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Projecting Saudi sectoral electricity demand in 2030 using a computable general equilibrium model

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ABSTRACT

Electricity demand in Saudi Arabia is undergoing unprecedented changes following the implementation of efficiency measures and energy price reforms. These changes raise uncertainties about the potential trajectory of long-term electricity demand. Thus, this study uses a computable general equilibrium model to project sectoral electricity demand in Saudi Arabia through 2030. We project that growth in total Saudi electricity demand will significantly decelerate over the coming decade compared with historical trends. In our reference scenario, this demand reaches 365.4 terawatthours (TWh) by 2030. However, our sectoral decomposition shows large disparities across sectors. Demand is projected to grow more rapidly in the industrial and services segments than in the residential sector. We also simulate four additional scenarios for domestic electricity price reforms and efficiency policies. Successfully implementing these measures may result in significant energy savings. Aligning Saudi electricity prices with the average electricity price among G20 countries can reduce total electricity demand by up to 71.6 TWh in 2030. Independently enforcing efficiency policies can reduce total electricity demand by up to 118.7 TWh. Moreover, alternative policy scenarios suggest that the macroeconomic gains from energy savings can alleviate some of the Saudi energy system's burden on public finance.

1. Introduction

Projecting future demand for electricity is central to power sector planning, as projections inform capacity investment requirements and related infrastructure expansions. Electricity is not currently economically storable in large volumes. Thus, the drivers of electricity demand and potential market shifts must be carefully considered to minimize power system costs.[1]

In the Kingdom of Saudi Arabia, electricity demand has grown rapidly since the development of the electricity sector in the early 1970s. This growth has been driven by a rapidly increasing population, dynamic economic growth, and low regulated energy prices. In 2018, total Saudi electricity demand reached 299.2 terawatthours (TWh).[2] Saudi Arabia is the fourteenth-largest electricity consumer in the world. Its consumption is similar to that of more populated countries (e.g., Mexico, whose 2019 population was 127.5 million, compared to 34.2 million for Saudi Arabia). It is also on par with more advanced economies (e.g., Italy, whose 2019 gross domestic product [GDP] was $2151.4 billion, compared to $704.0 billion for Saudi Arabia), according to The World Bank.

In recent years, the Saudi government has addressed the rapidly increasing fuel consumption of its power sector by expanding the use of efficient gas plants. This step has reduced the country's reliance on oil and refined products for power generation. Moreover, Saudi policymakers have also enacted some demand-side measures. In 2010, the Kingdom began promoting several efficiency initiatives to rationalize energy consumption with the establishment of the Saudi Energy Efficiency Center [1]. Additionally, the Saudi government implemented the first round of national energy price reforms (EPR) in 2016, with the second round in 2018.

The scale of these recently implemented EPR and efficiency measures is unprecedented in Saudi Arabia. Thus, these policies' potential effects

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[1] Pumped-storage hydropower is a large-volume electricity storage solution. However, we do not consider this option further in our analysis. See Matar and Shabaneh [41] for details on the potential of pumped-storage hydropower in the Kingdom.

[2] This figure (i.e., 299.2 TWh) corresponds to billed final consumption. It does not include in-plant power use or transmission and distribution losses.

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on future demand cannot be assessed based on past experiences. Instead, it is necessary to strengthen the methodological aspects of energy demand projections. Using advanced analytical tools to capture market transformations, behavioral adjustments and interdependencies across economic agents, we can better project electricity demand pathways. In doing so, we build upon the work of Soummane et al. [2]. They develop a hybrid energy-economy computable general equilibrium (CGE) model that accounts for specific features of the Saudi economy. These features include administered domestic energy prices and a currency peg to the United States (US) dollar.

The remainder of this paper is organized as follows. In section 2, we review the literature related to Saudi electricity demand and applications of general equilibrium models in energy-related studies. In section 3, we describe our projection methodology and present the sectoral components of Saudi electricity demand. Section 4 summarizes the scenarios and the underlying assumptions for the demand projections. Section 5 presents the main results of our analysis through 2030, and section 6 concludes the paper.

2. Literature review

2.1. Studies on Saudi electricity demand

To the best of our knowledge, Hasanov [3] is the only available study that provides partial projections of Saudi electricity demand. Unlike our study, Hasanov [3] focuses on industrial demand and uses a time horizon of 2025. The author models annual industrial electricity demand from 1984 to 2016. He uses the real price of electricity, industrial value-added, the working-age population and the cost of capital as explanatory variables. The model shows that industrial electricity demand is relatively price and income-inelastic, with long-run elasticities of −0.1 and within 0.2–0.3, respectively.

Additionally, most studies of Saudi electricity demand focus on its responsiveness to prices and income. Al-Sahlawi [4] and Diabi [5] both estimate aggregate Saudi demand for electricity as a function of income (proxied by real GDP) and real electricity prices. Both studies conclude that Saudi electricity demand is income and price inelastic. Likewise, Al-Faris [6] models aggregate Saudi electricity demand from 1970 to1997[3] as a function of income (proxied by real GDP) and real electricity prices. He finds that Saudi electricity demand is insensitive to price changes but elastic to income, with income elasticities of 0.05 in the short run and 1.65 in the long run.

Atalla and Hunt [7] model residential electricity demand in GCC countries using annual data from 1985 to 2012. Like other studies, they include the real price of electricity and real GDP as a proxy for income in their model and add population and weather conditions. They find that electricity demand is relatively inelastic to income and prices in the short and long terms. The absolute values of the corresponding elasticities are less than 0.5. However, the population and weather conditions have more significant short- and long-run impacts.

Lastly, two post-EPR studies model Saudi residential electricity demand to estimate price and income elasticities. Aldubyan and Gasim [8] and Mikayilov et al. [9] consider electricity prices, real GDP per capita as an income proxy and weather effects. Aldubyan and Gasim [8] confirm that residential electricity demand is price and income inelastic, as they estimate long-term elasticities of −0.09 and 0.22, respectively. Mikayilov et al. [9] show that although aggregate residential demand is inelastic to price and income changes, the results vary significantly across the regions. For instance, the long-term price elasticities range from −0.2 in the central region to −0.5 in the eastern region. Likewise, the long-term income elasticities range from 0.3 in the eastern region to 1.0 in the western region.

We can draw two conclusions from these studies. First, most prior studies develop econometric estimations of Saudi electricity demand. Moreover, they generally focus on aggregate demand or one segment of aggregate demand (e.g., residential *or* industrial demand). To the best of our knowledge, no prior study has modeled or projected Saudi electricity demand for several sectors simultaneously.[4] Second, few studies investigate the post-EPR period. However, as described above, the EPR initiated fundamental shifts in electricity demand patterns, and these shifts are likely to persist in the future. These changes must be considered when modeling future demand.

Thus, this study fills two gaps in the existing literature on Saudi electricity demand. First, it models and projects sectoral demand in a consistent framework, capturing interdependencies across sectors through the general equilibrium approach. Second, it accounts for recent changes in electricity demand patterns driven by price reforms and efficiency measures.

2.2. Energy and electricity modeling using the CGE framework

Since Johansen's [10] seminal work, general equilibrium modeling has been widely used to assess economic, energy and environmental trajectories in the context of significant changes. The purpose of a CGE model is to provide a comprehensive estimation of a policy's effects. Incorporating consumption and production functions within a multi-sector and multi-market framework allows for better estimations of supply and demand relative to partial equilibrium models.

Most recent studies applying CGE frameworks in an energy context estimate the energy demand response to price shifts, production mix evolutions and subsidy reforms. Chi et al. [11] investigate the impacts of subsidy reforms on energy demand and macroeconomic indicators in China. Kat et al. (2018) use a CGE framework to analyze the prospects of various energy scenarios in Turkey and the underlying emissions trajectories. Böhringer and Rutherford [12] explore energy and emissions scenarios for Poland. One recent application of a CGE model to Kuwait, a GCC country, shows that energy subsidy reforms have beneficial effects on economic diversification [13].

Holmøy [14] and He et al. [15] apply CGE models to investigate electricity demand. Specifically, they estimate the sensitivity of electricity demand to changes in electricity prices in Norway and China, respectively. Their studies emphasize the prominent role of substitution elasticities of demand functions. Beckman et al. [16] show that an adequately parameterized CGE model replicates historic energy demand and supply trajectories well.

In the Saudi context, several studies use the CGE framework to investigate specific policy issues. These issues include behavior within the oil market [17], the abrogation of trade tariffs [18] and exchange rate policies [19]. Recent studies include Blazquez et al.'s [20] dynamic equilibrium model estimating the long-run welfare impact of renewable energy penetration, Gonand et al. [21] implement a similar dynamic model, with overlapping generations, exploring the long-run consequences of energy pricing reforms, while Blazquez et al. [22] assess macroeconomic implications of domestic energy price reforms, the deployment of renewable energy, and fiscal reforms using a dynamic stochastic general equilibrium model. Finally, Soummane et al. [23] and Soummane et al. [2] recently developed a CGE model for the Kingdom that acknowledges certain features of the Saudi economy. This model includes administered energy prices within a detailed representation of the energy sector to assess economic diversification outcomes.

[3] He also models aggregate electricity demand in other Gulf Cooperation Council (GCC) countries (i.e., Bahrain, Kuwait, Oman, Qatar and the United Arab Emirates).

[4] Eltony and Mohammad [42] model sectoral electricity demand in aggregate across GCC countries.

3. Methodology

3.1. CGE model with improved electricity demand characteristics

This study employs IMACLIM-SAU, an economy-wide dynamic CGE model that embodies specific features of the Saudi economy. We extend Soummane et al. [2] by improving the model's representation of electricity demand. The model covers 13 sectors, as reported in Table 1. To be concise, we describe only the model features related to the electricity sector in this section.

Our model departs from that of Soummane et al. [2] in two ways to better represent electricity demand. First, we adjust the sectoral definitions to separate private and government services, which account for 13.2% of total demand on average between 2013 and 2018. Second, based on reviewed elasticities estimates, we assume that households' consumption of energy goods is relatively income and price inelastic. The original model treats this consumption as exogenous (imported from bottom-up expertise). For non-energy goods, it is based on constant shares of the budget remainder (i.e., the budget net of energy expenses).

The consumption function that we adopt for residential electricity demand helps address the shortcomings of using GDP as a proxy for income. Indeed, Atalla and Hunt [7] highlight that household income is more appropriate than GDP per capita in this setting. In GCC countries, GDP per capita is highly correlated with oil prices.[5] Similar to Le Treut [24]; we formulate household consumption of energy goods C_i as follows[6]:

$$\forall i \in \{OIL, GAS,\ RFN,\ ELE\} \quad C_i = \left(\frac{p_{C_i}}{CPI}\frac{1}{p_{C_{i_0}}}\right)^{\sigma_{CP_i}}\left(\frac{R_c}{CPI}\frac{1}{R_{c_0}}\right)^{\sigma_{CR_i}} C_{i_0} \qquad (1)$$

Here, σ_{CP_i} and σ_{CR_i} are the price and income elasticities, respectively. p_{C_i} and R_c are the consumer price of energy good i and consumed income, respectively. CPI is the consumer price index evolution from calibration year. An index of 0 denotes the calibration value of a variable, that is, the 2013 value.

For households, crude oil (OIL in our nomenclature) and natural gas (GAS) consumptions are essentially nil, and thus, we only need the values of price and income elasticities for electricity (ELE) and refined products (RFN). We derive these values from the estimates of Hasanov et al. [25] and Mikayilov et al. [26]; respectively. Thus, for electricity demand (ELE), the income and price elasticities are set to 0.33 and −0.13, respectively. For refined products demand (RFN), we set income and price elasticities to 0.13 and −0.27, respectively. IMACLIM-SAU computes households' income as proceeding from primary factor income, social transfers, property income and an aggregate of other secondary transfers.

The production function of goods and services, including electricity, takes a nested form. To simulate distinctive scenarios for price reforms and intensity gains, the model includes two alternative production specifications. In the first (Specification 1), capital, labor and electricity are substitutable inputs in the lower stage of the production function. They are incorporated in a constant elasticity of substitution function to create electrified value-added.[7] In the upper stage, electrified value-added is combined with all energy products except ELE to produce a composite good (*VA_Elec*) based on a Leontief function. *VA_Elec* is then combined with materials (i.e., non-energy products, denoted as M) to produce domestic output Y. In this specification, electricity use intensities (i.e., units of per unit of Y) are endogenously determined from the modeled prices of electricity and other factors. This specification is common to all sectors.

The second specification (Specification 2) uses a similar nested production function. However, in this specification, electricity intensities, like the intensities of other energy goods, are determined exogenously. The intensities of other energy goods remain constant at their calibration year levels. In both specifications, regulated energy prices (including ELE prices) are implemented by adjusting agent-specific margins to reflect departures of regulated agent-specific prices from average output costs augmented with agent-specific taxes and subsidies.

Table 1
Sectoral coverage of IMACLIM-SAU.

Abbreviation	Sector/product
Energy	
OIL	Crude oil
GAS	Natural gas
RFN	Refining
ELE	Electricity
Non-energy	
AGR	Agriculture, hunting, forestry and fishing
MIN	Other mining (excluding oil and gas extraction)
CHM	Chemicals and petrochemicals
NMM	Non-metallic minerals (including cement)
MAN	Manufacturing
PRV	Private sector services
PUB	Public services
TRA	Transport: air and sea
OTP	Other transport

Note: In line with CGE practice, all sectors are supposed to be the exclusive suppliers of corresponding products.

3.2. Simulation of 2014–2018 Saudi electricity demand

One way to validate CGE models and increase their credibility is to test their performance against historical data [27]. Thus, in this section, we test our model's ability to replicate sectoral electricity demand for 2014–2018, as the model's calibration year is 2013.

For residential electricity demand, we implement the price- and income-elastic demand function given by Equation (1). For intermediate electricity uses (i.e., industrial, commercial and government electricity demand), we implement the two specifications described in the previous subsection The test for these specifications indicates our model's ability to replicate sectoral activity levels.[8] For agriculture, we keep the electricity intensity constant over the calibration years in both specifications given its small share of electricity consumption (2% in 2013). Electricity prices are average sectoral prices based on observed regulated tariffs weighted by consumption brackets, as Soummane [28] presents.

Under both specifications, simulated total demand is within −6.5% and +0.6% of observed total demand (with an average absolute deviation of 2.8% in Specification 1 and 1.3% in Specification 2). Residential demand, which is simulated using the consumption function with price and income elasticities, captures the effects of the slower income increase and EPR. Estimated trajectories again fluctuate within −5.1% and

[5] Atalla et al. [43] compare total and non-oil GDP as proxies for income. The two proxies lead to significantly different estimates of the income elasticity of Saudi demand for gasoline of 0.09 and 0.61, respectively.

[6] Le Treut [24] models households' consumption of energy goods as the sum of exogenous basic needs and price-elastic uses. This distinction lacks a useable assessment in the case of Saudi Arabia.

[7] Because estimated elasticities of substitution for Saudi production are lacking, we use published estimates for other countries (see Ref. [2]. We analyze the sensitivity of our results to these key parameters and to other socioeconomic variables in Annex A.

[8] Industry corresponds to the SAMA [37] sectors of Other Mining and Quarrying Activities; Manufacturing; and Electricity, Gas and Water. Private services correspond to Construction; Wholesale & Retail Trade, Restaurants and Hotels; Transport, Storage & Communication; Finance, Insurance, Real Estate & Business Services; and Community, Social & Personal Services. The government sector corresponds to Producers of Government Services.

+4.1% of observed values. For industrial (IND), commercial (PRV), governmental (PUB), and agricultural (AGR) uses, modeled consumption values fluctuate between −19% and +21% under both specifications. The overestimations of industrial and commercial demand are compensated by the underestimation of governmental demand (Fig. 1).

4. Electricity demand scenarios through 2030

This section describes our projection scenarios and their underlying drivers and assumptions. For sectoral demand projections, we consider three scenarios reflecting Saudi electricity demand pathways with price reforms and energy efficiency measures to reduce electricity intensities. We simulate a reference scenario (REF) and two alternative scenarios. These alternative scenarios are called the price reform scenario (PR) and energy efficiency scenario (EE). The three scenarios use similar trajectories for socioeconomic indicators (i.e., the active population, labor productivity, oil prices, oil output, investment and non-energy exports). They differ only in aspects related to the electricity sector, as the following subsections explain.

4.1. Reference scenario

In this scenario, intermediate and final electricity prices remain at their post energy price reforms (post-EPR) levels, i.e., 2018 levels, through 2030. For the residential sector, prices are 139% greater than pre-EPR levels. For industry (IND), which corresponds to MIN, CHM, NMM and MAN in our nomenclature (Table 1), prices are 20% greater than pre-EPR levels. For PRV, PUB and AGR, prices are 20%, 30% and 50% greater than pre-EPR levels, respectively. The projected REF scenario is based on Specification 2, that is, the specification with exogenous electricity intensities. This specification deviates less from the observed 2013–2018 demand than Specification 1 does (see section 3.2).[9] In this scenario, we assume that the enforced intensity levels for IND, PRV, PUB and AGR remain constant at their 2013–2018 averages through 2030. This assumption avoids unduly placing a higher weight on the intensity in any specific year.

4.2. Price reform scenario

In this scenario, we consider additional price reforms beyond the two EPR rounds that have already taken place. The Saudi government's Fiscal Balance Program plans to progressively increase energy prices to meet "*market levels*" [30].

The PR scenario builds on Specification 1 of the production function (see section 3.1), which allows for trade-offs with value-added if electricity prices increase. We investigate two variants of price increases based on different international references. In the first variant, denoted as PR-EM, electricity prices converge to the average price across emerging countries in the G20, a group of leading rich and developing nations. In the second variant, denoted as PR-AVG, electricity prices converge to the average price across all G20 countries. Table 2 summarizes our assumptions for the PR scenario.

In the first variant (PR-EM), residential prices grow 72% above their post-EPR levels. They ultimately approach current prices in China and South Africa. Nevertheless, they remain two times lower than prices in countries with similar incomes (i.e., GDP per capita) to Saudi Arabia. Examples of such countries are the Czech Republic, Poland and Slovakia.

Because Saudi Arabia has a large (mainly energy-intensive) industrial base, reforming industrial prices is a sensitive issue. However, additional moderate reforms are necessary to support the economic viability of the country's power system [34]. Thus, we exclude the two countries with the highest industrial electricity prices, Brazil and India, from the computation of the prevailing industrial price in the PR-EM variant. As a result, the industrial electricity price in 2030 is 43% higher than the post-EPR price, which is maintained in the REF scenario. Hasanov [3] applies a similar price increase to the Saudi industrial segment based on matching the U.S. industrial electricity price for 2008–2017. For the remaining sectors, that is, PRV, PUB and AGR, we assume a similar conservative electricity price increase of 43% from post-EPR levels by 2030.

The second variant (PR-AVG) assumes that residential prices triple from their 2018 levels by 2030. As in the PR-EM variant, we exclude the countries with the two highest electricity prices (now Italy and Japan) from the computation for industrial prices. Under this assumption, industrial prices double by 2030 from their current levels. This price increase is again similar to the targeted industrial price in Hasanov's [3] alternative scenario.[10] Finally, we assume that the other sectoral prices double by 2030 compared to their 2018 levels.

In contrast to the REF scenario, variants of energy-pricing reforms like the PR scenario, because they modify Saudi prices relative to the rest of the world through unilateral increases of production costs, require yet another trade specification. We follow the reasoning of Soummane et al. [2]'s Annex A by dropping the correlation between the real effective exchange rate and the trade balance, which is adopted in the REF scenario. Similarly to their approach, we substitute to this rule the forcing of the ratio of the 'rental price' of domestic value-added to foreign prices of our REF scenario, in our PR scenario.

Finally, we highlight one important feature of our model of the electricity sector in this scenario. In our model, electricity is treated as one homogenous good, i.e., no differentiation between discrete generation technologies from a bottom-up perspective. Although this approach provides valuable indications of consumers' reactions to price changes, it cannot comprehensively illustrate the evolution of the supply-side mix or the costs facing technical constraints. Wing [35] and Cai and Arora [36] describe ways to integrate electricity sector technology within a CGE framework. We consider this integration as a potential direction for future work on the Saudi electricity market.

4.3. Energy efficiency scenario

In this scenario, changes in sectoral demand relative to the REF scenario are driven by decreases in the electricity intensities of different production types. Saudi authorities have set energy efficiency measures targeting various power-consuming segments to contain electricity demand growth. The government established the SEEC to set and coordinate national programs to rationalize energy consumption in buildings, industry and transportation. These measures are an application of the national strategy to reform the energy sector [30].

The energy efficiency (EE) scenario uses Specification 2 for the production function (see section 3.1), that is, we assume that the intensities of electricity use are exogenous. We simulate two variants of the EE: Moderate (EE-Mod) and High (EE-High). In these variants (Table 3), we adjust the sectors' exogenous electricity intensities (i.e., the electricity demand per unit of output). This specification, therefore, comprises the industry (RFN, MIN, CHM, NMM and MAN), commercial (PRV), government (PUB) and agriculture (AGR) sectors. We set residential electricity consumption based on the assumptions described below.

In the EE-Mod variant, we assume that the electricity intensity for IND decreases by 14% relative to 2018 by 2030, i.e. by 1.2% per year on average over the period. This decline corresponds to half of the electricity intensity improvement achieved between 2013 and 2018. The

[9] The choice of specification does not significantly impact projected demand. For instance, the projected demand in the REF scenario under Specification 1 deviates from the projected demand under Specification 2 by 1.8% in 2030 (359.0 TWh versus 365.4 TWh).

[10] Although our price targets are similar to those of Hasanov [3]; he assumes that the targets are reached in 2025.

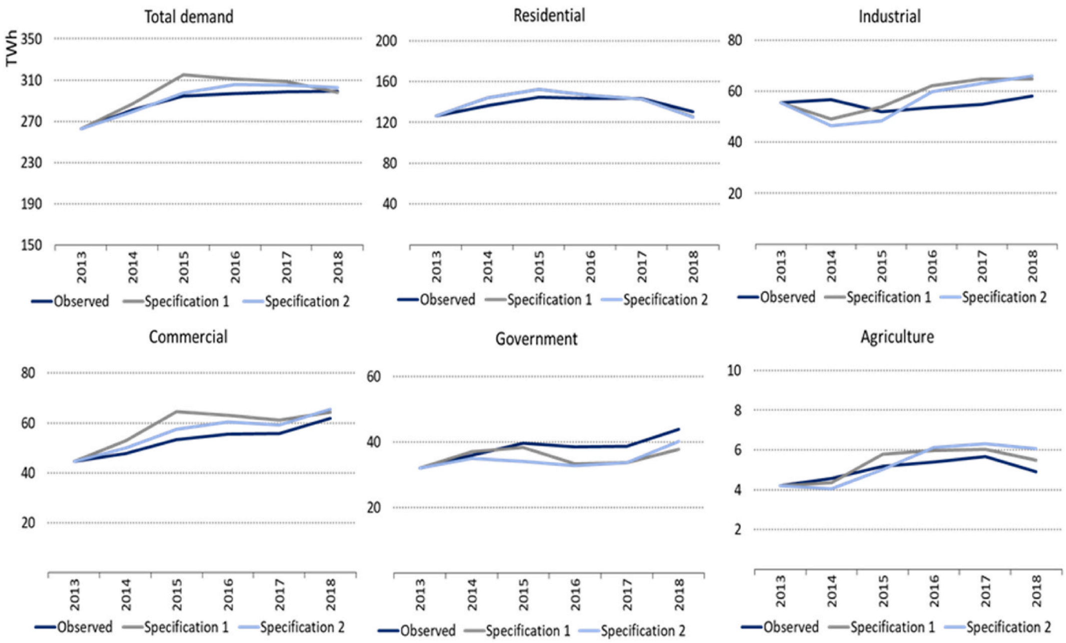

Fig. 1. Modeled versus observed electricity demand across sectors, 2013–2018 (in TWh). Sources: ECRA [29] for observed demand and IMACLIM-SAU results for modeled trajectories. Note: Specification 1 uses endogenous electricity intensities, and Specification 2 uses exogenous electricity intensities. Estimated versus observed sectoral activities are the remaining sources of discrepancy in specification 2.

Table 2
Assumptions for the two price reform scenarios (Saudi riyals [SAR]/kilowatt hour).

Variant	Sector	2013	2018	2025	2030	Δ 2018–2030
PR-EM	Residential	0.08	0.19	0.25	0.32	+72%
	Industrial	0.15	0.18	0.22	0.26	+43%
	Commercial	0.22	0.26	0.32	0.37	+43%
	Government	0.26	0.32	0.39	0.46	+43%
	Agriculture	0.11	0.17	0.21	0.24	+43%
PR-AVG	Residential	0.08	0.19	0.35	0.56	+200%
	Industrial	0.15	0.18	0.27	0.36	+100%
	Commercial	0.22	0.26	0.39	0.52	+100%
	Government	0.26	0.32	0.48	0.64	+100%
	Agriculture	0.11	0.17	0.25	0.34	+100%

Sources: The authors' computations of 2013 and 2018 data are based on Nachet and Aoun [31]; Kingdom of Saudi Arabia [30]; APICORP [32]; and Hasanov [3]. The assumptions for projected values are based on data from ENERDATA [33].

Table 3
Electricity intensities of the energy efficiency scenarios (index 1 in 2013).

Variant	Sector	2013	2018	2025	2030	Δ 2018–2030
EE-Mod	Residential[a]	1.00	1.14	1.08	1.03	−10%
	Industrial	1.00	0.85	0.72	0.64	−14%
	Commercial	1.00	1.23	1.05	0.94	−23%
	Government	1.00	1.25	1.07	0.95	−23%
	Agriculture	1.00	1.00	0.85	0.76	−23%
EE-High	Residential[a]	1.00	1.14	0.96	0.84	−26%
	Industrial	1.00	0.85	0.57	0.43	−25%
	Commercial	1.00	1.23	0.84	0.64	−50%
	Government	1.00	1.25	0.85	0.65	−50%
	Agriculture	1.00	1.00	0.68	0.52	−50%

[a] Scenarios of the residential sector are for the sector's total consumption.
Source: Authors' estimates based on ECRA [29]; ENERDATA [33] and SAMA [37] for 2013 and 2018. Authors' assumptions for projected values.

Saudi industrial base, whose energy mix is dominated by oil and gas, already has the lowest electricity intensity among the G20 countries.[11]

We assume that the electricity intensities of PRV, PUB and AGR decrease by 23% between 2018 and 2030 (i.e., 2.2% per year). This efficiency gain corresponds to the savings estimated by Krarti et al. [38] for Saudi buildings, including commercial and governmental buildings. They estimate these savings based on actions with no significant costs, such as thermostat adjustments or replacements of existing lighting. Finally, we assume that residential electricity consumption decreases by 10% between 2018 and 2030 (i.e., 0.9% per year). This assumption is based on the cost-free gains in Saudi residential buildings estimated by Krarti et al. [38].

In the EE-High variant, we assume that the observed 2013–2018 efficiency gains for IND of 2.4% per year continue through 2030, i.e., −25% by 2030 compared with 2018. For PRV, PUB and AGR, we assume that intensity falls by 50% from 2018 to 2030 (i.e., 5.6% per year). This assumption corresponds to the Level-3 efficiency improvements estimated by Krarti et al. [38].[12] Finally, we assume that residential electricity demand decreases by 26% from 2018 to 2030 (i.e., 2.5% per year). This assumption is based on the higher efficiency gains estimated by Krarti et al. [38].

Finally, we highlight one important aspect of this scenario's narrative. We model *efficiency only* variants to assess the potential energy savings that can be achieved under various intensity targets. Although efficiency measures may incur some costs, such as investments in new

[11] We compute electricity intensity as the ratio of value-added from industry (in real U.S. dollars) to the electricity consumption of the sector (in gigawatt hours) using data from ENERDATA [33].

[12] In addition to the measures cited for the EE-Mod variant, the main measure underpinning these gains is the replacement of air conditioning units.

appliances or retrofitting, we consider these costs to be insignificant. The prevailing electricity intensity in Saudi Arabia is high compared with other countries. This comparison may be biased for industrial consumption, as the Kingdom's power mix is dominated by fossil fuels. Nevertheless, Saudi electricity demand can be significantly reduced through costless or very-low-cost policies with relative immediate feasibility. Such policies may include awareness campaigns, updates to regulations to improve codes and standards for new buildings, and the introduction of dynamic pricing [39]. Moreover, the current deployment of smart meters in the Kingdom will help with tracking and reducing inefficient electricity use.[13] Finally, the mid-term projection horizon suggests that energy intensity reductions may be achievable through demand-side management measures.

5. Results

We begin our discussion of the results by presenting the electricity demand in the REF scenario. In this scenario, total electricity demand reaches 365.4 TWh in 2030, up from 299.2 TWh in 2018. In the period without statistical data, that is, from 2019 to 2030 (see section 3.2), projected demand growth is significantly below its historical trend, reflecting the observed slowdown over the past years. Between 2009 and 2018, total electricity demand grew at 5.3% per year on average and slowed to an average rate of 2.7% per year in the period between 2013 and 2018. In the REF scenario, we project average electricity demand growth of 1.6% per year between 2019 and 2030 (Fig. 2).

The residential sector remains the primary consumer of electricity. However, its share drops from 43.6% of the total electricity demand in 2018 to 39.0% in 2030 in this scenario. The two EPR rounds significantly impacted residential demand. In 2016, residential demand started to flatten for the first time. It then declined by 9.1% in 2018. The average growth rate between 2009 and 2018 therefore dropped to 3.2%.[14] Under our assumption that real prices remain at 2018 levels, residential demand slowly recovers at an average rate of 1.1% per year between 2019 and 2030, ending at 142.4 TWh.

In the other sectors, electricity demand grows faster than in the residential sector (Table 4). For instance, keeping electricity intensities stable results in electricity demand increasing in line with the sectors' outputs, which are driven by demand from other sectors through the input output feature of the general equilibrium framework, or from households for final uses. For instance, industrial's (IND) output grows at a rate of 1.8% through 2030, and its electricity demand increases from 58.2 TWh in 2018 to 81.9 TWh in 2030. IND comprises 22.4% of the total electricity demand in 2030 in the REF scenario, a 3.0% point (pp) increase from its share in 2018.

Next, we analyze the alternative demand scenarios. Table 4 summarizes the impacts of price reforms and efficiency measures on electricity demand. Aligning domestic electricity prices with those of emerging G20 countries (PR-EM variant) reduces annual demand growth by half compared with the REF scenario. Specifically, demand growth in the PR-EM variant is 0.8% per year between 2019 and 2030, compared with 1.6% per year for REF. In 2030, the total demand in the PR-EM variant is 37.8 TWh less than that in the REF scenario (i.e., 10.3% lower). Further tariff increases to meet average G20 price levels (PR-AVG variant) result in roughly stable total demand over the projection horizon. The growth rate is +0.1% per year on average through 2030. Total demand in this scenario is 65.0 TWh less than in the REF scenario (i.e., 19.6% lower).

The higher prices of PR scenarios prompt efficiency gains in all sectors. In the PR-EM variant, the electricity intensity of IND decreases by 7% compared to 2018. In PRV and PUB, electricity intensity abatement in 2030 reaches 19% and 21% compared with 2018, respectively. In the PR-AVG variant, higher prices drive even higher electricity intensity reductions. In 2030, the electricity intensity of IND is reduced by 14% compared with 2018. At the same horizon, PRV and PUB intensities are respectively 26% and 31% lower than 2018 levels.

In the EE scenarios, efforts to reduce electricity intensity in the IND, PRV and PUB sectors, along with reduced residential demand, drive higher energy savings. By 2030, achieving the objectives of the EE-Mod variant flattens electricity demand over the projection horizon. In 2030, aggregate electricity demand is 45.6 TWh lower in the EE-Mod variant than in the REF scenario (i.e., 12.5% lower). The larger efficiency gains of the EE-High variant reduce total electricity demand by 2.2% per year on average. This decrease is equivalent to around 6 TWh per year through 2030. In 2030, total demand is 118.7 TWh lower than in the REF scenario (i.e., 32.5% lower).

The electricity consumption patterns in the two alternative scenarios are similar to those in the REF scenario. The residential segment remains the largest consumer of electricity in all scenarios. In the PR-EM and PR-AVG variants, residential demand accounts for 40.7% and 41.3% of total demand in 2030, respectively. By comparison, it accounts for 39.0% of

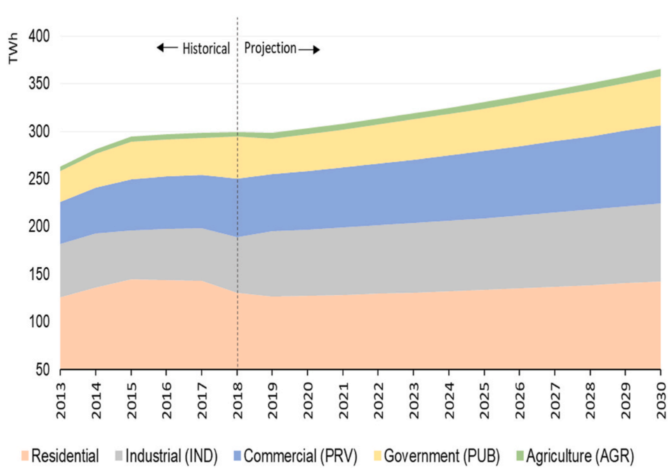

Fig. 2. Electricity demand by sector in the REF scenario. Sources: ECRA [29] for 2013–2018 data. IMACLIM-SAU for modeled values.

Table 4
Electricity demand by scenario, in TWh.

	2013	2018	2030				
			REF	PR		EE	
				PR-EM	PR-AVG	EE-Mod	EE-High
Residential	126.1	130.4	142.4	133.3	124.1	129.3	106.3
Industrial	55.6	58.2	81.9	73.1	67.3	69.4	60.9
Commercial	44.6	61.8	82.1	73.0	66.7	71.0	46.5
Government	32.1	43.9	51.5	42.4	37.0	44.3	29.2
Agriculture	4.2	4.9	7.4	5.9	5.3	5.8	3.8
Total	262.7	299.2	365.4	327.6	300.4	319.8	246.6

Sources: ECRA [29] for 2013 and 2018. IMACLIM-SAU results for projected values.

[13] https://www.se.com.sa/en-us/customers/Pages/SmartMeters.aspx.

[14] Between 1999 and 2008, residential electricity demand grew at an average rate of 6.6% per year.

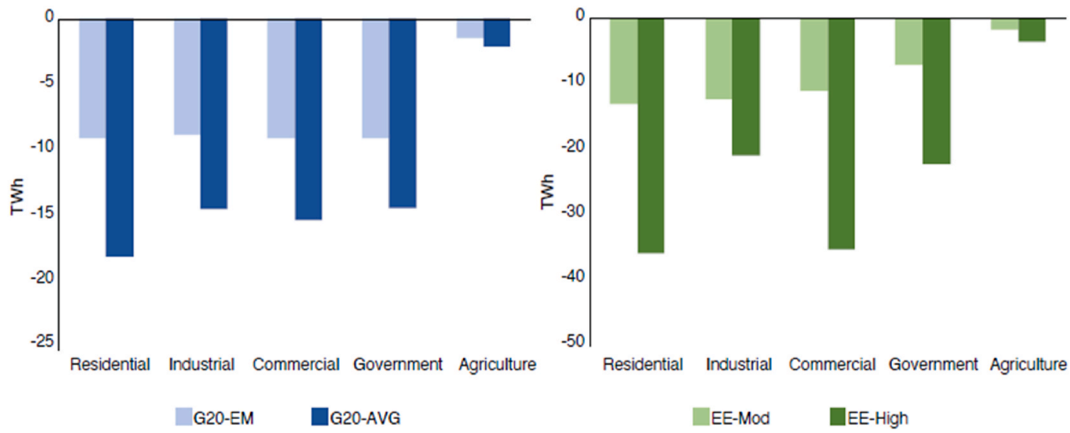

Fig. 3. Reductions in 2030 sectoral power consumptions relative to the REF scenario. Sources: IMACLIM-SAU simulation results.

total demand in the REF scenario. The shares of most of the other sectors in the PR-EM and PR-AVG variants are similar to those of the REF scenario. The exception is PUB's demand, which decreases slightly from 14.4% in the REF scenario to 12.9% and 12.3% in the PR-EM and PR-AVG variants, respectively.

In the EE-Mod and EE-High variants, residential demand in 2030 accounts for 40.4% and 43.1% of total demand, respectively. Moreover, the shares of IND in total demand in 2030 are 21.7% and 24.7% in the EE-Mod and EE-High variants, respectively. These shares are similar to those in the REF scenario. The shares of the remaining sectors in total demand are roughly similar for the EE-Mod variant and the REF scenario. They are slightly lower in the EE-High variant than in the REF scenario.

The PR-EM and PR-AVG variants achieve electricity savings of 37.8 TWh and 65.0 TWh, respectively, in 2030 (Fig. 3). In the PR-EM variant, the main electricity-consuming sectors reduce their consumption by around 9.0 TWh each. AGR, whose consumption is relatively marginal, contributes savings of 1.6 TWh. In this variant, the residential sector reduces its consumption by 6.4% relative to REF by 2030. Compared with REF, IND and PRV reduce their relative consumption by around 11%, and PUB's relative consumption falls by 17.7%. In the PR-AVG variant, residential demand is 12.8% less than in the REF scenario in 2030, amounting to savings of 18.3 TWh. IND, PRV, and PUB contribute 14.6 TWh, 15.5 TWh, and 14.5 respectively, to demand savings. These declines correspond to abatements of 17.8%, 18.8% and 28.2%, respectively, relative to the REF scenario in 2030.

The electricity demand savings of the EE scenarios are greater than those of the PR scenarios. Relative to the REF scenario, electricity demand is 45.6 TWh and 118.7 TWh lower in 2030 under the EE-Mod and EE-High variants, respectively. The residential sector accounts for declines of 13.1 TWh and 36.1 TWh, respectively. The efficiency gains for intermediate users result in significant demand abatement. Consumption in the IND sector is 12.5 TWh (−15.3%) and 21.1 TWh (−25.7%) lower under the EE-Mod and EE-High scenarios, respectively, than under the REF scenario in 2030. Likewise, demand in the PRV and PUB sectors is 11.2 TWh and 7.2 TWh lower under the EE-Mod variant, respectively. In both sectors, demand is about 14% lower than in the REF scenario. In the EE-High variant, the PRV and PUB sectors achieve electricity savings of 35.6 TWh and 22.3 TWh, respectively. Demand in these sectors is about 43% lower in this scenario than in the REF scenario.

Another important feature of modeling electricity demand in a general equilibrium framework with income distribution is the ability to assess the implications of simulated policy scenarios from a macroeconomic perspective. Table 5 reports the main macroeconomic indicators for our scenarios. The overall outcomes of our alternative scenarios are positive compared with the REF scenario. Indeed, real GDP is higher in all four variants than it is in the REF scenario, and it is the highest in the EE scenario. The mechanisms at play are quite distinct in the EE and the PR scenarios.

Under the assumption of efficiency measures of negligible costs (see Section 4.3), the efficiency gains of EE scenarios both reduce the production costs of firms and increase the purchasing power of households. Exports and domestic consumptions are consequently higher in the EE scenarios, resulting in improved employment outlooks. In 2030, the unemployment rates are 0.3 pp and 0.8 pp lower under the EE-Mod and EE-High variants, respectively, compared with the REF scenario. These numbers correspond to 42,000 and 126,000 jobs created, respectively. In 2030, GDP is 0.9% and 2.5% higher in the EE-Mod and EE-High variants, respectively, than in the REF scenario. Additionally, reducing the intensity of electricity use lowers overall electricity consumption in the targeted sectors, thereby decreasing public spending on financial incentives. The government balance improves by 0.3 pp and 0.7 pp in the EE-Mod and EE-High variants, respectively. Net debt as a share of GDP is 2.0 pp and 4.8 pp lower in the EE-Mod and EE-High variants than in the REF scenario, respectively.

Contrastingly, the energy consumption cuts of the PR scenarios rest on price increases that impair both the competitiveness of firms on export markets and the purchasing power of households. However, the low-cost shares of electricity in productions (maximum of 1.5% in CHM at calibration year 2013) and the low budget share of electricity for households (0.8% at calibration year) limit the negative impacts. Moreover, the increased oil rent from increased exports prompts higher public expenditures and investment.[15] The latter positive effects supplant the former negative ones as regards total activity (real GDP), which ends up 0.9% and 1.2% above REF levels in 2030 under PR-EM and PR-AVG, respectively. They balance out each other as regards unemployment (−0.1 point under PR-EM, +0.1 under PR-AVG) because of the sectoral focus of the activity gain and the comparative labor intensities of activities. Lastly, both the rent on increased exports and the

[15] Both public expenditures and investment expenses are exogenous GDP shares common to all scenarios. The increase is in fact caused by relative price effects: because of the increased rent, the GDP price index rises faster than investment costs or the output price of public services PUB.

Table 5
Macroeconomic indicators by scenario.

Variable	2013	REF 2030	Difference from REF in 2030			
			PR-EM	PR-AVG	EE-Mod	EE-High
Real GDP (billions of 2013 riyals)	2773.3	4177.2	+0.9%	+1.2%	+0.9%	+2.5%
Unemployment rate	5.6%	7.4%	−0.1 pp	+0.1 pp	−0.3 pp	−0.8 pp
Trade balance (% of GDP)	24.6%	8.7%	−0.1 pp	+0.0 pp	+0.1 pp	+0.2 pp
Government budget balance (% of GDP)	8.8%	2.9%	+0.7pp	+1.6 pp	+0.3 pp	+0.7 pp
Net public debt (% of GDP)	−95.9%	−108.0%	−5.2 pp	−13.3 pp	−2.0 pp	−4.8 pp

Source: IMACLIM-SAU simulations. 'pp' stands for 'percentage points'.

decreased public subsidies favorably affect public budgets, whose 2030 balance improves by 0.7 points under PR-EM and as much as 1.6 points under PR-AVG. The cumulated additional surplus allows the net public debt to decrease (i.e. the Saudi sovereign fund to increase) by 5.2 points under PR-EM and up to 13.3 points under PR-AVG.

6. Conclusions and policy implications

The Saudi electricity sector is undergoing structural changes. For decades, it grew rapidly, supported by government incentives through regulated low prices for electricity consumption. These demand trajectories were deemed unsustainable, threatening the government's fiscal sustainability and crowding out valuable fossil fuel exports. In recent years, the authorities have launched ambitious programs to curb demand growth and reduce wasteful uses of electricity. These public action plans have not only reformed prices but also promoted efficiency measures.

Given these structural changes, this study presents trajectories for future Saudi electricity demand through 2030. We discuss options for reducing electricity demand in different sectors while maintaining economic growth. The results from our pricing reform and energy efficiency scenarios can provide Saudi policymakers with insights into the potential outcomes of different policies.

We modify the dynamic CGE model, IMACLIM-SAU [2] to reflect the features of the electricity sector. We then use this model to explore three future power demand scenarios. Our reference scenario contains no additional electricity price reforms and no enforcement of efficiency measures. In our price reform scenario variants, we simulate regulated prices converging to the average prices for emerging G20 countries and all G20 countries. Finally, we run two variants of an energy efficiency scenario in which electricity intensity efficiency improvements are enforced, assuming either moderate or high gains.

In our reference scenario, demand growth is significantly below its historical trend, at 1.6% per year on average between 2019 and 2030. Demand reaches 365.4 TWh by 2030, up from 299.2 TWh in 2018. Our alternative scenarios show the potential for significant savings relative to the reference scenario. Aligning electricity prices with those of emerging G20 countries reduces aggregate demand by 40.5 TWh (11.1%) in 2030. Reaching the average price of all G20 countries abates total electricity demand by 71.6 TWh (19.6%) in the same year. However, opting for efficiency measures to rationalize electricity use may provide even greater savings. In the moderate energy efficiency variant, total electricity demand may be 45.6 TWh (12.5%) lower than in the reference scenario. This difference may reach 118.7 TWh (32.5%) under the ambitious energy efficiency targets of the high energy efficiency variant.

We also analyze the potential macroeconomic effects of our scenarios. In the four alternative variants, real GDP improves overall in 2030 compared with the reference scenario. This outcome stems from the favorable effects of price reforms and efficiency measures on the public budget and investment dynamics. Lower electricity demand improves the government's fiscal balance because it alleviates the financial burden associated with power generation subsidies. The impacts on the public budget and debt are greater under the price reform scenario than under the energy efficiency scenario. However, the gains in the former scenario are slightly undermined by the decreases in households' purchasing power and producer competitiveness due to higher electricity prices.

One important driver of electricity demand that our analyses do not explicitly account for is future large-scale projects. Indeed, although our model captures sectoral interdependencies, it does not incorporate the government's announcements of several large projects being established across Saudi Arabia. These projects include the development of the tourism industry, with expanded Hajj capacity, and several industrial initiatives (e.g., the National Industrial Development and Logistics Program). These projects may generate significant incremental electricity demand over the coming decade. Moreover, other factors could impact future Saudi electricity demand. Electric vehicles deployment and decentralized electricity generation are the main potential disruptive factors. The current study focuses on projecting structural sectoral electricity demand through 2030. Future research should account for these factors and extend the projection horizon.

Credit author statement

Salaheddine Soummane: Conceptualization, Data curation, Methodology, Software, Formal analysis, Writing – original draft. Frédéric Ghersi: Methodology, Software, Validation, Writing- Review & Editing.

Disclaimer

The views expressed in this paper are those of the authors and do not necessarily represent the views of their affiliated institutions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Sensitivity analysis

In this section, we present a sensitivity analysis of electricity demand to selected socioeconomic variables. For brevity, we present the sensitivity results for aggregate demand in the REF scenario and the variation in GDP at the end of the projection horizon. Figure A.1. summarizes our two production specifications.

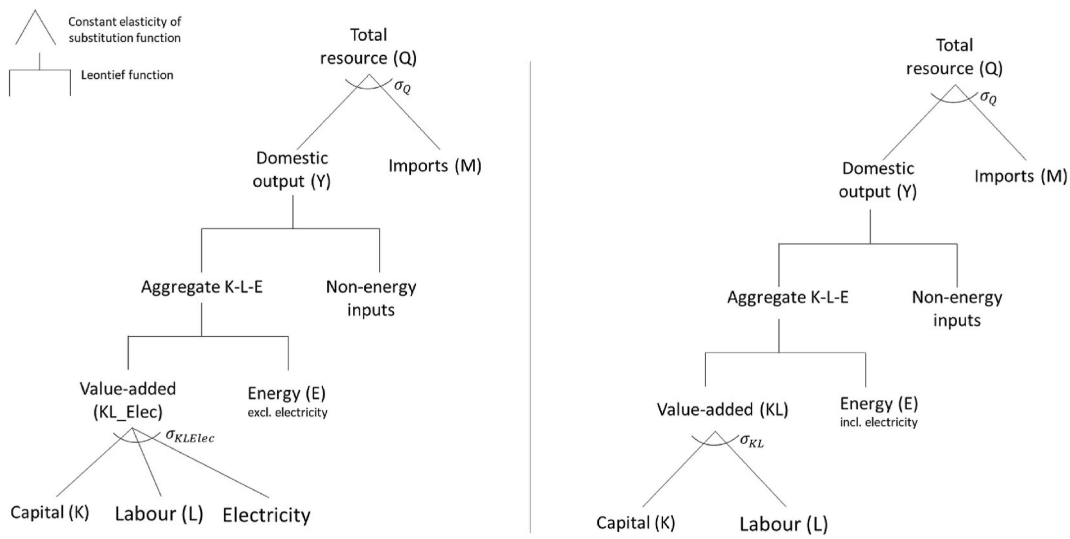

Fig. A.1. Nested production structures under Specification 1 (L) and Specification 2 (R).

The main goal of this analysis is to show how variations in the selected model drivers may impact electricity demand in 2030. The macroeconomic and social drivers in the model are subject to uncertainties. Thus, we test them within reasonable boundaries corresponding to "low" and "high" variants (Table A.1).

Table A1
Exogenous socioeconomic variables in the model in 2030

Variable	Unit	Low	REF	High
Active population	Million full-time equivalents	26.2	27.6	29.0
Labor productivity	Index equal to 1 in 2013	1.05	1.10	1.27
Default export trend	Index equal to 1 in 2013	1.41	1.76	2.12
Gross fixed capital formation	Share of GDP	23.9	26.1	29.8
Elasticity of substitution, σ_{VA}	n.a.	0.5* Reference value	Reference value	1.5* Reference value
Oil output	Million barrels per day	11.0	12.9	13.5
Oil price	U.S. dollars per barrel	62	88	111

We vary the active population endowment by −/+5% of the REF scenario target in 2030. For labor productivity, we assume a moderate gain of 5% by 2030 in the low variant, corresponding to the targeted increase from Oxford Economics. We assume a gain of 27% in the high variant, corresponding to the non-oil productivity gains estimated by Alkhareif et al. (2017). We vary the default export trend by −/+20% of the REF scenario target in 2030. We interpret the low export variant as weaker growth in the Middle East and North Africa as the region fails to economically recover from the COVID-19 pandemic. The high variant reflects a quick post-pandemic recovery of the region's economies.

No proper estimates of elasticities of substitution (σ_{VA}) in the Saudi context are available. Thus, we also conduct sensitivity analyses of electricity demand to the key model's parameters. To do so, we multiply these elasticities by factors of 0.5 (low variant) and 1.5 (high variant), respectively. For gross fixed capital formation, investment returns to its 2013 level in the low variant. In the high variant, investment reaches its 2015 level. In 2015, the government stimulated the non-oil sector with public spending in reaction to an oil price slump. We use the percentage variations in oil production in the Middle East region projected by the IEA [40]. Production in the low and high variants corresponds to the IEA's Sustainable Development Scenario (SDS) and Current Policies Scenario (CPS), respectively.[16] Likewise, the low and high variants for projected oil prices correspond to oil prices in the IEA [40] SDS and CPS.

The analysis reveals that electricity demand is more sensitive to variations in investment, oil prices and productivity levels. It is moderately sensitive to variations in the active population (Figure A.2.). Oil production levels and the default export trend for non-energy goods only marginally impact electricity demand. The variants used for the presented sensitivity analysis are based on the REF scenario. In other words, they have fixed electricity prices at 2018 levels and fixed electricity intensities of production at the 2013–2018 average. The exception is the sensitivity analysis for σ_{VA}, which is based on production Specification 1. Thus, the variations in electricity demand stem from impacts on households' revenue dynamics, sectoral outputs and the fiscal balance. These variables, along with other macroeconomic variables (e.g., the unemployment rate, trade balance and

[16] The IEA [40] does not project Saudi Arabia's oil production in its alternative CPS and SDS scenarios.

public debt) drive the changes in electricity demand trajectories. Together, these variations result in changes in GDP.

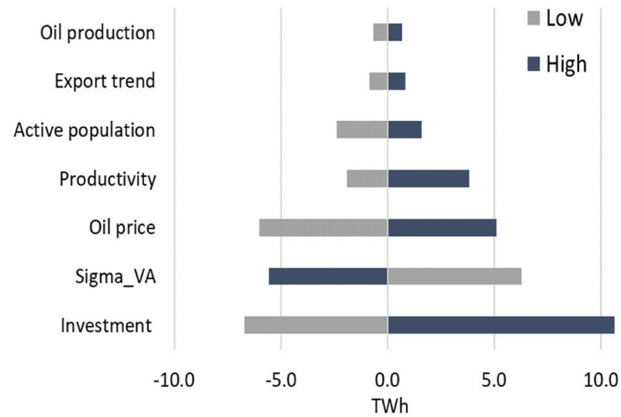

Fig. A.2. Sensitivity of total electricity demand to macroeconomic variables, difference from the REF scenario in 2030. Source: IMACLIM-SAU simulations.

As stated previously, we restrict the sensitivity analysis for macroeconomic variables to induced variations in real GDP relative to its 2030 level in the REF scenario. As expected, higher variation in real GDP is associated with higher variation in total electricity demand, with the exception of oil production. GDP in 2030 varies by −2.1% and +3.4% relative to the REF scenario in the low and high investment variants, respectively. Oil prices in the low and high variants are associated with GDP changes of −2.3% and +1.8%, respectively. In the low variants for the active population, productivity and the default export trend, GDP changes by −0.8%, −0.6% and −0.3%, respectively. In the high variants for those factors, it changes by +0.5%, +1.3% and +0.3%, respectively, compared to the REF scenario.

Finally, reducing the elasticity of substitution of the inputs to electrified value added is associated with higher electricity consumption but reduces GDP by 0.5%. Increasing this elasticity of substitution improves GDP by 0.2%. Indeed, lowering the substitutability of primary production factors increases the share of electricity, as it becomes a rigid production factor with fewer substitutes. However, because electricity has a lower share of value added, increasing its share compared with the other factors slightly reduces GDP. Conversely, increasing substitutability at the bottom of the production function allows competing factors (i.e., labor and capital) to substitute for electricity in the production process. However, this substitutability warrants additional bottom-up expertise, as further electrifying some industrial processes requires retrofits or upgrades to production mechanisms.

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