDT was upward sloping or flat, suggesting a lack of improvement in energy efficiency during this period. From 2010 onwards, the UEDT became downward sloping with a negative derivative, suggesting a growing role for energy efficiency in reducing industrial energy consumption in the Kingdom.

Decomposition results

Decomposition analysis was used to quantify the contributions of the different drivers to the historical growth in energy consumption. Figure 4 shows the decomposition results. They reveal that year-to-year industrial energy consumption grew in most periods, with only a handful of exceptions (see the black dots in Figure 4). The decomposition results also reveal what drove the net changes in industrial energy consumption from year to year (see the stacked columns in Figure 4).

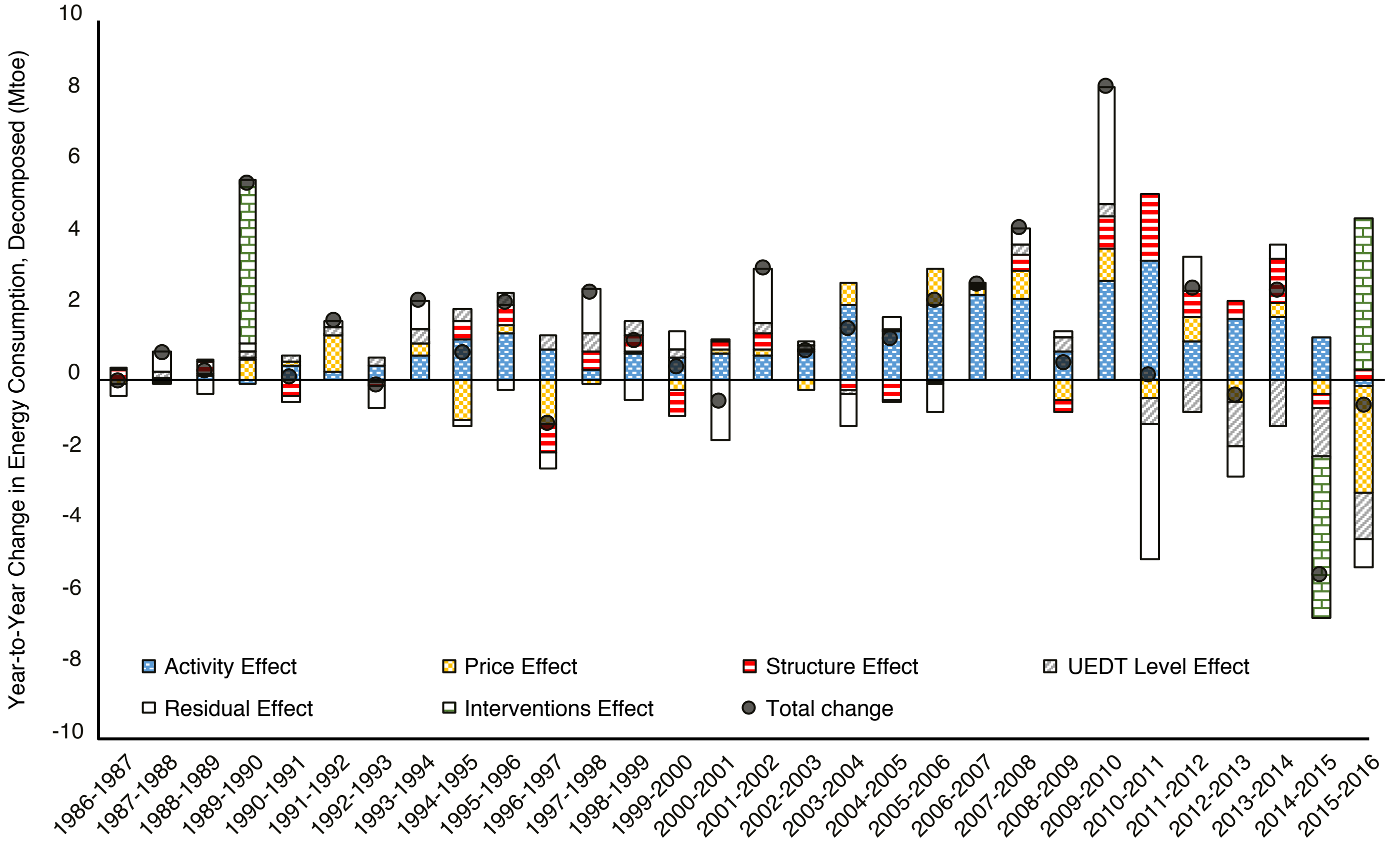
The results show that between 1986 and 2016 the activity effect (the growth in output) was consistently positive, driving energy demand growth, with 1986-1987, 1989-1990, and 2015-2016 the only

Figure 3: The evolution of the estimated UEDT (minus interventions) for Saudi industrial energy demand. (The UEDT is dimensionless.)



Source: KAPSARC analysis.

Figure 4. The total change in actual energy consumption (year-to-year) decomposed into five drivers.



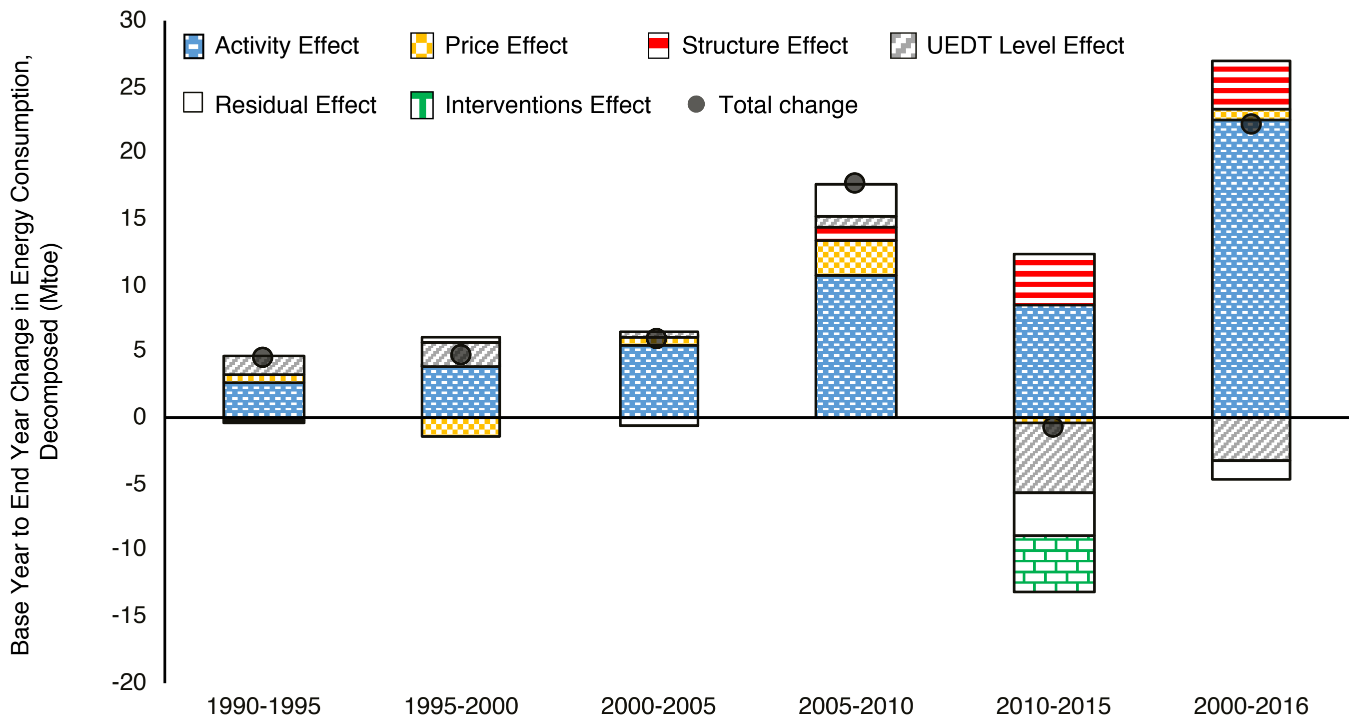
Source: KAPSARC analysis.

years during which Saudi industry contracted. In fact, the activity effect appears to have played the biggest role in driving industrial energy demand growth. Another important driver that consistently exerted upward pressure on industrial energy demand was the structure effect. Positive values reflect the impact of Saudi Arabia's move toward more energy-intensive manufacturing in the year-to-year change in energy consumption. In contrast, the price effect played a limited role, with small negative and positive values observed in the results. This is unsurprising given that energy prices were largely flat, with minor increases scattered throughout the study period (for example, the industrial diesel price increased in 1995). Energy prices occasionally had a positive impact on energy consumption growth because they decreased in real terms, even if they remained flat in nominal terms. However, between 2016 and 2015, energy price reforms resulted in a significant 3 Mtoe decrease in energy consumption, highlighting the potential role that energy price reform can play in managing the growth of industrial energy demand. The efficiency effect also appears to have played a limited role up to 2010. However, from 2010 onward, the efficiency effect consistently exerted downward pressure on industrial energy demand, suggesting that energy efficiency improved in the industrial sector. Around this time, the Saudi government displayed increasing interest in energy efficiency, establishing a number of initiatives around it.

The interventions effect reflects the impact that interventions added to the estimated econometric model had on the decomposition results. These interventions were added to the model to improve its fit and may capture issues in the data, such as the break in the IEA data starting in 1990, global events that affected the Saudi economy, and local economic reforms. In some cases, the intervention can be attributed to an easily identifiable event. In other cases, it can be difficult to attribute the intervention to a specific event or policy, particularly when there are lags between them and their impact on a variable such as energy consumption.

Figure 5 shows the decomposition results over longer periods. These results make it possible to see the longer-term impacts of the drivers of energy demand. Focusing on the decomposition results for the period 2000-2016, we can see that actual energy consumption grew by 22.2 Mtoe. The activity effect, which reflects the growth in output, was the primary driver, contributing 22.6 Mtoe to this growth. The structure effect, which reflects Saudi Arabia's shift toward energy-intensive manufacturing, contributed an additional 3.6 Mtoe. The price effect also contributed 0.7 Mtoe to this growth, even though energy prices were reformed in 2016. There are two reasons for this. First, industrial fuel prices have remained largely flat since 2000, which implies that they have been decreasing each year in real terms. Therefore, even after the first stage of price reform, the real average industrial energy

Figure 5. The total change in actual energy consumption between an end year and a base year decomposed into drivers.



Source: KAPSARC analysis.

price in 2016 was only slightly higher than in 2000 when adjusted for inflation. Second, even though contemporaneous industrial fuel prices in 2016 were higher than in 2000, the price effect captures both differences in contemporaneous prices (2000-2016) and differences in lagged prices (1998-2014). The data shows that the lagged price in 2014 was far lower than in 1998, leading to the estimated result of 0.7 Mtoe. In contrast to the activity, structure, and price effects, the energy efficiency effect helped lessen the growth in industrial energy consumption, contributing -3.2 Mtoe. The error term or residual effect accounted for the remainder.

Conclusions

This study is, to the best of our knowledge, the first to model aggregate industrial energy demand in Saudi Arabia econometrically and quantify the drivers of its growth. The estimated model revealed long-run income and price elasticities of 0.60 and -0.34, respectively. The long-run income elasticity suggests that Saudi Arabian industrial energy consumption will continue to grow over the coming decades as economic activity expands. However, the long-run price elasticity suggests there is the potential for mitigating this growth through increased energy prices. The price elasticity also demonstrates that industrial companies are more responsive than households to changes in energy prices.

The estimated econometric model also showed that Saudi Arabia could increase its industrial energy productivity substantially by moving away from energy-intensive manufacturing. The structural elasticity shows that a 10 percentage point shift away from energy-intensive exports, for example, could reduce industrial energy consumption by as much as 6.7% in the long run, holding all else fixed. This underscores the important role economic structure can play over the next decade as Saudi Arabia moves toward higher value-added manufacturing.

Decomposition analysis was then applied to the estimated econometric model to quantify the drivers of growth in Saudi Arabia's industrial energy consumption over the past several decades. The decomposition results showed that the activity effect was the primary driver. Additionally, the shift toward energy-intensive manufacturing exerted upward pressure on industrial energy consumption throughout the study period. In contrast, the efficiency effect exerted downward pressure from 2010 onward, helping to mitigate some of the growth in industrial energy consumption. Finally, the decomposition analysis revealed that energy prices, which had not changed significantly prior to 2016, played a limited role.

On December 29, 2015, Saudi Arabia implemented the first stage of its energy price reform program, affecting households and companies across all sectors of the economy (Alriyadh 2015). Saudi Arabia's energy price reform program aims to raise domestic energy prices toward international benchmarks, which will raise government revenues, stimulate productivity and encourage Saudi Arabia to make investments to help diversify its energy mix. The decomposition analysis showed that higher industrial fuel prices in 2016 reduced the sector's annual energy consumption by 6.9%, the equivalent to energy savings of around 3 Mtoe. Further gradual price reform for industrial fuels is expected over the coming years, which will likely mitigate the growth rates of industrial energy consumption in Saudi Arabia.

Although we quantify the impact of higher energy prices on consumption, we do not show the possible impact of higher energy prices on competitiveness. Saudi Arabia's relatively low energy prices have steered its domestic industries toward the production and export of energy-intensive goods. Higher energy prices would likely weaken their advantage in energy-intensive exports, but may also drive them toward the production and export of higher value-added goods. The latter scenario already appears to be the case, with the petrochemical industry moving toward the production of higher value-added chemicals (Jadwa 2017).

Since higher domestic energy prices lift government revenues, they may be combined with a subsidy scheme (or similar program) that promotes industrial energy efficiency to lessen the negative impact of higher energy prices on competitiveness. In fact, the decomposition analysis showed that improvements in energy efficiency between 2010 and 2016 delivered cumulative energy savings of around 7 Mtoe. Energy efficiency measures thus carry the potential to mitigate the rapid growth in industrial energy consumption and support the competitiveness of industrial companies.

In summary, the econometric results revealed the relationships between prices, income, structure, efficiency, and energy consumption in the Saudi industrial sector, while the decomposition results showed the drivers of the growth in industrial energy consumption. The results also highlight how energy efficiency has been a key factor in mitigating the rapid growth of industrial energy consumption over the last decade. Furthermore, in 2016, higher energy prices helped to significantly reduce consumption in that year. This shows that policymakers could build on Saudi Arabia’s current policy of energy price reform and energy efficiency measures to mitigate the rate of growth of industrial energy consumption, increase economic efficiency, and maintain industrial competitiveness.

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Appendix A: Methods

A.1 Econometric modeling of industrial energy demand

Equation (1) is estimated using the following dynamic autoregressive distributed lag specification:

$$e_t = \alpha_1 e_{t-1} + \alpha_2 e_{t-2} + \beta_0 gva_t + \beta_1 gva_{t-1} + \beta_2 gva_{t-2} + \gamma_0 p_t + \gamma_1 p_{t-1} + \gamma_2 p_{t-2} + \delta_0 SF_t \quad \text{(A1)}$$

$$+ \delta_1 SF_{t-1} + \delta_2 SF_{t-2} + UEDT_t + \varepsilon_t$$

The variables e_t, gva_t, and p_t are the natural logarithms of E_t, GVA_t, and P_t in year t, respectively, and ε_t is a random white noise error term. A two-year lag, which is considered reasonable given the 30-year time horizon, was employed to capture any possible dynamic effects. The coefficients β_0 and γ_0 represent the short-run (impact) elasticities for gross value added and price, respectively. The coefficient δ_0 reflects the short-run impact of economic structure on energy demand (the structural factor is the only independent variable that is not measured in logs). The corresponding long-run output, price and structure coefficients are given by

$B = \frac{\beta_o + \beta_1 + \beta_2}{1 - \alpha_1 - \alpha_2}$, $\Gamma = \frac{\gamma_o + \gamma_1 + \gamma_2}{1 - \alpha_1 - \alpha_2}$, and $\Delta = \frac{\delta_o + \delta_1 + \delta_2}{1 - \alpha_1 - \alpha_2}$, respectively.

The UEDT is a stochastic trend estimated through the STSM as follows:

$$\mu_t = \mu_{t-1} + \rho_{t-1} + \eta_t \, ; \qquad \eta_t \sim NID\,(0, \sigma_\eta^2) \quad \text{(A2)}$$

$$\rho_t = \rho_{t-1} + \xi_t \, ; \qquad \xi_t \sim NID\,(0, \sigma_\xi^2) \quad \text{(A3)}$$

The parameters μ_t and ρ_t are the level and slope of the UEDT, respectively, which together determine the shape of the stochastic trend component (Harvey and Shephard 1993). The hyper-parameters η_t and ξ_t are the mutually uncorrelated white noise disturbances with zero means and variances σ_η^2 and σ_ξ^2, respectively.

Equations (A2), (A3), and (A4) are estimated by a combination of maximum likelihood and the Kalman filter using the software package STAMP 8.30 (Koopman et al. 2007). When necessary, irregular/outlier interventions (Irr), level interventions (Lvl), and/or slope interventions (Slp) are added to the model to improve the fit and to help ensure it passes an array of diagnostic tests for the standard and auxiliary (irregular, level, and slope) residuals. Moreover, the interventions provide information about important breaks and structural changes during the estimation period (Harvey and Koopman 1992). The estimation strategy thus involves initially estimating the general model given by Equations (A2), (A3), and (A4) and then eliminating insignificant variables and adding interventions but ensuring the model passes an array of diagnostic tests until the preferred parsimonious model is obtained.

Interventions can change the shape of the UEDT and, in their presence, the UEDT is given by the following equation according to Dilaver and Hunt (2011):

$UEDT_t = \mu_t$ + irregular interventions + level interventions + slope interventions (A4)

As noted by Hunt et al. (2003), the UEDT is a non-linear stochastic trend that reflects exogenous factors that affect energy demand, such as energy efficiency and changes in consumer tastes and preferences, which often vary in non-linear ways throughout time.

A.2 Decomposition of the estimated energy demand equation

The first step in our approach requires the estimated version of Equation (B2), the energy demand function, to be converted to a multiplicative form by taking anti-logs:

$$E_t = E_{t-1}^{\widehat{\alpha_1}} E_{t-2}^{\widehat{\alpha_2}} GVA_t^{\widehat{\beta_0}} GVA_{t-1}^{\widehat{\beta_1}} GVA_{t-2}^{\widehat{\beta_2}} P_t^{\widehat{\gamma_0}} P_{t-1}^{\widehat{\gamma_1}} P_{t-2}^{\widehat{\gamma_2}} \quad \text{(A5)}$$

$$* \, exp\,(\widehat{\delta_0} SF_t) exp\,(\widehat{\delta_1} SF_{t-1}) exp\,(\widehat{\delta_2} SF_{t-2}) exp\,(\widehat{UEDT_t}) exp\,(\widehat{\varepsilon_t})$$

Similarly, energy demand in a base year denoted by the subscript 'r' when expressed in multiplicative form becomes:

$$E_r = E_{r-1}^{\widehat{\alpha_1}} E_{r-2}^{\widehat{\alpha_2}} GVA_r^{\widehat{\beta_0}} GVA_{r-1}^{\widehat{\beta_1}} GVA_{r-2}^{\widehat{\beta_2}} P_r^{\widehat{\gamma_0}} P_{r-1}^{\widehat{\gamma_1}} P_{r-2}^{\widehat{\gamma_2}} \quad \text{(A6)}$$

$$* \exp\,(\widehat{\delta_0} SF_r) \exp\,(\widehat{\delta_1} SF_{r-1}) \exp\,(\widehat{\delta_2} SF_{r-2}) \exp\,(\widehat{UEDT_r}) \exp\,(\widehat{\varepsilon_r})$$

The goal of additive decomposition analysis is to decompose the change in energy consumption between an end year and a base year into additive components which we call drivers. Given that in its most general form our estimated energy demand equation is a product of 13 factors, LMDI will thus generate 13 drivers of energy demand as follows:

$$E_t - E_r = \Delta E_{E_{t-1}} + \Delta E_{E_{t-2}} + \Delta E_{GVA_t} + \Delta E_{GVA_{t-1}} + \Delta E_{GVA_{t-2}} + \Delta E_{P_t} + \Delta E_{P_{t-1}} + \Delta E_{P_{t-2}}$$

$$+ \Delta E_{SF_t} + \Delta E_{SF_{t-1}} + \Delta E_{SF_{t-2}} + \Delta E_{UEDT} + \Delta E_{\varepsilon} \quad \text{(A7)}$$

Where:

$$\Delta E_{E_{t-1}} = w_i ln \left(\frac{E_{t-1}{}^{\widehat{\alpha_1}}}{E_{r-1}{}^{\widehat{\alpha_1}}}\right) \quad \text{(A8)}$$

$$\Delta E_{E_{t-2}} = w_i ln \left(\frac{E_{t-2}{}^{\widehat{\alpha_2}}}{E_{r-2}{}^{\widehat{\alpha_2}}}\right) \quad \text{(A9)}$$

$$\Delta E_{GVA_t} = w_i ln \left(\frac{GVA_t{}^{\widehat{\beta_0}}}{GVA_r{}^{\widehat{\beta_0}}}\right) \quad \text{(A10)}$$

$$\Delta E_{GVA_{t-1}} = w_i ln \left(\frac{GVA_{t-1}{}^{\widehat{\beta_1}}}{GVA_{r-1}{}^{\widehat{\beta_1}}}\right) \quad \text{(A11)}$$

$$\Delta E_{GVA_{t-2}} = w_i ln \left(\frac{GVA_{t-2}{}^{\widehat{\beta_2}}}{GVA_{r-2}{}^{\widehat{\beta_2}}}\right) \quad \text{(A12)}$$

$$\Delta E_{P_t} = w_i ln \left(\frac{P_t{}^{\widehat{\gamma_0}}}{P_r{}^{\widehat{\gamma_0}}}\right) \quad \text{(A13)}$$

$$\Delta E_{P_{t-1}} = w_i ln \left(\frac{P_{t-1}{}^{\widehat{\gamma_1}}}{P_{r-1}{}^{\widehat{\gamma_1}}}\right) \quad \text{(A14)}$$

$$\Delta E_{P_{t-2}} = w_i ln \left(\frac{P_{t-2}{}^{\widehat{\gamma_2}}}{P_{r-2}{}^{\widehat{\gamma_2}}}\right) \quad \text{(A15)}$$

$$\Delta E_{SF_t} = w_i ln \left(\frac{exp\ (\widehat{\delta_0} SF_t)}{exp\ (\widehat{\delta_0} SF_r)}\right) \quad \text{(A16)}$$

$$\Delta E_{SF_{t-1}} = w_i ln \left(\frac{exp\ (\widehat{\delta_1} SF_{t-1})}{exp\ (\widehat{\delta_1} SF_{r-1})}\right) \quad \text{(A17)}$$

$$\Delta E_{SF_{t-2}} = w_i ln \left(\frac{exp\ (\widehat{\delta_2} SF_{t-2})}{exp\ (\widehat{\delta_2} SF_{r-2})}\right) \quad \text{(A18)}$$

$$\Delta E_{UEDT} = w_i ln \left(\frac{exp\ (\widehat{UEDT_t})}{exp\ (\widehat{UEDT_r})}\right) \quad \text{(A19)}$$

$$\Delta E_{\varepsilon} = w_i ln \left(\frac{exp\ (\widehat{\varepsilon_t})}{exp\ (\widehat{\varepsilon_r})}\right) \quad \text{(A20)}$$

$$w_i = \frac{E_t - E_r}{e_t - e_r} \quad \text{(A21)}$$

Thus, each independent variable, each lagged dependent variable, the UEDT, and the error term become determinants or drivers of the absolute change in energy consumption between year t and year r. By combining similar terms, the 13 drivers can be reduced to 6: A lagged energy effect ΔE_{lag}, an activity effect ΔE_{act}, a price effect ΔE_{pri}, a structure effect ΔE_{str}, an efficiency effect ΔE_{eff}(assuming the UEDT mainly captures energy efficiency), and an error term effect ΔE_{err}. These terms are defined below:

$$\Delta E_{lag} = \Delta E_{E_{t-1}} + \Delta E_{E_{t-2}} \quad \text{(A22)}$$

$$\Delta E_{act} = \Delta E_{GVA_t} + \Delta E_{GVA_{t-1}} + \Delta E_{GVA_{t-2}} \quad \text{(A23)}$$

$$\Delta E_{pri} = \Delta E_{P_t} + \Delta E_{P_{t-1}} + \Delta E_{P_{t-2}} \quad \text{(A24)}$$

$$\Delta E_{str} = \Delta E_{SF_t} + \Delta E_{SF_{t-1}} + \Delta E_{SF_{t-2}} \quad \text{(A25)}$$

$$\Delta E_{eff} = \Delta E_{UEDT} \quad \text{(A26)}$$

$$\Delta E_{err} = \Delta E_{\varepsilon} \quad \text{(A27)}$$

Appendix B: The Estimated Econometric Model

Following the estimation strategy outlined in the Methods section of this paper, the preferred estimated energy demand equation was obtained for the period 1986-2016 and is shown in Table B1, along with the interventions that were needed to ensure that it passed all the tests. Table B1 also presents the results of the summary statistics and residual diagnostics tests.

Table B1. The preferred econometric model.

Estimated Coefficients	
α_1	N/A
α_2	N/A
β_0	0.60022***
β_1	N/A
β_2	N/A
γ_0	-0.18325*
γ_1	N/A
γ_2	-0.15669**
δ_0	N/A
δ_1	0.67164**
δ_2	N/A
Estimated Long-Run Coefficients	
Income (Elasticity)	0.60
Price (Elasticity)	-0.34
Structure	0.67
Hyper-Parameters	
Level	0.000352050
Slope	6.97848e-005
Irregular	0.00137767
Interventions	LVL1990***
	IRR2015*
Goodness of Fit	
p.e.v.	0.0023648
AIC	-5.4664
R^2	0.99639
R_d^2	0.90482

Appendix B: The Estimated Econometric Model

Residual Diagnostics	
Std Error	0.0023648
Normality	1.0847
H(h)	H(6) = 2.1168
r(1)	-0.063756
r(2)	-0.010035
r(3)	-0.22444
DW	1.9385
Q(p, d)	$\chi^2_{5,3} = 2.0977$
r(q)	*r(5) = 0.12556*
Auxiliary residuals:	
Normality – Irregular	0.62668
Normality – Level	2.6622
Normality – Slope	1.1162
Prediction failure	$\chi^2_7 = 9.9265$

Note: The *, **, and *** represent significance at the 10%, 5%, and 1% level, respectively.
Sources: KAPSARC analysis.

These include the prediction error variance (PEV), the Akaike information criterion (AIC), R^2 (the coefficient of determination), and R_d^2 (the coefficient of determination based on differences). All the normality tests are based on the Bowman-Shenton test distributed approximately as $X^2{}_2$, while $H_{(h)}$ is the test for heteroscedasticity, distributed approximately as $F_{(h,h)}$. These are complemented by the Durbin-Watson statistic (DW), the residual autocorrelation coefficients at lag 1 *r(1)*, lag 2 *r(2)*, lag 3 *r(3)*, and lag q *r(q)*, distributed approximately as N(0, 1/T), and $Q_{(p,d)}$, which is the Box-Ljung statistic based on the first p residuals' autocorrelations and distributed approximately as χ^2_d. Finally, there is the Predictive Failure test χ^2_f for the last eight years of the estimation period, distributed approximately as χ^2_8. Table B1 demonstrates that the preferred model passed all of these diagnostic tests.

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About the Project

This paper is part of the project titled 'Modeling Final Energy Demand Using the Structural Time Series Model.' This project examines how factors such as economic growth, income, energy prices, economic structure, and energy efficiency influence the demand for energy at national, sectoral, and household levels. This project also measures the impact of various energy policies, such as energy price reform, on energy demand, government revenues, and social welfare in the Kingdom.

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