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Regional Fuel Consumption and Carbon Dioxide Emissions in Saudi Arabia: Impacts of Electricity Price Reforms

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Contributions

All authors conceived the study and have approved the final article. Abdulelah Darandary and Jeyhun Mikayilov developed the econometric methodology, and Salaheddine Soummane developed the power system methodology. All authors contributed to writing the manuscript.

Declaration of Interest Statement

No conflicts of interest exist, and no external funding was received for this work. The views expressed in the paper are those of the authors and do not reflect the position of their institution.

About KAPSARC

KAPSARC is an advisory think tank within global energy economics and sustainability providing advisory services to entities and authorities in the Saudi energy sector to advance Saudi Arabia's energy sector and inform global policies through evidence-based advice and applied research.

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Key Points

Evaluating the potential outcomes of energy price reforms is essential for policymakers to assess their effectiveness. In 2016 and 2018, the Saudi government enacted two waves of energy price reforms to curb historically fast-growing electricity demand. We quantify the effects of these measures on regional fuel consumption and carbon emissions. We use a regional econometric model to assess demand changes following the price reforms, and we adopt an optimization model to quantify fuel savings and carbon emissions reductions. We estimate that between 2016 and 2019, electricity demand fell by 8.8% per year, on average, following the price reforms, resulting in US$1.3-1.4 billion in fuel savings. If international oil prices are considered, the total savings increase to US$9.8 billion. Moreover, we show that the two waves of electricity price reforms reduced carbon dioxide emissions by 81-102 million tonnes, a decrease of 8.2%-10.4% of the power sector's emissions. Our results for Saudi Arabia demonstrate the benefits of reforming energy prices for countries with administered tariffs. Such reforms can serve as an effective tool for achieving climate pledges by reducing inefficient demand and carbon emissions.

We quantify the effects of energy price reforms on electricity demand in Saudi Arabia.

We consider regional characteristics of electricity demand and supply.

Price reforms lowered electricity demand by 8.8% per year, on average, from 2016 to 2019.

We estimate the total cost savings from reduced electricity demand at US$1.3-1.4 billion.

When the opportunity cost of saved fuels is considered, the total savings are US$2.1-8.01 billion.

Total avoided carbon emissions amounted to 81-102 million tonnes from 2016 to 2019.

1.Introduction

1.1 Background and Saudi context

Many countries have implemented direct policies such as carbon taxes and trading schemes as effective tools to mitigate emissions (Stiglitz et al. 2017). Indirect policies can also benefit countries that continue to administer domestic energy prices. Reforming domestic energy prices to reflect market-driven levels could bring substantial fiscal and environmental impacts (Coady, Parry and Shang 2015). The literature illustrates that implicit carbon policies, such as removing fossil fuel energy incentives or rationalizing energy prices, are more helpful in developing countries. This is because they allow for emissions mitigation without negatively affecting international competitiveness (Klenert et al. 2018). In that spirit, several Middle Eastern countries, notably Saudi Arabia, have implemented rounds of energy price reforms to curb unsustainable growth in domestic fuel consumption and rising fiscal stress (Krane 2018).

Following the sharp decline in international oil prices in 2014, Saudi Arabia launched an economic diversification plan, Vision 2030, to reduce its reliance on hydrocarbon revenues (SV2030 2016). As part of the Vision 2030 plan, the government launched the Fiscal Balance Program (FBP), a medium-term fiscal plan to sustain public finance (FBP 2017). The program is based on five key pillars, including the Energy and Water Price Reform plan. This plan seeks to stimulate rational energy consumption, strengthen the country's fiscal stance and redirect financial support based on several social criteria. In 2016, the first wave of energy prices reforms (EPR) was implemented, followed by the second round in 2018.

Prior to the EPR rounds, Saudi electricity consumption had increased at an average rate of 5.3% per year between 2010 and 2016 (SAMA 2020). Over the same period, carbon emissions from power generation grew at a similar pace, accounting for 41% of Saudi Arabia's 601 million tonnes of carbon dioxide (CO2) emissions in 2016 (Crippa et al. 2019). During the first EPR wave in 2016, electricity prices for various non-residential customer categories increased by around 20%. In the second EPR wave in 2018, reforms mainly targeted residential consumers, with a price increase of around 260% for the first consumption slab (Aldubyan and Gasim 2021). Following the two EPR rounds, Saudi electricity consumption growth slowed considerably. Average demand growth dropped to 0.5% between 2016 and 2018, and the first decline in electricity demand was recorded in 2019 (Soummane 2020). However, recent studies have shown that the impacts of the EPRs have been regionally heterogeneous, reflecting the significant disparities that exist in temperature, income and population (Mikayilov et al. 2020a). The four regions that typically characterize Saudi Arabia have significant differences with regard to their electricity demand drivers. This is also true for the two largest customer groups: residential and industrial.

To the best of our knowledge, this study is the first to quantify, at the regional level, the fuel consumption and carbon emissions that have been avoided as a result of the electricity price reforms in Saudi Arabia. Other approaches found in the literature consider the aggregate level or use a single unit conversion factor for power generation emissions. Sarrakh et al. (2020) used the price gap approach coupled with an input-output framework. They found that 98 million tonnes of CO2 emissions would have been avoided in 2012 if administered prices were removed. Aldubyan and Gasim (2021) investigated aggregate drivers of electricity consumption using a structural time series model to obtain estimates of national residential electricity and gasoline demand. However, their calculation relies on invoice-based rather than consumption-based prices to estimate elasticities.[1]

They reported a price elasticity of -0.09 and assumed that each kilowatthour (kWh) of electricity savings prevents 0.6 kilograms (kg) of CO2 emissions. Their findings suggest that 5.6 million tonnes of CO2 emissions were avoided as a result of the price reforms in 2018. Finally, Darandary, Mikayilov and Al Atawi (2021) used a partial equilibrium and power model to estimate the regional carbon emissions avoided in the residential sector because of the price reforms. They found that the electricity price reforms helped the sector avoid approximately 36 million tonnes of CO2 emissions from 2016 to 2018. In this study, we extend this approach to all electricity customers.

The contribution of this study, which quantifies the impact of price reforms on fuel consumption and emissions, is threefold. First, we assess consumers' responsiveness to electricity price changes at the regional level through a partial equilibrium model. This allows for region-specific income and price elasticities. Second, we simulate a counterfactual scenario, where we estimate regional electricity consumption in the absence of the two rounds of price reforms in 2016 and 2018. Third, we simulate the electricity demand scenarios using a power system dispatch model to generate fuel consumption and CO2 emissions.

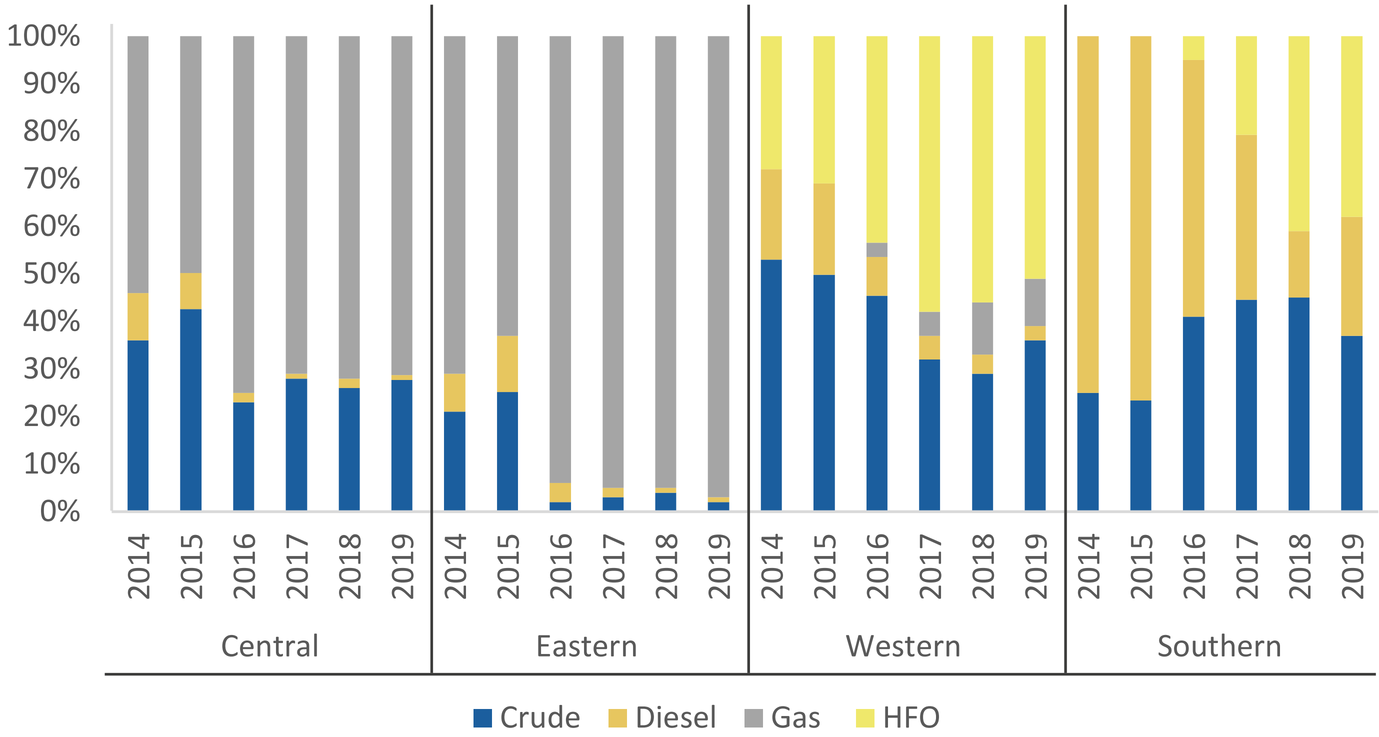
The remainder of this paper is divided into four sections: The rest of section 1 details the regional composition of electricity demand in terms of customers and fuel mix. Section 2 provides an overview of the data, methodologies and scenarios used in the study. Section 3 discusses the results of our empirical findings and the subsequent impacts of the counterfactual scenarios. Section 4 concludes the paper and discusses the study's policy implications.

1.2 Regional electricity consumption: Different customer and fuel mixes

Electricity generation in Saudi Arabia depends on four conventional energy sources (crude oil, diesel, heavy fuel oil [HFO] and natural gas) as well as a negligible amount of renewables (ECRA 2019). The two waves of price reforms were impactful, as customers switched to more efficient appliances and rationalized their consumption (GaStat 2018). However, aggregating electricity demand omits considerable variation across regions and might exclude valuable information (Lee, Pesaran and Pierse 1990). Regional supply disparities and differences in the demand drivers of electricity warrant a region-specific approach.

First, the disparity in power generation sources between regions is significant because of infrastructure, access and capacity differences. Figure 1 highlights the 2015-2019 power generation by fuel type for each region of Saudi Arabia. The figure shows how significantly different the four regions are in their fuel mix. For example, the eastern region's electricity generation is almost entirely powered by natural gas, as the region hosts extraction facilities. All other regions rely on crude oil, while HFO is exclusively used in the western and southern regions. Finally, diesel use has been declining in prominent regions of the country, but it remains a significant source in the southern region for supplying power to remote areas and water desalination plants. However, overall fuel use in the southern region is relatively small, accounting for only 7% of the fuel consumption needed for electricity and seawater desalination (ECRA 2019).

Figure 1. Fuel mix by region, 2015-2019.

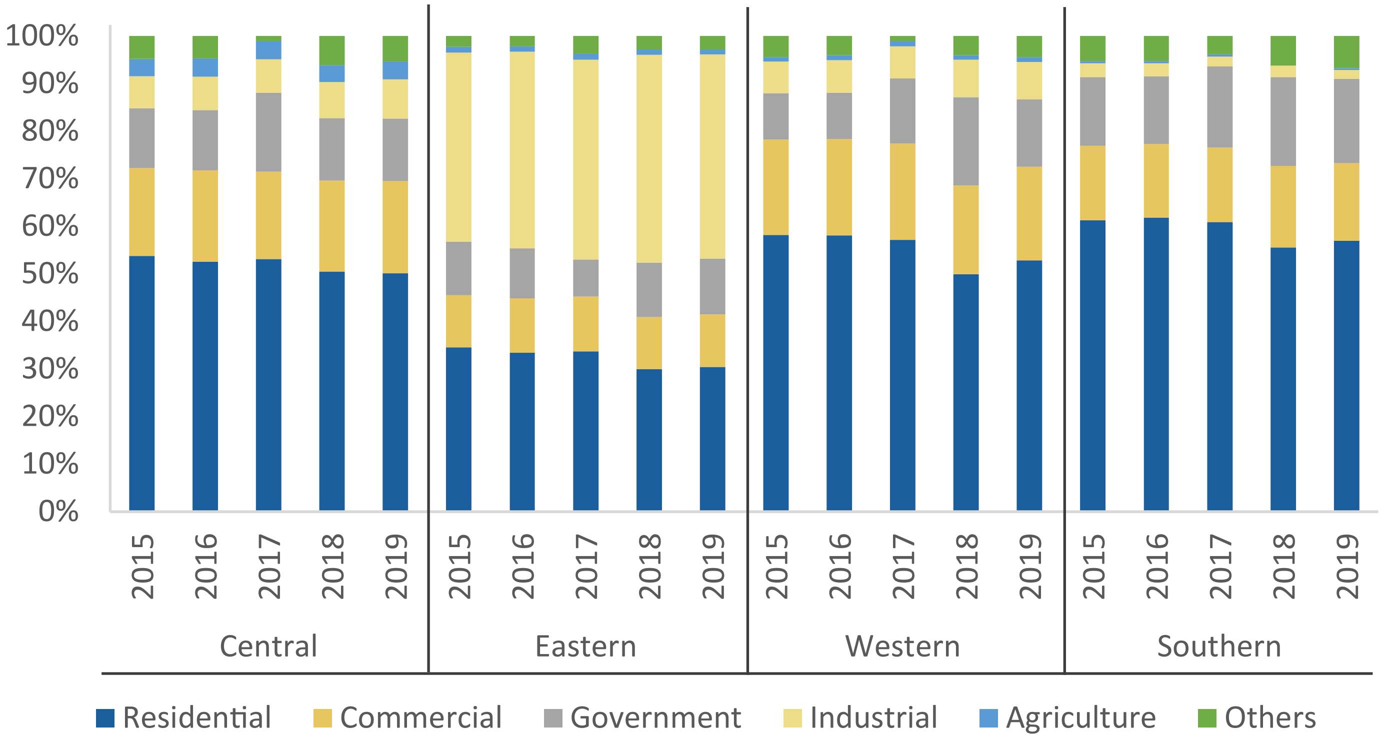


Source: ECRA.

Note: Reported fuel consumption data from ECRA are for electricity generation and water desalination.

Second, each region differs in terms of its electricity customers (see Figure 2). The largest difference lies within the industrial sector in the eastern region, which accounts for 43% of all electricity consumption in the region. By contrast, the sector accounts for no more than 8% of total consumption in the other regions (ECRA 2019). The eastern region houses Saudi Arabia's oil and gas sector, and it is involved in many associated economic activities. Moreover, residential customers make up a large percentage of electricity users – over 50% – for the central, western, and southern regions. However, they only account for about 30% of electricity users in the eastern region. These regional disparities in customers, along with other regional differences such as weather conditions and economic structure, help explain the regional responsiveness to price reforms and its implications. Studies have shown that electricity consumption drivers are not uniform, with regards to their impacts, across Saudi regions. The income and price elasticities of electricity demand differ for the residential sector (Mikayilov et al. 2020a) and industrial sector (Mikayilov et al. 2022). Hence, previous and potential price reforms will impact regions differently depending on their customer composition, environment and available fuel mix.

Figure 2. Shares of Saudi electricity demand by sector and region, 2015-2019.



Source: SAMA (2020).

Note: Demand in "Others" includes educational, health and desalination purposes.

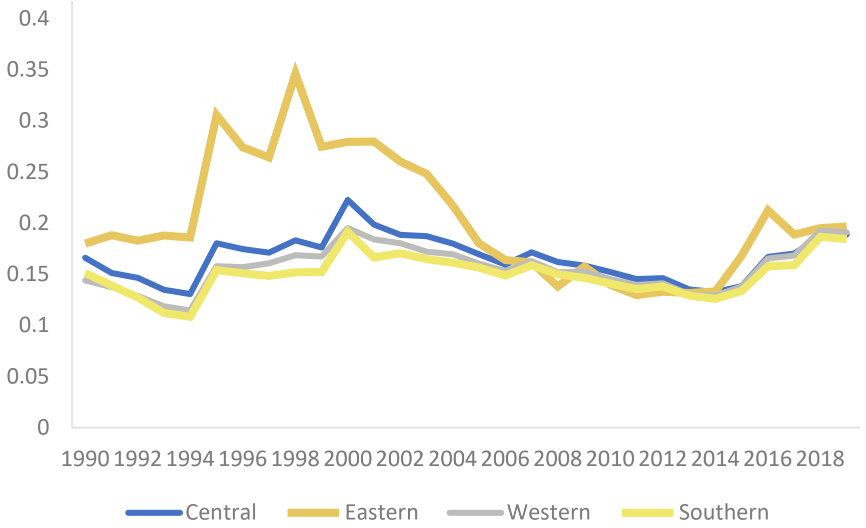
2.Data, Methodologies and Scenarios

2.1 Data

We used annual data for the period 1990 to 2019, based on data availability. Total electricity consumption (TEC) data in megawatthours (MWh) for 1990-2004 were obtained from the Saudi Electricity Company (SEC), while the 2005-2019 data came from the Saudi Central Bank's Annual Statistics (SAMA 2020). Regional annual population data for 1990-2006 were collected from population surveys conducted by the General Authority for Statistics (GaStat) of Saudi Arabia, while data for the 2007-2019 period were retrieved from SAMA (2020). We use gross domestic product (GDP) and non-oil gross value added (GVA) as income proxies, depending on the region. Since the eastern region is solely responsible for the oil sector's output, we used GDP as an income proxy for this region. Following Hasanov et al. (2016), the income for the other three regions was proxied by non-oil GVA.

Data on nominal electricity prices were collected from multiple sources, including the Saudi Electricity Company (2017), the Water & Electricity Regulatory Authority (ECRA 2019) and AlGhamdi (2019). Saudi authorities administer nominal prices for each customer type: government, agriculture, residential, industrial and commercial users. Electricity prices often remain fixed for long periods with minor revisions and can only be changed by the Saudi Council of Ministers. To obtain a representative price for each region, we aggregated real electricity prices using each region's customer consumption weights in each year (see Table 1). To convert nominal electricity prices to real[2] prices, we used sector-specific deflators obtained from GaStat. The consumer price index was used to deflate residential prices. In addition, we used a non-oil manufacturing sector deflator for industrial prices, except for the eastern region, where the oil refining sector deflator was used to adjust its industrial price.[3] We used the government sector deflator for government prices, the services sector deflator for the commercial prices and the agriculture sector deflator for agriculture prices. Figure 3 displays the weighted real prices for each region.

Figure 3. Real weighted regional electricity prices.



Source: Authors' calculations based on data from Saudi Electricity Company (2017), ECRA (2019) and AlGhamdi (2019).

Note: The Saudi Riyal (SAR) is pegged to the United States Dollar (US$) at US$1 = 3.75 Saudi Riyals (SAR); kWh=kilowatthours.

Finally, temperature data were obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information. For cooling degree days (CDD), the sum of the annual regional days with temperatures exceeding 21.1 degrees Celsius (°C) was used, following Atalla et al. (2018). This variable captures the amount of cooling required for households to achieve a comfortable indoor temperature. Heating degree days (HDD) captures the heating required for each region. Following the CDD calculation method, we calculated the annual days in each region in which temperatures were below the 18.3°C threshold (Atalla et al. 2015). Additionally, following Mikayilov et al. (2020a), we used humidity-adjusted CDD and HDD data. NOAA's National Weather Service Heat Index (NWS HI) measures the human-perceived equivalent temperature. The NWS HI was calculated through a multiple regression analysis of Steadman's equations (Steadman 1979) for wind and solar radiation using two independent variables: ambient temperature (T) and relative humidity (Rh) (Rothfusz 1990).

2.2 Methodologies

2.2.1 Econometric approach for the regional electricity demand

Electricity consumption is a function of income, prices, weather and population. The approach we use to estimate electricity consumption follows the theoretical framework of Beenstock and Dalziel (1986) and Atallah and Hunt (2016).

Our modeling technique utilizes the general-to-specific (Gets) approach (see Hendry and Doornik [2014]). First, we form the general unrestricted model (GUM), including all the relevant variables. Second, we use the autometrics multipath-search machine-learning algorithm (Doornik and Hendry 2018). This algorithm helps to capture potential exogenous interventions, such as one-time pulses, blips, changes in levels and breaks in trends, using the impulse-indicator saturation (IIS), differenced impulse-indicator saturation (DIS), step-indicator saturation (SIS) and trend-indicator saturation (TIS) dummies. Additionally, the autometrics algorithm enables testing parameters for potential variation over time using the multiplicative-indicator saturation approach (Castle and Hendry 2019; Castle, Hendry and Martinez 2017; Ericsson et al. 2012).

The general functional specification used in the empirical estimations is:

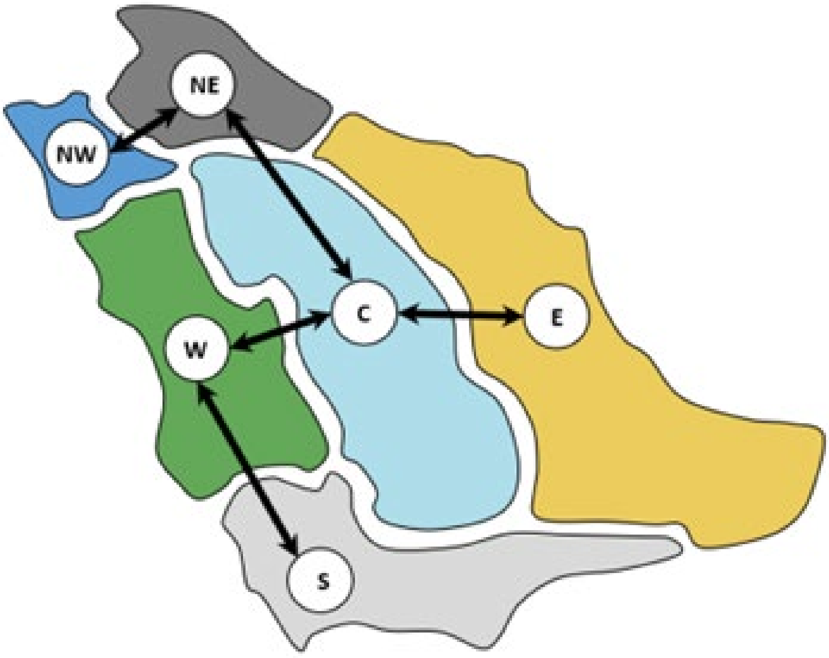
$$dele_t = \alpha_0 + \sum_1^2 \alpha_i\, dele_{t-i} + \sum_0^2 \beta_i\, inc_{t-i} + \sum_0^2 \gamma_i\, p_{t-i} + \sum_0^2 \delta_i\, cdd_{t-i} + \sum_0^2 \theta_i\, hdd_{t-i} + \sum_1^T \vartheta_i\, IIS_t + \sum_1^T \tau_i\, SIS_t + \sum_1^T \varphi_i\, DIIS_t + \sum_1^T \omega_i\, TIS_t + \varepsilon_t \quad (1)$$

where $dele$ is regional per capita electricity demand in period t for region r. inc is per capita income, p is electricity price, cdd is regional cooling degree days and hdd is regional heating degree days. All variables are in logarithmic form. IIS, SIS, $DIIS$ and TIS stand for impulse-indicator saturation, step-indicator saturation, differenced impulse-indicator saturation and trend-indicator saturation dummies. Following the Gets methodology, after first fixing theory-related variables with two lags, the intervention dummies are chosen using a tight significance level. In the second step, fixing the chosen dummies, the final model is chosen based on a battery of diagnostic tests. The multipath selection procedure uses the PcGive econometric modeling program (Doornik and Hendry 2018).

2.2.2 Optimization model of the Saudi power system

The KAPSARC Power Model (KPM) is an optimization model calibrated for Saudi Arabia. The model uses the PLEXOS software, calibrated to the 2018 power fleet, with a detailed representation of over 100 generation units (Elshurafa and Peerbocus 2020). The model has an hourly resolution of unit commitment based on the marginal cost of generation, and it represents six operating regions, as depicted in Figure 4.

Figure 4. Schematic representation of the KAPSARC power model.



Source: Authors' representation.

Note: Each region is denoted by a single node. "C" = central region; "E" = eastern region; "NE" = north-eastern region; "NW" = north-western region; "S" = southern region; "W" = western region.

The model adopts a cost-minimization approach, generating average and marginal electricity production costs and CO2 emissions, which can also be used for capacity expansion planning (Elshurafa et al. 2021). Moreover, KPM considers specific features of the Saudi power system, such as the must-run units based on fuel availability. We use administered fuel costs and emissions factors as detailed in Table 1.

The regional representations are mismatched between the load curves used in the KPM, which represent six operational regions, and the consumption data used in the econometric analysis (see Section 2.2.1), which represent four regions. To overcome this mismatch, we combined the north-eastern operating region (NEOA) with the eastern operating region and the north-western operating region (NWOA) with the western operating region. Both the NEOA and NWOA account for a small fraction of the national load. Thus, they do not affect the results' interpretation. During the calibration year 2018, NEOA and NWOA accounted for only 2.2% and 1.8% of the national load, respectively.

We simulate the power mix from 2016 to 2019 using the following approach. The starting point is the calibration year 2018, which we rescale on an hourly basis in 2016, 2017 and 2019 based on observed total electricity demand variations derived from ECRA (2019).[4] This approach is not expected to have a significant impact on our simulations as electricity demand was relatively flat in 2016 and 2017 compared with 2018, with less than a 1% difference from its 2018 value. In 2019, demand dropped by 3.5% compared with 2018. Moreover, the observed peak load during 2018, at 61.7 GW, remained flat during the simulated years, with only the 2016 peak demand being 1.5% lower than 2018.

After creating the hourly load profiles of the actual demand, that is, the actual load curve for the year 2018, in addition to the rescaled curves for the years 2016, 2017 and 2019, we apply the estimated demand variations (as detailed in Section 4.1). Each year's load is then weighted by the underlying contribution of the four regions to the load to derive the associated regional counterfactual demand.[5] To address the absence of behavioral data, such as consumer surveys or smart meter readings, we assume an even distribution of the variation across the hourly loads.[6] We do this to assess how consumers adjusted their consumption throughout the year following the price reforms. Soummane et al. (2022) analyzes the sensitivity of the Saudi power mix to displacing load using several scenarios, including varying the load across all hours of the day or targeting working or peak hours. They find that the former scenario yields relatively higher savings in Saudi Arabia at the power-system level than the latter scenario.

Table 1. Administered fuel prices and emissions factors.

Fuel	Price (US$/MMBtu)	Emission factor (kg/MMBtu)
Crude oil	1.144	77.5
Diesel	2.41	78.0
Natural gas	1.25	59.1
Heavy fuel oil	0.6	85.9

Source: Elshurafa et al. (2021).

Notes: kg= kilograms; MMBtu= million British thermal units.

2.2.3 Scenarios considering natural gas constraint

Natural gas accounts for 57% of Saudi power generation (ECRA 2019). Moreover, Saudi Arabia is the ninth-largest natural gas producer worldwide, with an annual output of 113.6 billion cubic meters in 2019 (BP 2020). Power generation and water desalination consume around 55% of the Kingdom's gas supply (ECRA 2019). Moreover, the high seasonality in power demand could cause congestion in the gas distribution network and potentially prompt investment in storage and import facilities (Matar and Shabaneh 2020). To reflect this congestion, we impose a constraint on the KPM by limiting natural gas feedstock for power generation to the daily limit for power generation using the daily caps from Matar and Shabaneh (2020). Moreover, to account for potential supply uncertainty related to resource development, we simulate the following two scenarios:

Unconstrained Gas (UG): In this scenario, we assume that the demand variation in meeting the no price reform case can be satisfied with a ramp-up of gas supply without imposing an additional cost on other sectors' demand for natural gas. In other words, we assume that the country's total supply will increase to meet the natural gas requirement under the no reform case through increases in natural gas production, mainly from non-associated gas fields (Shabaneh and Schenckery 2020).

Constrained Gas (CG): While UG considers the daily infrastructure constraint, which we maintain under CG, the latter caps annual gas use under the no price reform case. Gas use is capped so as not to exceed the levels observed under the price reform case. Therefore, we impose an annual upper limit on natural gas use in the power sector in this scenario. Doing so acknowledges the sectoral allocation of natural gas based on a quota system (Krane 2019; Matar et al. 2015).

3.Results and Discussion

3.1 Empirical results and discussion

Before estimation, the variables were first tested for stationarity properties using the augmented Dickey-Fuller test (Dickey and Fuller 1981). We found that all the variables are stationary at the first difference (see Appendix A.1.). The existence of cointegration (i.e., long-run relationships) for all regions was found through the tests proposed by Banerjee et al. (1993) and Banerjee et al. (1998), as detailed in Appendix A.2. To check for potential non-linearity in parameters, in addition to the conventional Ramsey RESET test (Ramsey 1969), a general test for heteroscedasticity (White 1980), we also used the non-linearity test proposed by Castle and Hendry (2010). We did not find evidence of non-linearity in the parameters (see Appendix A.3.). Additionally, we used the structural time series modeling (STSM) framework (Harvey 1990) as a robustness check to examine whether the parameters vary over time. We did not find evidence of varying parameters or stochastic trends in any region, as detailed in Appendix A.4. The findings of the STSM are similar in terms of magnitude, with few exceptions, to the two-step estimation technique adopted in this study.

The model for each region was first estimated with two lags using the specification in Equation 1. The final specification was chosen based on the multipath search, and the detailed estimation results are reported in Appendix A.5. The long- and short-run income and price elasticities are reported in Table 2.

For all regions, the impact of price and income is statistically significant. As expected, the range of the estimated elasticities highlights the heterogeneity of income level and customer mix embedded in the regions. Consequently, the price effects are also heterogeneous. For example, income elasticities are higher in lower-income regions than in richer ones, as found in similar studies. See Mikayilov et al. (2020a) for the residential sector and Mikayilov et al. (2022) for the industrial sector. The highest long-run income elasticity (1.455) is found in the southern region, the least productive region in terms of GDP (Lopez et al. 2019). Therefore, changes in income impact this region the most. It is followed by the western region (0.694), eastern region (0.554)

Table 2. Administered fuel prices and emissions factors.

	Central		Eastern		Western		Southern	
	Short-run	Long-run	Short-run	Long-run	Short-run	Long-run	Short-run	Long-run
Income	-	0.535***	0.334***	0.554**	0.259**	0.694***	-	1.445***
Price	-0.087*	-0.461***	-	-0.188**	-0.096**	-0.258*	-0.141**	-0.378*
cdd	-	-	-	-	0.212*	0.568**	-	-

Notes: “-” no short-run impact; “*”, “**” and “***” stand for rejection of null hypothesis at the 10%, 5% and 1% significance levels, respectively; cdd= cooling degree days.

Source: Authors’ calculations.

and central region (0.535). As for the short-run impact of income on electricity demand, only two regions have had significant income impacts, the eastern and western regions, as found in (Mikayilov et al. 2020b).

The estimated price elasticities reflect the stylized facts of each region's customer mix. Regions with a high share of residential customers are expected to be more responsive to price changes. Over 50% of all electricity consumption in the western, central and southern regions comes from the residential sector, corresponding to price elasticities of -0.49, -0.46 and -0.38, respectively. In comparison, residential customers in the eastern region only represent 37% of the total electricity bill, whereas the industrial sector accounts for more than 40%. Hence, the estimated price elasticity is -0.19.

The estimation results of our electricity demand econometric model indicate that the main drivers of demand are income and price, with heterogeneous responses across Saudi Arabia's regions. In line with the literature, income is higher in less productive regions, such as the southern region (Chang et al. 2014). Meanwhile, the price elasticity is lower in the more productive eastern region, because the industrial sector is the most significant electricity consumer. However, in the other three regions, most consumption is from residential consumers. Studies have found that the industrial sectors in the eastern region are substantially less responsive to electricity demand than residential consumers (see Mikayilov et al. [2020a, 2022]).

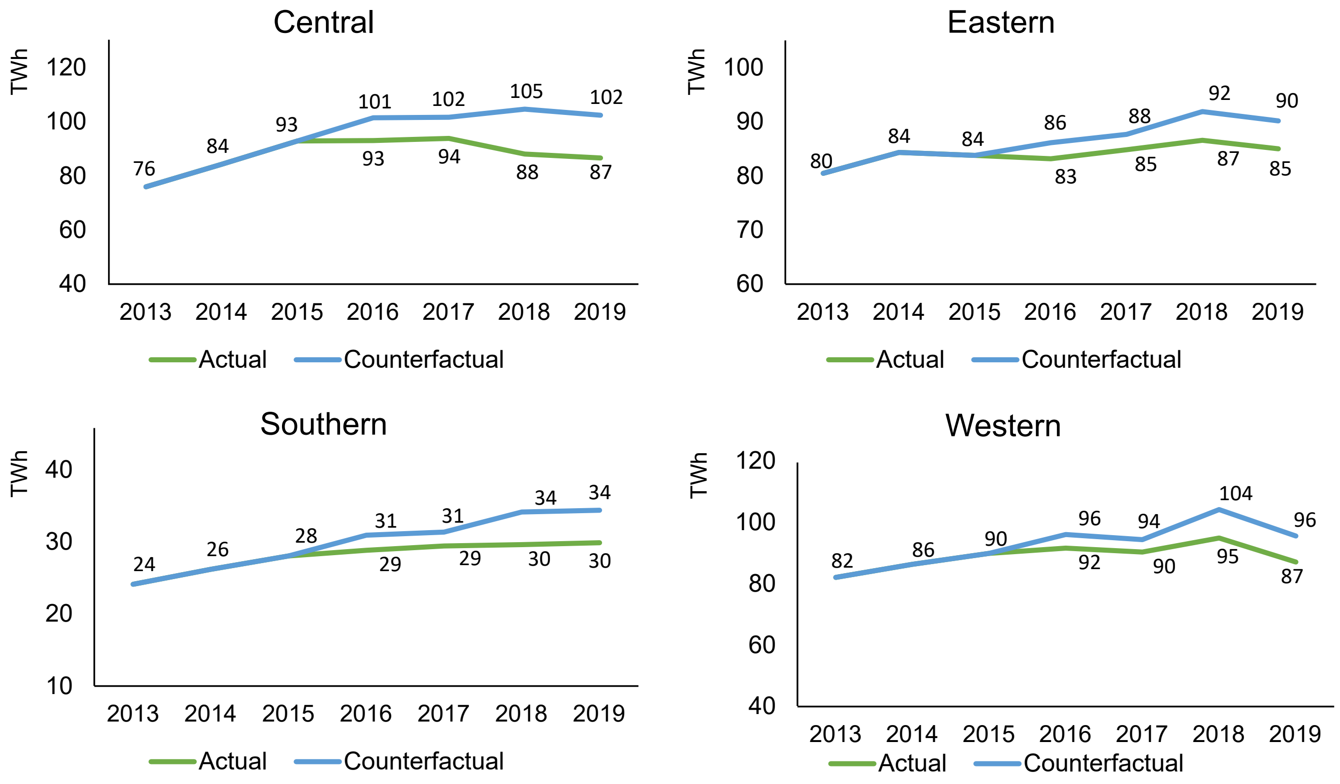
The income elasticities for the central and western regions are close to the findings of Mikayilov et al. (2020a). By contrast, the elasticities in the other two regions (eastern and southern) are higher than their findings. These differences might have resulted from updates to historical data by the authorities, which consider new methodologies and more comprehensive data-related approaches. In addition, their sample ends in 2016 and contains less information. Moreover, the sample does not include the second wave of energy price reforms that occurred in 2018. Moreover, Mikayilov et al. (2020a) used estimated disposable income as an income proxy for the eastern region, representing only residential consumers (around 30% of all consumers).

3.2 Counterfactual electricity consumption under the no price reform setting

What would regional electricity demand have been if Saudi Arabia had not implemented residential electricity price reforms in 2016 and 2018? We used the estimated long-run specification for each region (see Table 2) to draw a counterfactual electricity demand scenario that holds electricity prices constant at the 2015 level. Figure 5 visualizes this counterfactual and overlays it on the actual demand response for each region.

The counterfactual estimates indicate that the highest demand without price reforms would have been generated in the central, southern, western and eastern regions, in that sequence. Holding prices constant at 2015 levels in nominal terms yields lower prices in real terms. Thus, regions with higher price elasticity estimates would accrue higher demand, all else being equal. The central region would have seen an average of 14% growth, with 11% in the southern region, 7% in the western region and 5% in the eastern region. The counterfactual estimates have heterogeneous impacts because fuel access for power generation varies by region.

Figure 5. Actual and counterfactual electricity demand by region.



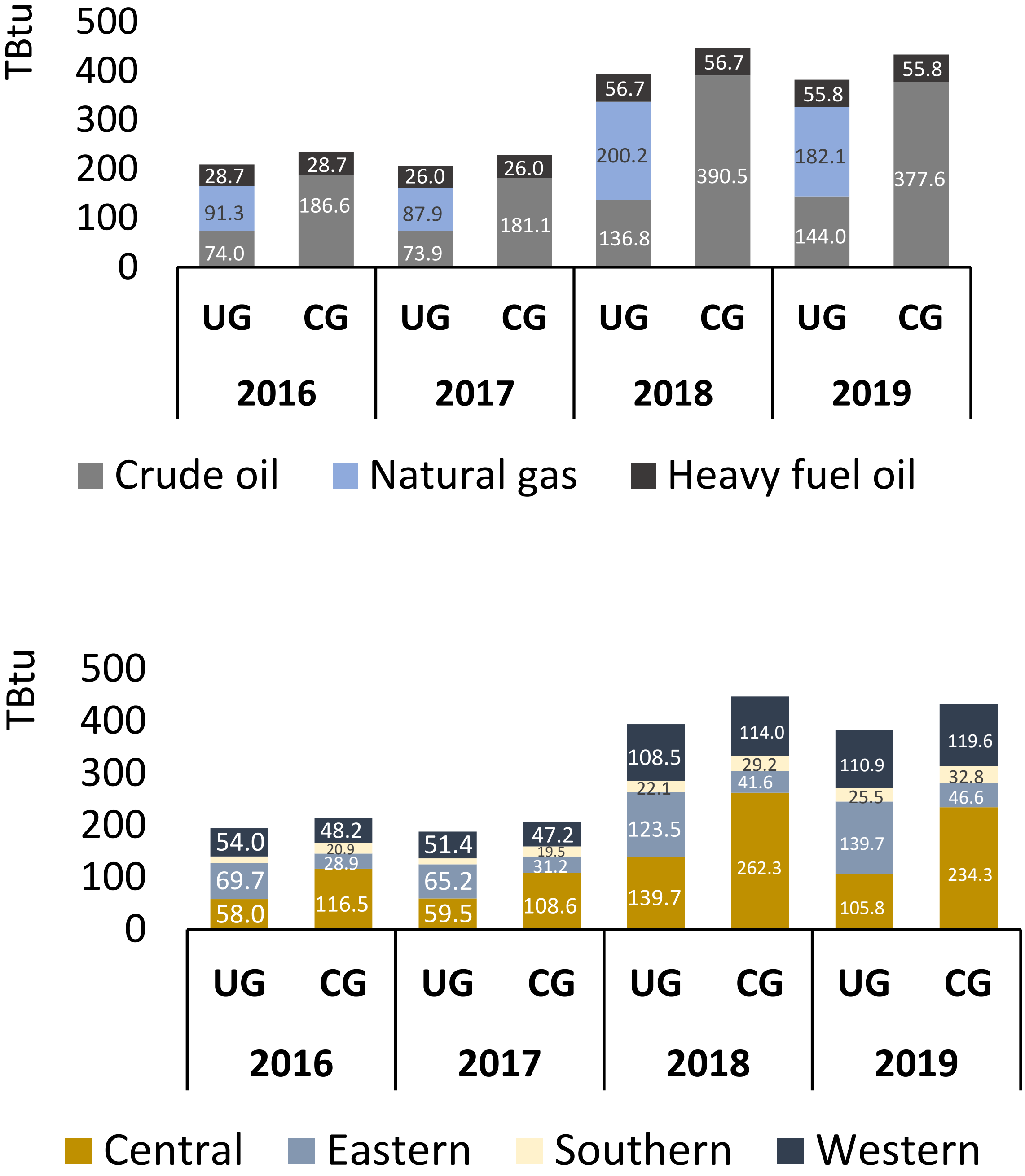
Source: ECRA (2019) for actual electricity demand, and authors' estimates for counterfactual demand.

Note: North-eastern region is included with the eastern region, and the north-western region is included with the western region.

3.3 Fuel cost savings from the energy price reform

We present the underlying fuel requirement after presenting the potential demand variations associated with the counterfactual. From a power system perspective, we run the simulations for the actual and counterfactual loads described in Section 3.2 under the UG and CG scenarios detailed in Section 3.3. Figure 6 summarizes the avoided energy; that is, the energy needed to meet demand under the counterfactual case.

Figure 6. Avoided energy consumption by fuel type and region.



Source: Authors' analysis based on KPM simulations.

Notes: Diesel is not displayed in the emissions as the model reports no diesel generation. The north-eastern region is included with the eastern region, and the north-western region is included with the western regio; UG=unconstrained gas; CG=constrained gas; TBtu=trillion British thermal units.

Between 2016 and 2019, meeting demand under the counterfactual scenario would require an additional cumulative fuel supply of 1,157.4 trillion British thermal units (TBtu) under the UG scenario and 1,301.4 TBtu under the CG scenario. The model's disaggregated fuel and regional resolution allow for an in-depth analysis of the potential energy requirements.

By lifting the constraint on natural gas supply in the UG scenario, around half (48.5%) of the cumulative energy needs are met by natural gas, while crude oil and HFO supply 37.0% and 14.4%, respectively. Imposing a constraint on natural gas under the CG scenario increases the incremental use of crude oil for fuel to 87.3% and of HFO to 12.8%, while natural gas remains almost flat (-0.1%) compared to the price reform case. The two scenarios show contrasting regional contributions as we impose limits on natural gas. For instance, the eastern region shows the lowest variation in demand between the two scenarios: The counterfactual scenario is on average 4.8% above the actual scenario versus 13.6% for the central region. By contrast, the contribution of the eastern region to energy requirements is the highest among the four regions. Around 34.4% of the additional energy needs would be supplied from the eastern region, followed by 31.4% from the central region in the UG scenario. Under similar demand patterns but with a constraint on natural gas supply (i.e., the CG scenario), the contribution from the central region would increase to 55.5%, as potential demand would primarily depend on crude oil generation.

Different demand features across regions justify disparities in fuel and regional energy requirements. The rationale behind this finding is that while incremental demand would primarily come from the central region, which is dominated by the residential segment, the bulk of the underlying generation would be met by the eastern region. For instance, the eastern region's low variation is caused by its high share of industrial demand, which is relatively inelastic compared to demand in other regions (Mikayilov et al. 2022). Since the eastern region's fleet consists exclusively of natural gas generation units, it accounts for the highest potential generation compared with the remaining regions in the UG scenario. This is because of its proximity to fuel extraction facilities. In the CG scenario, 65.2% of the cumulative natural gas feedstock needed to meet the no reform case comes from the eastern region.

Table 3 shows fuel costs by fuel type and region, valued at regulated prices. Over the considered period, 2016-2019, the fuel cost associated with the counterfactual case amounts to US$1,292.6 million under the UG scenario and US$1,397.6 million under the CG scenario. As expected, the potential cost was highest in 2018, when the second price reform wave, targeting residential consumers, was implemented.

Table 3. Potential cost by fuel type and region.

Unconstrained gas (UG)

	Cost by fuel type, in million US$					Cost by region, in million US$				
	Crude oil	Diesel	Natural gas	Heavy fuel oil	Total	Central	Eastern	Southern	Western	Total
2016	84.6	0.0	114.1	17.2	216.0	68.7	86.5	14.0	46.8	216.0
2017	84.6	0.0	109.8	15.6	210.0	70.5	80.9	13.4	45.2	210.0
2018	156.5	0.0	250.2	34.0	440.8	164.6	155.9	25.1	95.0	440.8
2019	164.8	0.0	227.6	33.5	425.8	125.4	173.5	29.2	97.7	425.8

Constrained gas (CG)

	Cost by fuel type, in million US$					Cost by region, in million US$				
	Crude oil	Diesel	Natural gas	Heavy fuel oil	Total	Central	Eastern	Southern	Western	Total
2016	213.5	0.0	-1.2	17.2	229.6	134.3	33.7	23.9	37.7	229.6
2017	207.2	0.0	-0.8	15.6	222.0	125.0	36.6	22.3	38.2	222.0
2018	446.8	0.0	-0.2	34.0	480.5	303.0	46.4	33.4	97.7	480.5
2019	432.0	0.0	0.0	33.5	465.5	270.0	53.0	37.6	104.9	465.5

Source: Authors’ analysis based on KPM simulations.

Notes: Numbers may not sum because of rounding. The north-eastern region is included with the eastern region, and the north-western region is included with the western region.

Under the UG scenario, natural gas accounts for US$701.8 5 million, or 54.3%, of the additional cost arising from the no reform case. This is followed by crude oil, which accounts for US$490.5 million, or 37.9%. Unsurprisingly, the eastern region accounts for the highest share of potential costs, at 38.4%, while the central region represents 33.2% of that cost. Although the two scenarios are based on similar demand patterns, limiting natural gas supply in the CG scenario increases the total potential fuel cost by 8.1%. Imposing the constraint on natural gas increases the contribution of the central and western regions, where most of the generation comes from crude oil, to 59.6% and 19.9%, respectively. The cost differential is caused by the lower efficiency of steam plants in these regions compared to the higher efficiency gas-fired plants in the eastern region. Constraining gas supply under the CG scenario imposes an additional cost of US$105.0 million from 2016-2019 compared with the available gas supply under the UG scenario. The gap stems from the differential between the extra cost from crude oil, US$809.0 million, and the avoided natural gas generation resulting from the constrained supply, reducing the cost by US$704.0 million in the CG scenario.

Although these estimates provide helpful information regarding fuel cost with and without price reforms, they reflect administered tariffs. Thus, they provide only a partial assessment of the potential cost. Indeed, fuel consumption for power generation could be used in other sectors, such as the petrochemical industry, or it could be exported instead. This warrants an additional analysis of the opportunity cost from saved fuel. Karanfil and Pierru (2021) estimate the potential opportunity cost of crude oil to be a fraction of the international price. Their findings suggest that the freed crude oil value from saved fuel, as a percentage of the international price, would range between 30.6% and 61.7% in the short run and 83.7% in the long run. These levels would inflate the potential cost of fuel under the CG scenario to US$2.1-8.0 billion compared to the UG scenario. The savings would amount to US$9.8 billion, calculated using the international oil price.[7] Soummane et al. (2022) discuss the significance of opportunity cost in the Saudi power mix when displacing load from peak to off-peak seasons, including for natural gas. Their findings suggest that reforming natural gas prices is relevant only when displacing significant loads (i.e., above 25% of the industrial load from the peak season to the off-peak season), but it could negatively affect the potential fuel savings if the displaced loads are insignificant.

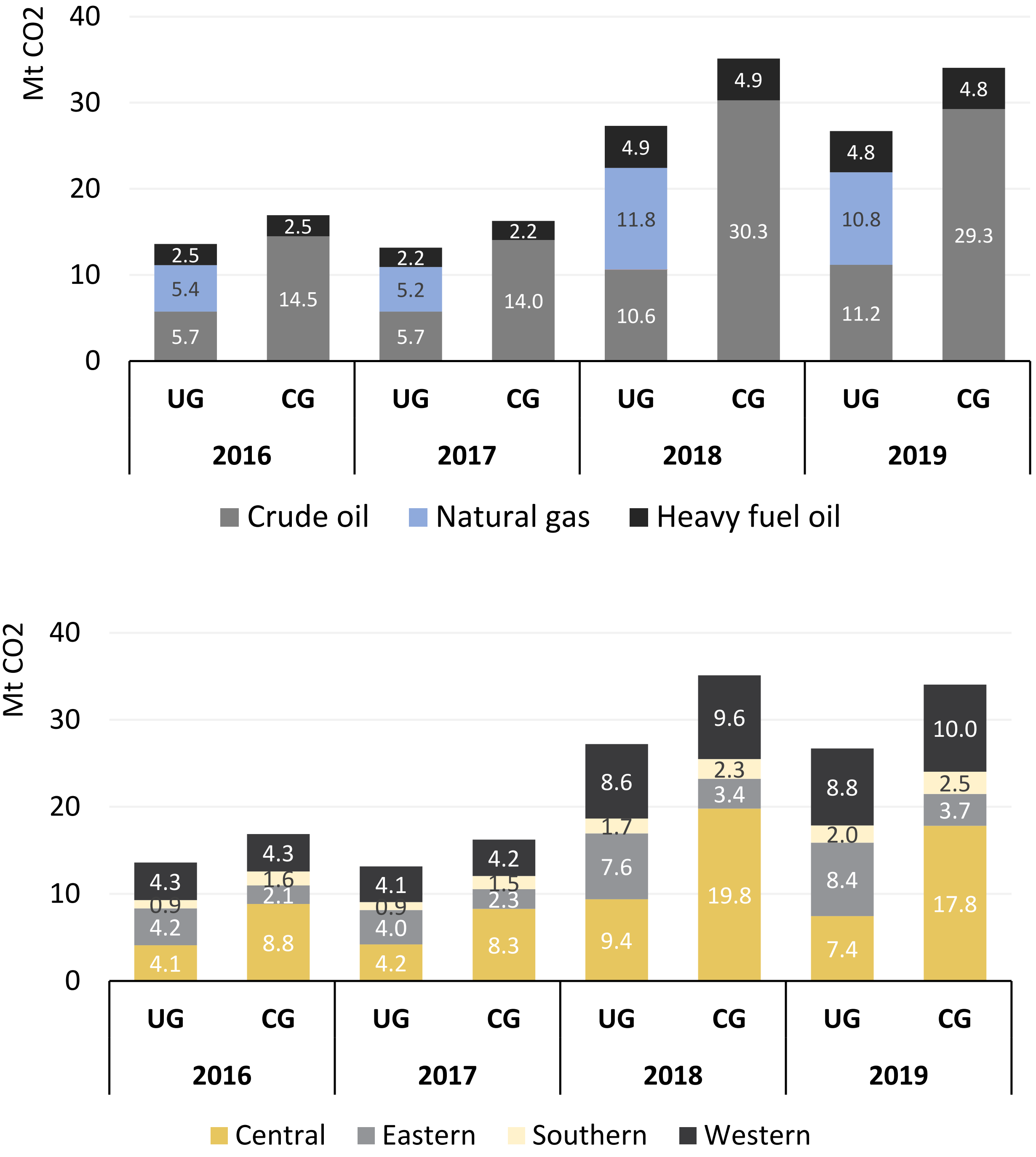
3.4 Carbon emissions reduction from energy price reforms

This section discusses the underlying carbon emissions associated with the counterfactual scenario, i.e., the no-price reform case. Figure 7 shows CO2 emissions by fuel and region for the counterfactual demand from 2016 to 2019 under the UG and CG scenarios. Our simulations indicate avoided cumulative emissions of 80.7 million tonnes (Mt) and 102.3 Mt under the UG and CG scenarios, respectively. Crude oil contributes to the highest share of emissions, at the fuel level, under both the UG and CG scenarios, accounting for 41.1% and 86.1%, respectively. Although natural gas accounts for almost half the energy supply in the no-reform case in the UG scenario, its contribution to carbon emissions is similar to that of crude oil, which accounts for 37% of the total energy needs. Two factors drive crude oil's significant share in emissions. First, on an energy basis, its carbon intensity is higher than that of natural gas by around 31%. Second, steam generation (oil-fired plants) has a higher heat rate, and thus lower efficiency, compared with natural gas generation.

At the regional level, emissions display marginally different patterns than energy demand does. Although the western region contributes less energy demand under UG generation than the eastern and central regions do, it accounts for the highest share of emissions, at 32.0%. The western region's mix relies heavily on HFO, which has a higher carbon intensity than natural gas (+45.3%) and crude oil (+10.8%), as shown in Table 1. Ultimately, HFO accounts for 58.5% of the western region's additional emissions in the UG scenario. Imposing a constraint on natural gas supply under the CG scenario shifts generation to the central and western regions, which have higher liquid-based generation than the eastern region, resulting in a cumulative 26.8% increase in CO2 emissions compared with the UG scenario.

Like many countries, Saudi Arabia submitted an updated target to reduce its greenhouse gas (GHG) and CO2 emissions in 2021. It also updated its nationally determined contribution (NDC), which sets a path to reach net-zero carbon by 2060 and aims to displace liquid fuels from its power sector (Kingdom of Saudi Arabia 2021). It has set an ambitious target to generate 50% all its electricity from natural gas and 50% from renewables by 2030 (Saudi Arabia NDC 2021). The goal is to reduce, avoid and remove 278 million tonnes of CO2 annually by 2030. This policy change follows Vision 2030, a national transformation program that mandates curbing wasteful consumption and reinforcing efficiency-driven incentives for rational energy consumption (SV2030 2016). The findings on carbon emission avoidance reflect the impact of previous energy policies that predate Saudi Arabia's updated NDC.

Figure 7. **Avoided carbon emissions by fuel type and region.**



Source: Authors' analysis based on KPM simulations.

Notes: Diesel is not displayed in the emissions as the model reports no diesel generation. The north-eastern region is included with the eastern region, and the north-western region is included with the western region.

4. Conclusions and Policy Implications

Conventional policy tools to curb inefficient energy demand and mitigate emissions remain challenging to implement in the absence of global collective action and coordination among countries. Implicit carbon policies, such as reforming energy prices, can be a viable and competition-friendly policy lever. In many resource-rich economies that continue to administer energy prices, reforming domestic tariffs could bring economic gains and support the curbing of carbon emissions.

This study quantifies the effects of price reforms on regional fuel consumption and carbon emissions from avoided power generation in Saudi Arabia. Our partial equilibrium models derive the regional income and price elasticities, which are used to simulate demand scenarios in which tariffs remain constant, i.e., as if no energy price reforms occurred in 2016 and 2018. We calculate the potential fuel consumption and carbon emissions levels through a power system model calibrated for Saudi Arabia. We show that the two waves of Saudi electricity price reforms prevented electricity generation equivalent to US$1.3-1.4 billion in fuel costs and avoided 81-102 million tonnes of carbon dioxide emissions between 2016 and 2019. When considering the opportunity cost of saved fuel, the national fuel cost would amount to US$2.1-8.0 billion, and up to US$9.8 billion when benchmarked against international oil prices. Finally, our results show that limiting natural gas flows to the power system is associated with higher fuel use and emissions because of regional capacity and infrastructure disparities.

This study aims to inform policymakers of the unobserved contribution and effectiveness of price reforms. It aims to quantify the impact of implementing price reforms and the subsequent financial and environmental gains. Saudi Arabia can serve as an example case study for countries that administer prices and aim to curb fast-growing energy demand and move closer to meeting their net zero-emission paths. EPRs have improved Saudi Arabia’s fiscal position, reduced its electricity consumption growth and moved it away from a higher carbon emissions path.

Other approaches that add additional dynamics to the modeled relationships can be considered as avenues of future research. One consideration would be utilizing a country-specific general equilibrium model to view the impacts of energy price reforms comprehensively and to measure other interdependent drivers and capture feedback effects across various sectors and agents. Additionally, future research could consider scenarios that provide options for the revenue recycling mechanisms, the additional revenues stemming from domestic fuel savings, and additional export revenue. Another consideration would be quantifying additional welfare gains from such reforms, taking into account environmental externalities.

Endnotes

[1] Electricity is priced per bracket in Saudi Arabia, and to calculate a single representative price, two approaches are feasible. An invoice-based price uses the number of invoices as a weight for each bracket's price, whereas consumption prices use the weight of consumption to calculate a single representative price.

[2] 2010 was used as the base year.

[3] The price deflator used for deflating the industrial electricity price for the eastern region is a weighted average of non-oil manufacturing and oil refining deflators, where the corresponding shares of their gross value added are used as weights.

[4] Note that 2016 is a leap year. We assume that the consumption pattern on February 29 is similar to that of February 28, as the two are working days.

[5] Note that, as mentioned previously, the NEOA and NWOA loads were respectively included with the Eastern and Western load. Thus, their actual and counterfactual loads remained unchanged.

[6] For example, if the econometric analysis suggests that the Eastern region's demand for the year 2016 would have been 10% higher under the no-price reform case, we increment the region's 8760 hourly loads by 10%.

[7] We use the following real oil prices of the Arabian Light reference from SAMA (2020): US$38.3 per barrel ($/b) in 2016, 48.5 $/b in 2017, 61.9 $/b in 2018 and 58.2 $/b in 2020.

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Appendix

Appendix A.1. Unit-root test results.

	dele	d(dele)	p	d(p)	inc	d(inc)	cdd	d(cdd)
Central region	-2.2791	-3.2534**	-1.9281	-5.8197***	-0.7939	-1.8587*	-1.6132	-7.9828***
Eastern region	-0.4388	-4.1998***	-1.8688	-5.6433***	-1.6170	-5.7397***	-2.1538	-10.4161***
Southern region	-1.5118	-4.4538***	-1.8985	-5.6310***			-1.7938	-7.0667***
Western region	-2.1568	-5.0827***	-1.4702	-5.1164***			-2.5178	-8.0917***

Notes: ***, ** and * stand for rejection of the no cointegration null hypothesis at the 1%, 5% and 10% significance levels, respectively; d stands for the difference operator.

Source: Estimation results.

Appendix A.2. Cointegration test results.

	COA	EOA	SOA	WOA
Unit-root t-test	-5.4605**	-4.9703*	-4.1403*	-4.9442*

Notes: ** and * stand for rejection of the no cointegration null hypothesis at the 5% and 10% significance levels, respectively.

Source: Estimation results.

Appendix A.3. Non-linearity test results.

	COA	EOA	SOA	WOA
Unit-root t-test	1.3666	2.1964	0.91619	0.38005
	[0.3001]	[0.0989]	[0.5611]	[0.7037]
Core Index test (F-form)	0.67683	0.43110	1.6774	0.3268
	[0.7277]	[0.9041]	[0.2002]	[0.9111]

Notes: The null hypotheses of both tests state linearity of the parameters; p-values are in brackets.

Source: Estimation results.

Appendix A.4. Diagnostic test results.

	COA	EOA	SOA	WOA
AR 1-2 test	0.42829	0.18192	1.7460	0.9627
	[0.6575]	[0.8350]	[0.1989]	[0.4017]
ARCH 1-1 test	0.16751	0.75195	0.52711	0.0160
	[0.6856]	[0.3935]	[0.4741]	[0.9005]
Normality test	1.0603	0.61395	1.1144	1.4115
	[0.5885]	[0.7357]	[0.5728]	[0.4937]
Hetero test	1.0060	1.3060	1.8512	0.8130
	[0.4800]	[0.2984]	[0.1291]	[0.6427]
RESET23 test	0.52420	0.38451	2.1909	0.9593
	[0.5999]	[0.6857]	[0.1367]	[0.4030]
R-square	0.996	0.989	0.997	0.997

Notes: AR=autocorrelation test (Godfrey 1978); ARCH= autoregressive conditional heteroscedasticity test (Engle 1982); Normality test=Doornik and Hansen (1994) Normality test; Hetero test=heteroscedasticity test (White 1980); RESET23= Regression Specification Test (Ramsey 1969). p-values are in brackets.

Source: Estimation results.

Appendix

Appendix A.5. Detailed estimation results.

	dele(-1)	p	p(-1)	inc	inc(-1)	cdd	cdd(-1)
COA	0.4545***	- 0.0870*	- 0.1644***	-	0.2918**	-	-
EOA	0.3975***	-	- 0.1133**	0.3336**	-	-	-
SOA	0.6274***	- 0.1407**	-	0.5396***	-	-	-
WOA	0.6270***	-0.0962**	-	0.2587**	-	0.2118*	-

Notes: ***, ** and * stand for rejection of the no cointegration null hypothesis at the 1%, 5% and 10% significance levels, respectively; Dummies chosen by the autometrics algorithm for each region are: COA step dummy S1:1999, trend dummy T1:1998; EOA step dummy S1:2008, trend dummies T1:2002, T1:2003; SOA impulse dummy I:1998, trend dummy T1:2000; WOA blip dummy DI:2011, impulse dummies I:1992, I:2019, trend dummies T1:1997, T1:1998. '-' means that the term was found to be insignificant and dropped from the final specification.

Source: Estimation results.

Appendix A.6. Short- and long-run elasticities from the STSM approach.

	COA		**EOA**		**WOA**		**SOA**	
	Short-run	Long-run	Short-run	Long-run	Short-run	Long-run	Short-run	Long-run
Income	-	0.695***	0.181*	0.233***	0.216*	0.602*	-	0.741***
Price	-0.107*	-0.200***	-	-0.080***	-0.180***	-0.501***	-0.197***	-0.368***

Notes: “-” means no short-run impact; “*”, “**” and “***” stand for rejection of the null hypothesis at the 10%, 5% and 1% significance levels, respectively.

Source: Estimation results.

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About the Authors

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Abdulelah is an economist and a senior research associate at KAPSARC. He primarily works with econometric modeling, with a research focus on macroeconomics and energy, international trade and investment flows, financial development, and public policy.
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About the Project

The Modeling Energy Consumption and its Impacts in Saudi Arabia project aims to conduct advisory and applied research activities focused on modeling and forecasting indicators of energy consumption and their impacts in Saudi Arabia. In line with the ongoing energy policies the Kingdom is implementing, the project focuses on three main areas:

- Modeling and forecasting energy consumption indicators.
- Modeling and forecasting the environmental impacts of energy consumption.
- Investigating the trajectories and potential of energy efficiency.

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