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Cross-seasonal Fuel Savings from Load Shifting in the Saudi Industrial Sector: Insights Using a Power System Model

Salaheddine Soummane, Amro Elshurafa, Hatem Alatawi, Frank Felder

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Disclaimer

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Declaration of Competing Interests

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

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Abstract

Load shifting, that is, moving demand from peak to off-peak hours, is an important type of demand response. It can reduce the overall operating costs of a power system and improve the reliability of the power grid. This study estimates the financial implications of load shifting in the Saudi industrial sector. We use a national Saudi power system dispatch optimization model to simulate three scenarios. With this model, we quantify the impacts of shifting industrial loads from the peak summer to the off-peak winter months, keeping industrial electricity tariffs unchanged. Our analysis shows that load shifting can save between $7.9 million and $17.7 million per year at the prevailing administered fuel prices. However, the full cost savings range from $127.2 million to $239.4 million per year when considering the opportunity costs of saved fuel (mostly crude oil). These potential savings represent 8.1% of the system's annual fuel costs. Furthermore, we recommend aiming to shift at least 15% of the total industrial load to increase fuel savings if natural gas prices are reformed. We conclude with a discussion of potential enablers and barriers to adopting load shifting in Saudi Arabia.

Keywords: Demand response, Load shifting, Industrial electricity demand, Power system modeling.

Highlights

- We quantify the financial implications of load shifting in the Saudi industrial sector.
- We simulate several scenarios using a Saudi power system model.
- At regulated fuel prices, cost savings range from $7.9 million to $17.7 million per year.
- At international oil prices, cost savings amount to 8.1% of the system's total fuel cost.
- Shifting more than 15% of the industrial load increases savings.

1. Introduction and National Context

Providing affordable and reliable electricity is an important but challenging objective for governments worldwide. Demand response (DR) mechanisms are a proven method to effectively reduce electricity supply costs (Bradley, Leach, and Torriti 2013). The industrial sector, in particular, can facilitate a significant amount of DR through load shifting. Load shifting means moving loads from higher to lower marginal generation cost periods without necessarily reducing overall consumption (Dutta and Mitra 2017; Pechmann et al. 2017). The flexibility of certain segments within the industrial sector is an important characteristic of load shifting. In this sector, large loads concentrated in a handful of customers can be shifted. These shifts do not compromise the continuity of the industrial process or the quality of the final service offered (Lund et al. 2015). Nevertheless, the industrial potential of DR remains underutilized (Shoreh et al. 2016).

Saudi Arabia's electricity demand increased significantly during the 1970s. Over the subsequent decades, the growing demand for electricity has burdened the Kingdom's domestic fuel supply and public finances (Alyousef and Stevens 2011; Fattouh and El-Katiri 2013). Saudi Arabia recently implemented energy price reforms and energy efficiency programs to rationalize consumption and curb the fast-growing demand (Mikayilov et al. 2020; Aldubyan and Gasim 2021). Although Saudi electricity demand has flattened since 2016, the cost of supplying electricity remains high. The power sector was responsible for 62.5% of the Kingdom's natural gas consumption and 8.6% of its crude oil and refined products consumption in 2019 (Enerdata 2019).

In Saudi Arabia, regulations set fuel prices for power generation below international levels. Thus, using oil and gas domestically incurs an opportunity cost (Gately, Al-Yousef, and Al-Sheikh 2012; Shabaneh and Schenckery 2020; Karanfil and Pierru 2021). Moreover, the power system's summer load is twice its winter load (Howarth et al. 2020). The fuel supply is therefore tighter in the summer, with low utilization of the power system in the winter. As a result, the cost of power generation in Saudi Arabia differs greatly between the summer and winter months. This variance may increase further if fuel prices are deregulated (Matar and Anwer 2017).

Between 2010 and 2019, Saudi industrial electricity demand grew at a rate of 3.3% per year on average. Currently, the industrial sector consumes 58 terawatt-hours (TWh) of electricity annually, accounting for about 20% of the country's total electricity demand (ECRA 2020). Over the same period, the number of operating industrial units increased from 4,858 to 7,625. Of these, about 61% engage in energy-intensive activities (SAMA 2019).[1] Administered energy prices have supported the development of these energy-intensive industries in Saudi Arabia (Alarenan, Gasim, and Hunt 2020). As a result, Saudi Arabia has become a leading global producer in some electricity-intensive areas. For example, the Kingdom is currently a major producer of aluminum and chemicals (Moya and Boulamanti 2016), cement (Matar and Elshurafa 2017) and steel (World Steel Association 2020).

Prior to 2016, Saudi Arabia implemented a time-of-use (ToU) pricing scheme for industrial customers. ToU tariffs are designed to reflect the variability in the marginal cost of electricity supply. In other words, they ensure that prices are higher during peak hours and lower during off-peak hours. These schemes incentivize load shifting from peak to off-peak hours (Dutta and Mitra 2017). Using this approach, the Saudi electricity regulator initiated tariff-driven load shifting programs for large consumers. These programs aimed to curtail load during targeted critical peak hours in summer months (Faruqui et al. 2011). The ToU scheme shifted about 10% of the energy demand in peak periods to off-peak periods. Industrial consumers across 145 industrial units contributed 69% of the realized total energy shift, reducing costs by 22% (Alyousef and Abu-Ebid 2012).

In 2016, industrial electricity prices were set at a flat rate of 0.048 United States dollars per kilowatt-hour ($/kWh) throughout the year. Thus, the potential benefits of other policies besides variable rates should be considered to reduce the generation costs of the national power system. This study assesses the potential financial impacts of implementing a large-scale industrial load shifting program in the Saudi national power system. The program does not change overall electricity consumption or electricity rates, thereby maintaining the utility's revenue.

The remainder of the paper is organized as follows: Section 2 reviews the literature on load shifting in sectors relevant to the Saudi context. Section 3 presents the modeling framework and the design of the scenarios. Section 4 discusses the findings, and Section 5 concludes.

2. Literature on Load Shifting in the Industrial Sector

Demand-side management (DSM) can be adopted by the industrial sector to adjust demand and ultimately reduce energy costs. DSM encompasses a range of measures. These measures may aim to temporarily reduce demand by modifying the shape of the load curve or permanently cut consumption through efficiency. The following DSM techniques are widely used (O'Connell et al. 2014; Lund et al. 2015).

> Energy efficiency (EE) measures aim to reduce the electricity used for a given service. They are permanent measures that scale down customers' load curves. However, EE measures require investments in appliance retrofits or upgrades.

> Peak clipping reduces load during peak hours. Thus, it eliminates the need for additional generation units and transmission and distribution assets to meet peak demand.

> Dynamic pricing refers to time-varying pricing schemes (e.g., ToU) to reflect the time-varying costs of generation and transmission. These measures incentivize consumption reduction during peak times.

> Load shifting (LS) shifts demand at times when the electricity network is congested. Moving load from peak to off-peak hours lowers system costs.

Many studies assess the feasibility of LS at the plant level for industrial production. Yang, DeFrain, and Faruqui (2020) investigate cross-seasonal LS in a polysilicon manufacturing facility. Their estimates show the potential electricity cost savings associated with various LS scenarios. Shifting 50% of the load from summer to spring has the potential to reduce annual electricity costs by about $7 million. These savings represent 20% of total yearly electricity costs and 2% to 3% of annual production costs.

We restrict our literature review to LS in the industrial sector. LS is an approach to DR that schedules production at times when electricity generation costs are relatively low (i.e., off-peak hours). By doing so, overall production within the manufacturing facility is unchanged because the industrial unit recovers lost output during off-peak times. We particularly focus on LS in industries relevant to the Saudi context, that is, aluminum, chemicals, cement and steel. We choose these industries to highlight the feasibility and relevance of LS as a means of DR in Saudi Arabia. Based on the output levels and average production intensities of these four industries, they represent about 25 TWh (i.e., about 43%) of industrial electricity demand.[2]

In the aluminum industry, Nebel et al. (2020) report that LS in the German aluminum production process can shift 25% of the industry's load. They argue that flexibility measures in operations can both increase the load shifted and sustain the duration of the shift. Their estimates show that LS can abate electricity costs at the plant level by about 5%. This cost saving stems primarily from rescheduling the production process to match the renewable generation schedule. Increasing the share of renewable energy lowers wholesale electricity prices. Shafie-khah et al. (2019) and Paulus and Borggrefe (2011) estimate an LS potential in the aluminum industry of 25% that can be sustained for four hours.

In the chemical industry, Paulus and Borggrefe (2011) consider the chloride production process. They estimate that electricity use can be reduced by up to 40% for up to two hours. Moreover, Babu and Ashok (2008) develop an optimization model for rescheduling the caustic soda production process, an electrolytic chemical process. Optimally scheduling operations using a ToU scheme reduces the plant's peak demand by 19%, with electricity cost savings of 3.9%. Ashok and Banerjee (2000) show that LS at a fertilization plant improves the plant's load factor by 4.5%. It reduces the plant's daily electricity cost by about 3%.

In the cement industry, Summerbell et al. (2017) use data from a British plant to optimize its production process. They aim to minimize electricity costs without reducing overall output. The load that can be shifted from peak to off-peak hours is estimated to represent about 30% of the plant's total load. They estimate that LS can reduce the plant's electricity cost by 4.2%. Shoreh et al. (2016) argue that for cement production, the potential shiftable load can represent between 60% and 70% of total electricity consumption. The resulting electricity cost savings can reach 20% of consumers' electricity costs. They highlight, however, the importance of accounting for any cement storage limitations when shifting production. Yao et al. (2015) estimate the flexibility for LS in the cement production process. Their estimates range from 16% to 20% for raw mills and from 20% to 24% for cement mills. These shifts can be sustained for several hours. In South Africa, Lidbetter and Liebenberg (2013) show that LS in a cement plant can reduce the peak load by up to 35%. The shift can be sustained for six hours and can decrease the factory's electricity costs by 2%.

Finally, in the steel industry, Zhao et al. (2017) investigate LS in a Chinese steel plant. They show that price-driven (i.e., ToU) LS reduces electricity costs by 29.7% without compromising the production process. Similarly, Maneschijn, Vosloo, and Mathews (2016) investigate the potential of ToU LS in a South African steel plant. They estimate that the savings from shifting 25% of the plant's load from peak to off-peak hours are about $158,000 per year.[3] In Germany, Paulus and Borggrefe (2011) show that DR has significant potential in the steel industry. The shiftable load may amount to 100% of a plant's load. However, such a large shift can only be sustained for 30 minutes. Finally, Ashok (2006) conducts a case study of an Indian steel plant. Rescheduling production based on a ToU scheme can reduce peak load demand by about 50% and the plant's electricity cost by 5.7%.

Although electricity-intensive industrial activities are the primary targets of LS programs given the large potential savings, small and medium-sized plants can also provide meaningful LS. Pechmann et al. (2017) analyze four small and medium-sized industrial plants carrying out metal processing, metal casting and glass processing. They find that the technical LS potential ranges from 1.2% to 5.6%. The types of machines, production strategies and the flexibility of the production schedule are the main cause of the disparities in LS potential. These factors should be considered in LS program design. Table 1 summarizes the reviewed studies on LS and the potential for electricity cost reductions that they estimate.

Some studies investigate LS at the multi-plant or industry level. Investigating the impact of LS at an aggregate level is useful for reasons beyond economic factors. For instance, using LS to reduce carbon dioxide emissions associated with power supply is gaining interest as governments seek to curb power sector emissions. Zohrabian and Sanders (2021) investigate the LS potential of 97 water supply plants in California. They consider shifting 5% of the daily load from high emission periods (i.e., when the renewable energy supply is low) to low emission periods. Doing so can reduce the associated annual carbon dioxide emissions by 2% to 5% without affecting total electricity demand.

Table 1. Summary of industrial LS studies.

Reference	Industry	LS potential	Potential electricity cost savings
Nebel et al. (2020)	Aluminum	25%	5%
Shafie-khah et al. (2019)	Aluminum	25%	Not reported
Paulus and Borggrefe (2011)	Aluminum	25%	Not reported
Paulus and Borggrefe (2011)	Chloride	40%	Not reported
Babu and Ashok (2008)	Caustic-chlorine	19%	3.9%
Ashok and Banerjee (2000)	Fertilizers	Not reported	3%
Summerbell et al. (2017)	Cement	30%	4.2%
Shoreh et al. (2016)	Cement	60%-70%	20%
Yao et al. (2015)	Cement	16%-24%	Not reported
Lidbetter and Liebenberg (2013)	Cement	35%	2%
Zhao et al. (2017)	Steel	Not reported	29.7%
Maneschijn, Vosloo, and Mathews (2016)	Steel	25%	~$158,000
Ashok (2006)	Steel	50%	5.70%
Alyousef and Abu-Ebid (2012)	Various industries	10%	22%
Yang, DeFrain, and Faruqui (2020)	Polysilicon	30%-50%	$0.5-7 M

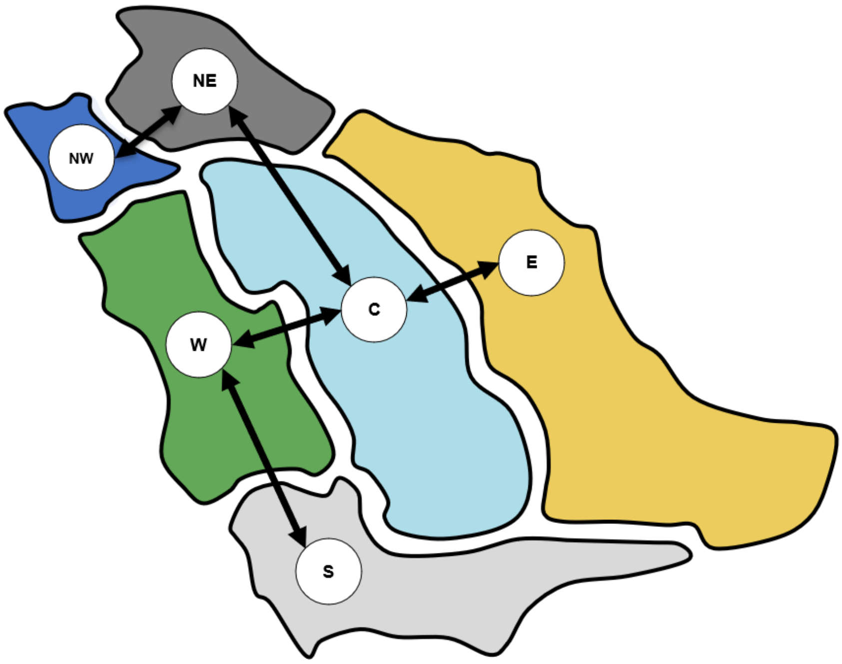
This study contributes to the existing literature by analyzing the financial implications of cross-seasonal DR based upon different scenarios. We seek to understand the potential amounts and durations of LS and its impact on the overall cost of electricity in Saudi Arabia. This study helps to address the large seasonal variation in Saudi power demand. This variation is associated with significant disparities in generation costs and fuel uses. Since regulated fuel prices in Saudi Arabia are below international levels, using resources for power generation incurs opportunity costs for large fossil fuel producers. In this study, we quantify the potential returns associated with avoided fuel consumption from power generation. These returns demonstrate the ability of LS to increase the government's revenues.

3. Methods and Scenarios

KAPSARC Power Sector Model

We use a power system model built specifically for Saudi Arabia. The KAPSARC power model (KPM) is a cost minimization model that uses the commercially available software package PLEXOS.[4] It treats the Kingdom as six regions, as shown in Figure 1. Figure 1 also depicts the transmission topology, which connects the regions within the Kingdom. The detailed representation of the generation fleet, fuels and heat rates in the model is based upon previous studies (Elshurafa and Peerbocus 2020; Elshurafa et al. 2021).

Figure 1. Six power system operating regions in the Kingdom of Saudi Arabia.



Source: Authors' illustration.

Note: Each region is represented by a single node, and each node is labeled with an abbreviation based on its location. 'C' represents the central region, 'E' represents the eastern region, 'NE' represents the northeastern region, 'NW' represents the northwestern region, 'S' represents the southern region, and 'W' represents the western region.

The modeling runs consist of short-term energy dispatches, meaning that no investment is possible. These runs are conducted based on the hourly load profiles for each region. Thus, the estimated LS gains stem from fuel savings and exclude capital cost savings (i.e., avoided investments in generation capacity and transmission lines). Power can flow between the regions given the capacities of the existing transmission lines. Four main fuels are used in Saudi Arabia's power sector: heavy fuel oil (HFO), crude oil, natural gas and diesel. Table 2 summarizes their administered prices.

Table 2. Assumed prices of fuels for power generation.

	Cost ($/MMBtu)
Crude oil	1.144
Diesel	2.41
Natural gas	1.25
Heavy fuel oil	0.6

Source: Elshurafa and Matar (2017).

Note: MMBtu stands for million British thermal units.

LS Scenarios

Modeling industrial LS requires energy data and detailed operational criteria to determine if a facility is fit for LS. A potential shift must also be categorized as technical or organizational at the industrial facility level (Pechmann et al. 2017). Most DR strategies at the factory level are financially motivated. By contrast, this analysis evaluates a case study driven primarily by Saudi Arabia's national-level strategic priority of reducing the overall cost of supplying electricity. We aggregate the data at the industrial facility level rather than at the plant level owing to data limitations. We expect these limitations to be partially addressed in the foreseeable future based on data from smart meters, which are currently being deployed.[5]

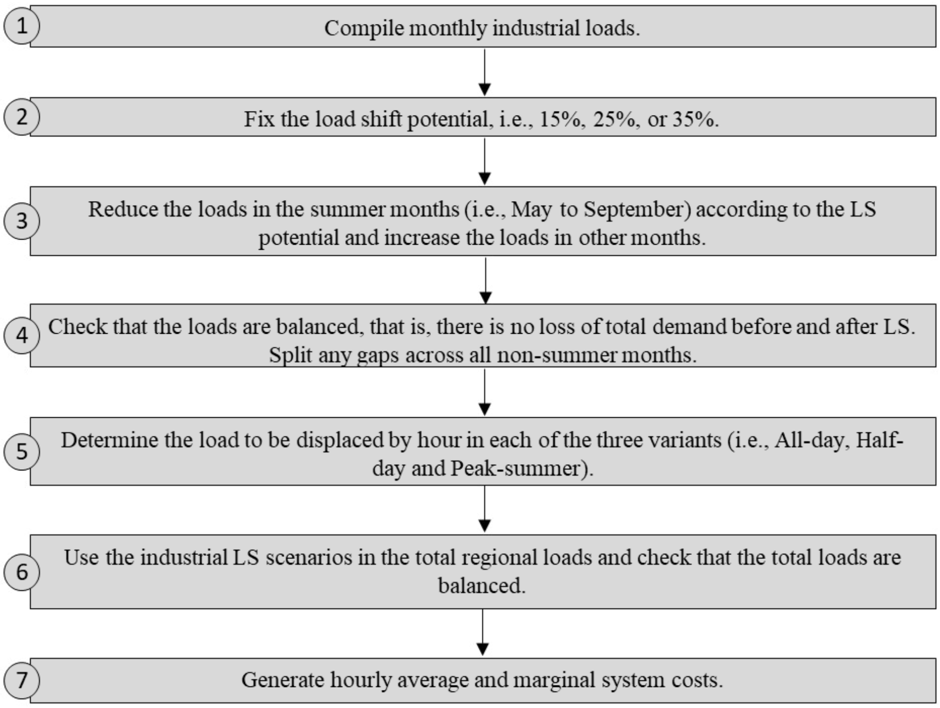
As discussed earlier, LS may also be environmentally motivated, as in the case of LS to reduce carbon dioxide emissions associated with power supply. Zohrabian and Sanders's (2021) LS study follows a similar methodology to ours, but their study focuses on environmental motivations. Specifically, they look at the use of LS to reduce emissions from power generation. Moreover, their LS potential and targeted hours differ from ours because they aim to capture California's power system and industry-specific features.

Our analysis is at the aggregated industrial load level. Thus, we use different scenarios to account for the technical, economic and organizational uncertainties associated with aggregated LS. We simulate scenarios with 15%, 25% and 35% LS potential. A 25% LS potential means that 25% of the total industrial load that is consumed during the targeted summer months is shifted to non-summer months. These shifts are assumed to be sustained for several hours. See Annex A for a detailed description and mathematical representation of the LS procedure.

We consider 25% to be the baseline LS potential, with 15% and 35% as variants. This choice is reasonable based on the data in Table 1, as the average reported rate is close to our selected baseline shift. Moreover, for each scenario, we simulate three additional variants according to the time of day when the load is shifted. These variants are referred to as the *All-day*, *Half-day* and *Peak-summer* variants. Figure 2 summarizes the procedures for data processing and scenario creation.

3. Methods and Scenarios

Figure 2. Schematic LS procedure used in this study.



Source: Authors' illustration.

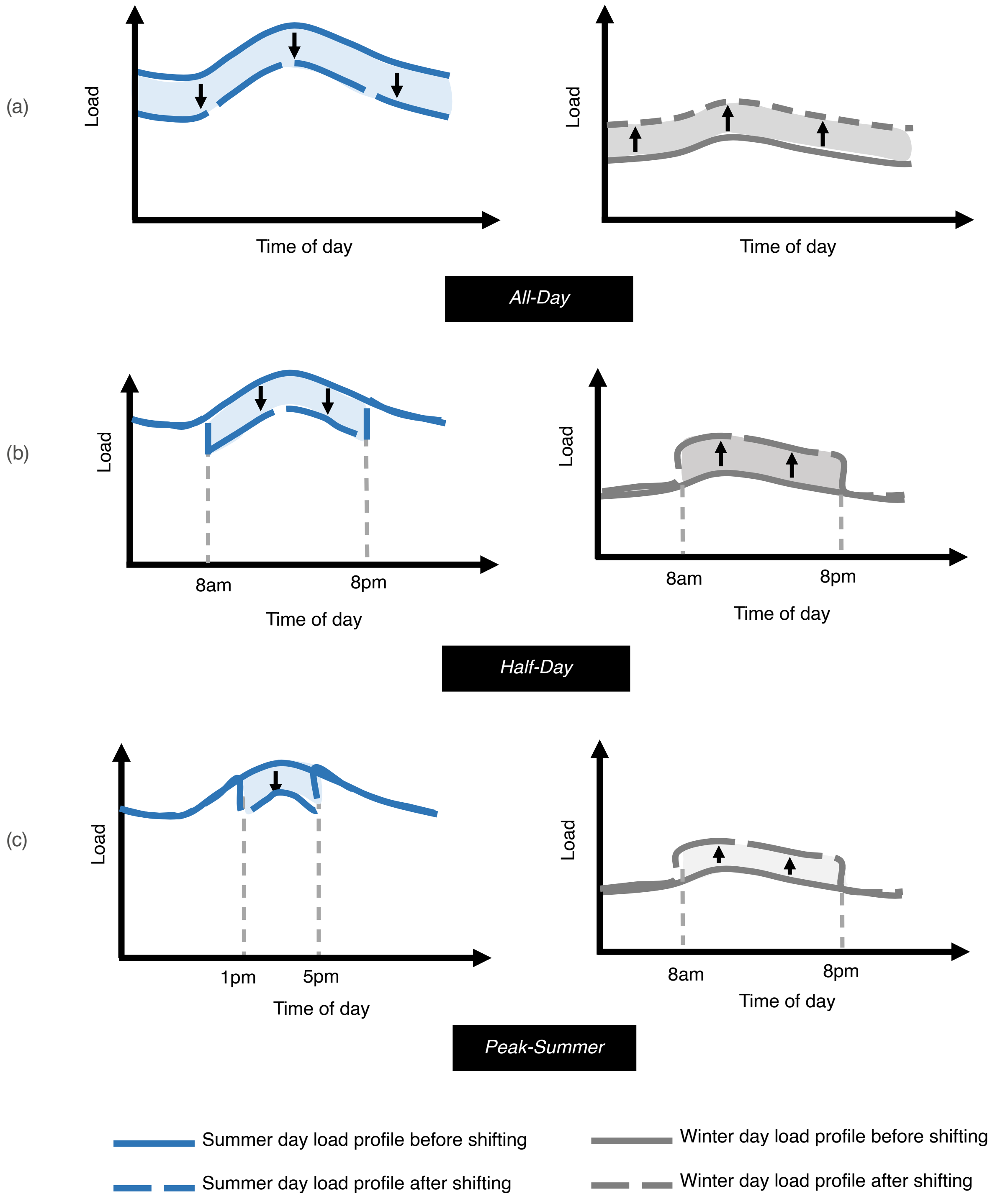
The monthly industrial loads compiled in step 1 are provided by the Saudi Electricity Company under a non-disclosure agreement. Thus, information regarding load patterns, such as that presented in Figure A of the Appendix, is redacted from this paper. We discuss the differences between the baseline and alternative scenarios in Section 4. In step 2, we assign a low (15%), moderate (25%) or high (35%) LS potential. In step 3, we define the summer months, in which the load is reduced, as May through September, following the Saudi regulator's definition (Faruqui et al. 2011). LS requires no change in the total load. Thus, in step 4, we ensure that the annual load is equal before and after the shift. We do so by distributing any lost load after the shift equally across the winter months. Then, in step 5, we shift the load according to each of our three variants. For each variant, we define the hours for which the load will be shifted. We focus on business days during the simulation year (i.e., Sundays to Thursdays in 2018). The variants are illustrated in Figure 3, and their definitions are as follows:

> *All-day* variant: For each hour of each summer business day, load is shifted to a non-summer business day.

> *Half-day* variant: For every hour between 8:00 a.m. and 8:00 p.m. on summer business days, load is shifted to equivalent hours on non-summer business days.

> *Peak-summer* variant: For each summer business day, load is shifted from peak hours (i.e., 1:00 p.m. to 5:00 p.m.) based on the Saudi Electricity Company's (SEC's) recommendations.[6] This load is shifted to working hours in non-summer months (i.e., 8 a.m. to 8 p.m.).

Figure 3. LS variants (panel (a): *All-day*, panel (b): *Half-day*, panel (c): *Peak-summer*).



Source: Authors' illustration.

As described in Section 3.1, the Kingdom has six operating regions, each with a load profile covering various sectors, including industry. The distribution of LS by region matches the shares of industrial electricity demand by region, as shown in Figure 1. Note that industrial consumption is reported by the regulator in every region except the northwestern and northeastern regions.[7] These two regions each account for about 1.5% of the Kingdom's total load. Thus, we weight the total industrial load shifted from summer to winter by the regional shares of industrial demand in the four regions with data. For example, because the central region accounts for 12.6% of Saudi industrial power demand, we assume that 12.6% of the shiftable load is in that region.

Table 3. Assumed shares of industrial electricity consumption by region.

	Central	Eastern	Southern	Western
Share (%)	12.6	71.9	1.3	14.2

Source: SAMA (2019).

4. Results and Discussion

Before presenting the energy savings stemming from demand shifting in the industrial sector, we first simulate a baseline scenario without LS. This scenario uses the exogenous hourly regional loads in the national optimization model to determine the underlying fuel consumption. We use default regional loads with no LS to determine the hourly solved mix for 2018, the simulation year. The system's total fuel consumption is 3,011.8 trillion British thermal units (Btu). Almost half (i.e., 47%) of the generated power is from gas-fired plants, followed by HFO at 38%. Crude oil contributed 15% of power generation, and no diesel-based generation was used. In the baseline scenario, the total fuel cost at regulated fuel prices is $2.73 billion (see Table 2). This cost excludes capacity, transmission, depreciation, operation and maintenance costs.

Savings Due to LS Based on Regulated Fuel Prices

In the LS scenarios, some industrial demand is moved from periods of higher to lower marginal cost of electricity supply. However, total electricity consumption is maintained. The overall financial gains in the nine variants stem from fuel savings, as Table 4 shows. In all scenarios and variants, LS leads to lower crude oil consumption, roughly stable natural gas consumption and a marginal increase in HFO consumption. In the low LS potential scenario (i.e., 15%), the power system's crude oil consumption is reduced by 2.4% in the *Peak-summer* variant. It is reduced by 2.8% in the *All-day* variant. Natural gas consumption remains roughly stable (i.e., +0.1%) in the three variants. Heavy fuel consumption partially offsets the drop in crude oil consumption, as its use increases by 0.5% compared with the baseline scenario.

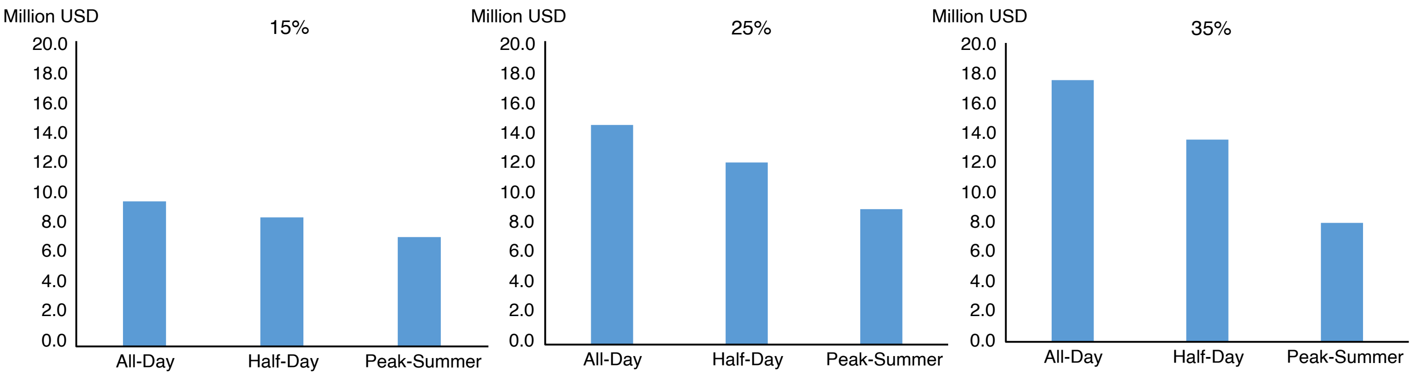
Table 4. Fuel consumption variation by scenario compared with the baseline scenario.

LS potential	Cost ($/MMBtu)	Fuel			
		Crude oil	Diesel	Natural gas	Heavy fuel oil
15%	*All-day*	-2.82%	NA	0.12%	0.46%
	Half-day	-2.69%	NA	0.10%	0.45%
	Peak-summer	-2.37%	NA	0.05%	0.46%
25%	*All-day*	-3.60%	NA	-0.04%	0.75%
	Half-day	-3.30%	NA	-0.02%	0.73%
	Peak-summer	-2.82%	NA	-0.02%	0.75%
35%	*All-day*	-4.17%	NA	-0.21%	1.04%
	Half-day	-3.63%	NA	-0.12%	0.99%
	Peak-summer	-2.92%	NA	-0.01%	1.00%

Source: Authors' analysis based on KPM results.

Figure 4 shows the potential financial gains from fuel cost savings across the system based on the regulated prices in Table 2. As the LS potential increases, the crude oil savings become more substantial. With moderate LS potential (25%), crude oil consumption in the *Half-day* and *All-day* variants is 3.3% and 3.6% less than in the baseline scenario, respectively. At this level of potential, natural gas consumption remains unchanged across the three simulated variants. HFO use increases by about 0.8% compared with the baseline scenario. Finally, a high LS potential of 35% achieves higher crude oil savings. In the *All-day* variant, crude oil use is 4.2% less than in the baseline scenario, and natural gas use is 0.2% less. These declines are compensated by a 1.0% increase in HFO use. With this scenario and variant, the overall savings are $17.6 million at regulated fuel prices. Note that the differences in fuel consumption are due to the characteristics of the power sector. These characteristics include the heat rates of power plants, transmission losses, must-run units and energy flow between regions.

Figure 4. Annual cost savings in LS scenarios (15%, 25% or 35%) relative to the baseline scenario based on regulated fuel prices.



Source: KPM simulations.

The savings are greater when the shifted loads are spread across longer periods. In other words, the *All-day* and *Half-day* variants achieve higher savings than the *Peak-summer* variant does. Surprisingly, targeting peak hours (1 p.m. to 5 p.m.), as in the latter variant, yields lower savings. The savings gap between the *Peak-summer* variant and the variants with shifts over longer periods (i.e., *All-day* and *Half-day*) widens as the LS potential increases. Indeed, the fuel cost savings range from $7.8 million to $9.4 million in the *Peak-summer* variant. By contrast, they range from $8.7 million to $17.6 million in the other variants, with fuel savings increasing as the LS potential grows.

Savings Due to LS Based on Opportunity Costs

Assessing savings in LS scenarios based on regulated fuel prices is only the first step in our analysis. Fuel can be used for other, more lucrative activities, such as petrochemicals or exports to international markets. Thus, using fuel in the power sector creates opportunity costs, and these costs should be considered in our analysis. To do so, we evaluate the fuel savings from LS by assigning alternative *values* to the saved fuel.

Table 5 shows the net savings from fuel reduction at various prices for the nine simulated cases. Note that the savings include the costs of (or savings from) HFO at regulated prices. We exclude HFO from our opportunity cost analysis and keep its value at the administered price of $0.6 per million British thermal units (MMBtu). This fuel must comply with a more stringent sulfur content regulation imposed by the International Maritime Organization (Li et al. 2020).[8]

Karanfil and Pierru (2021) estimate the opportunity cost of using fuel domestically in Saudi Arabia. According to their findings, this cost ranges from $14.9 per barrel to $59.4 per barrel in 2018, our reference year. These estimates consider several constraints that an oil-exporting country may face when freeing a certain quantity of oil. Examples include production quotas, the elasticity of the international demand for Saudi oil exports and the supply elasticity of non-Saudi production. Given these results and the prevailing domestic natural gas price of $1.25 per MMBtu, total financial savings from LS range from $24.2 million to $194.4 million. The former reflects a 15% LS potential and the *Peak-summer* variant, and the latter reflects a 35% LS potential and the *All-day* variant. These savings are three and eleven times greater, respectively, than the savings associated with crude oil at the regulated price.

The results in Table 5 show that in the 15% LS scenario, the savings decrease as the gas price increases. This result is because LS at this level increases natural gas use relative to the baseline scenario, as Table 4 shows. Thus, an increase in the natural gas price negatively impacts savings. Conversely, we find that the savings in the other scenarios (i.e., 25% and 35% LS potential) are increasing as the price of gas increases. This result is driven by the reduction in natural gas use relative to the baseline scenario. As the value of that fuel increases, the savings increase as well.

As a final illustration of the savings opportunity, we consider the international price of Arabian light crude oil as a reference for the opportunity cost. This price is currently $70.6 per barrel. Under this assumption, the financial gains at the regulated natural gas price are $129.3 million in the 15% LS potential scenario with the *Peak-summer* variant. They reach $231.4 million in the 35% LS potential scenario with the *All-day* variant (Table 5).

Virtually all of the financial savings stem from avoided crude oil (Table 4). Hence, an increase in the price of natural gas impacts the savings only marginally. For example, consider an increase in the gas price from $1.25 per MMBtu to $4 per MMBtu. In this case, in the 35% LS potential scenario with the *All-day* variant, the Kingdom's total savings will increase by $8 million. Specifically, they will increase from $231.4 million to $239.4 million, as Table 5 shows. Thus, in this example, including the additional cost of HFO, 98% of the savings are derived from crude oil ($234.6 million of $239.4 million).

Table 5. Net annual savings in millions of dollars including the crude oil and natural gas opportunity costs.

				All-day shifting				*Half-day shifting*				*Peak-summer shifting*			
				Natural gas price ($/MMBtu)				Natural gas price ($/MMBtu)				Natural gas price ($/MMBtu)			
				1.25	2.0	3.0	4.0	1.25	2.0	3.0	4.0	1.25	2.0	3.0	4.0
LS potential	15%	Crude oil price ($/ barrel)	6.4	9.1	7.8	6.2	4.5	8.7	7.6	6.2	4.7	7.9	7.3	6.5	5.7
			22.0	44.8	43.5	41.9	40.2	42.8	41.7	40.2	38.8	37.9	37.3	36.5	35.7
			43.8	94.8	93.5	91.9	90.2	90.5	89.4	87.9	86.5	79.9	79.4	78.6	77.8
			70.6	153.5	152.3	150.6	148.9	146.5	145.4	143.9	142.5	129.3	128.7	128.0	127.2
	25%	Crude oil price ($/ barrel)	6.4	13.8	14.3	14.9	15.5	12.0	12.2	12.4	12.7	9.5	9.7	9.9	10.2
			22.0	59.4	59.8	60.4	61.0	53.7	53.9	54.1	54.4	45.1	45.3	45.6	45.8
			43.8	123.2	123.6	124.2	124.8	112.1	112.3	112.6	112.8	95.0	95.2	95.5	95.8
			70.6	198.1	198.6	199.1	199.7	180.8	181.0	181.2	181.4	153.7	153.9	154.1	154.4
	35%	Crude oil price ($/ barrel)	6.4	17.7	19.9	22.8	25.7	13.6	14.9	16.5	18.2	8.0	8.1	8.2	8.3
			22.0	70.5	72.7	75.6	78.5	59.5	60.7	62.4	64.0	45.0	45.1	45.2	45.2
			43.8	144.5	146.7	149.6	152.5	123.8	125.0	126.7	128.3	96.8	96.9	96.9	97.0
			70.6	231.4	233.5	236.5	239.4	199.2	200.5	202.1	203.8	157.6	157.7	157.8	157.9

Source: Authors' estimates based on KPM results.

Our LS scenarios only marginally reduce overall natural gas consumption in the power sector. However, they enable the improved dispatch of allocated gas volumes to the power sector. The Kingdom relies on natural gas for almost half of its power generation. Using a Saudi energy system model, Matar and Shabaneh (2020) show that the Kingdom can overcome the seasonal variability of demand with investments in natural gas storage. This variability causes congestion in the natural gas pipeline infrastructure during the summer, partially to meet the peaking electricity load. They estimate that investments in storage facilities may cost about $11.5 billion. Strategically shifting the industrial load to off-peak periods may limit or defer investments in such infrastructure.

Shabaneh and Schenckery (2020) assess the financial viability of using liquefied natural gas (LNG) imports to displace crude oil in the power sector. Our simulations demonstrate that shifting load from the summer season displaces oil from power generation while keeping natural gas consumption roughly unchanged. Thus, LS can avoid the need to import LNG to fill the gap caused by reducing oil consumption in power generation.

Potential Enablers, Barriers and Future Developments

Important barriers to and enablers for achieving the estimated fuel and financial savings should be discussed. The enablers can make LS in the industrial sector applicable and attractive in the Saudi context. As stated previously, large Saudi electricity-intensive industries can apply LS to activities with a high potential for LS based on international experience. However, the potential for LS is not limited to these activities. More importantly, these activities are clustered across a few large industrial operators. For instance, although the Kingdom is a large cement producer, this sector comprises about 17 companies. Of these, five companies share about 50% of the market (Aljazira Capital 2021). Aluminum and petrochemical activities are dominated by the national companies Ma'aden and Saudi Basic Industries Corporation. This aggregated scheme of clustered activities increases the flexibility to adapt contractual aspects to specific industry load patterns and business requirements. Furthermore, the deployment of smart meters can act as a technological enabler for LS. Installing smart meters at the machine level is considered critical for LS operations to balance energy use in manufacturing companies (Pechmann et al. 2017).

The composition of the saved fuel basket is another important aspect of LS. Our LS scenarios show that the saved fuel is generally crude oil, and these savings are partially offset by an increase in HFO. In international markets, HFO traded at a discount of about $150 per tonne below the Brent crude price between 2017 and mid-2019. In late 2019, the enforcement date of an International Maritime Organization regulation regarding the sulfur content of HFO approached. At that time, the discount relative to crude oil reached $300 per tonne (Shabaneh, Al Sadoon, and Al Mestneer 2019). Thus, LS can reduce the domestic use of crude oil, which can be exported at a premium compared with HFO. At the same time, it only marginally increases HFO's share in the power mix.

Throughout this study, we assess LS from a national power system perspective. The financial gains arise from the savings as the total quantity of fuel in the power system is reduced. This approach is motivated by the fact that electricity prices are the same throughout the year. Thus, several factors may create barriers to the implementation of LS in the industrial sector. Olsthoorn, Schleich, and Klobasa (2015) analyze a survey of German manufacturing sites. They find that the risk of operations disruptions, the impact on product quality and uncertainty about cost savings are the greatest barriers to considering LS. However, access to capital, a lack of trained workers and data security are less important barriers to LS implementation in industrial sites. Moreover, processing constraints may be important, as industrial processes have various load features and costs. Cross-seasonal capabilities may not be applicable owing to the lack of economic incentives or technical constraints (Yang, DeFrain, and Faruqui 2020).

Finally, our results may be affected by changes in the Saudi power mix in the future. The Kingdom has set a target of 50% of power from renewable sources and 50% from natural gas by 2030.[9] Thus, the outcomes of our simulations may change as the share of renewable resources in the Kingdom's power mix increases.

5. Conclusions

This study conducted simulations using a national power dispatch optimization model. We showed that partially displacing the industrial load from the peak season (i.e., summer) to the rest of the year results in fuel savings. These savings are achieved without reducing overall electricity consumption. More specifically, we found that increasing the natural gas price improves total fuel savings only when the total industrial LS is above 15%. Moreover, the savings are sensitive to the LS potential and the time of the day at which the shift takes place. Overall, the projected gains at the national level range from $7.9 million to $17.7 million per year at regulated fuel prices. These savings are relatively small for several reasons, such as the regional distribution of industrial demand, the power mix and low prevailing administered fuel prices. However, when considering the opportunity cost of saved fuel from LS, the savings range from $127.2 million to $239.4 million per year. These savings comprise between 4.2% and 8.1% of the power system's annual fuel cost.

Our study underscores the potential benefits of LS in the industrial sector. Nevertheless, several factors may impede the active implementation of a national LS plan. Future research efforts should focus on investigating factors that may accelerate the introduction of this synergistic strategy involving industrial consumers, electricity producers and fuel suppliers. We make the following recommendations.

> Conduct pilot experiments at the industrial plant level to identify the technical flexibility potential of LS.

> Consider various payment structures to incentivize scheduling demand to reflect the variability in the cost of supplying electricity.

> Improve the understanding of the opportunity cost of saved fuel to optimize its value across domestic uses and exports to international markets.

Endnotes

1 These activities include base metal products, chemical materials and products, rubber and plastic products, other nonmetal products and reformed metals (excluding machines and equipment) (SAMA 2019).

2 This value is based on production of 967 thousand tonnes of aluminum and 4 million tonnes of ammonia (a major manufactured chemical product in Saudi Arabia). Cement and steel production are 44 million tonnes and 8.2 million tonnes, respectively (Arab Iron and Steel Union 2019; Saudi Arabian Mining Company 2019; SAMA 2019; World Steel Association 2020). All production amounts reflect 2018 data. We assume electricity intensities of 15,100 kWh/tonne, 160 kWh/tonne, 110 kWh/tonne and 585 kWh/tonne for aluminum, ammonia, cement and steel, respectively (Worrell et al. 2000; Albelwi, Kwan, and Rezgui 2017; CEPS and Ecofys 2018; IEA 2021). We do not account for captive power generation.

3 The study reports the savings in South African rand (ZAR). We use an exchange rate of 1 United States dollar = 14.6 ZAR.

4 The software is available at: https://energyexemplar.com/solutions/plexos/

5 As of April 2021, the Kingdom has installed about 10 million smart meters across all customer types (https://www.smart-energy.com/industry-sectors/energy-grid-management/saudi-arabias-ami-project-progresses-with-10-million-smart-meter-rollout/).

6 The SEC's consumption optimization recommendations are summarized at: https://www.se.com.sa/en-us/Pages/IndustrialSector.aspx

7 The power model has six operating areas. The regulator, however, reports data for four operating areas of the Kingdom. To calculate the load shares, we add the northeastern operating area's load to the eastern operating area's load. We add the northwestern operating area's load to the western operating area's load.

8 For instance, the Kingdom's HFO exports dropped 51% from 2019 to 2020.

9 Elshurafa et al. (2021) assess pathways to reach this target.

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Appendix

This appendix provides a detailed mathematical representation of the load shifting procedure presented in Section 3.2. We start with the total monthly industrial electricity consumption (IL) data provided by the Saudi Electricity Company. The loads are classified into two segments. The first is the load to be reduced, that is, the load during summer months (LS_i). The second is the load to be increased, that is, the load in the rest of the year (LS_j). We determine these loads by applying the load shifting potential (SP).

$$\begin{cases} LS_i = IL_i \times (1 - SP) \\ LS_j = IL_j \times (1 + SP) \end{cases}, \text{with } SP = 15\%, 25\%, 35\%,$$

where i= *May, June, July, August, September*

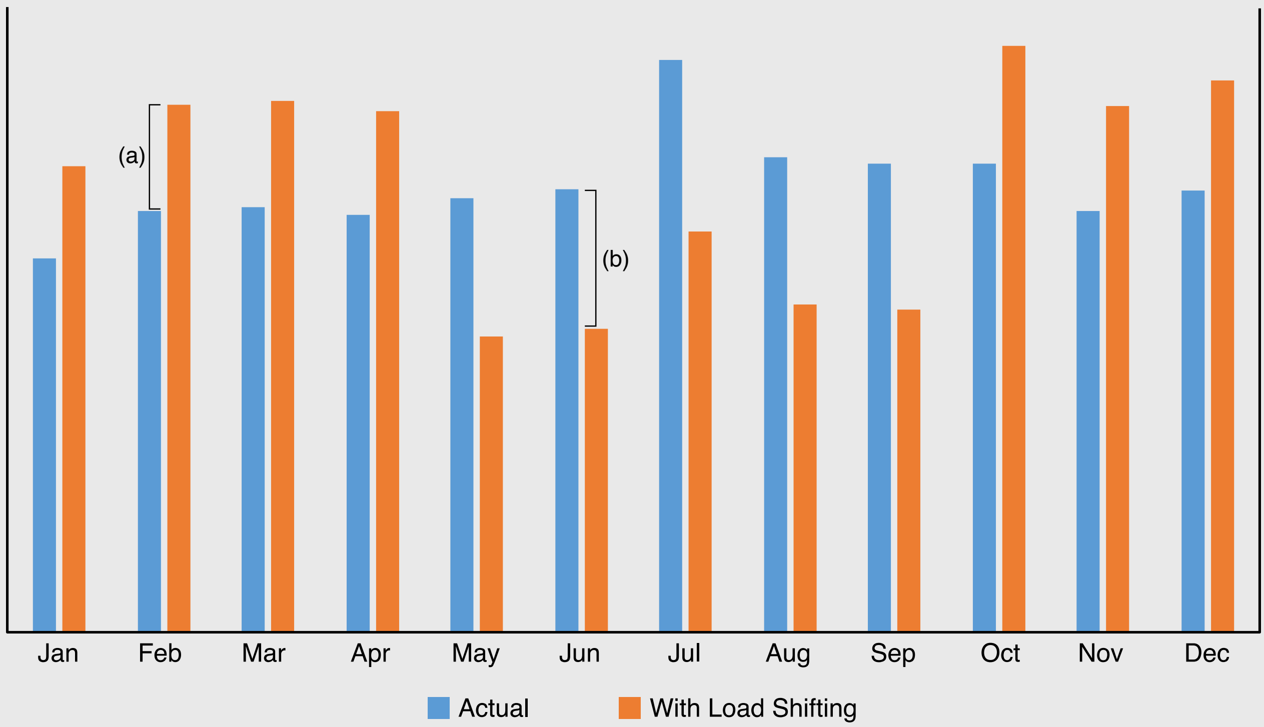
and j=*January, February, March, April, October, November, December.*

The shifted load (SL) is the difference between the initial industrial load and the load after applying the shift potential. Thus, the shifted load is negative in summer months (i.e., $SL_i<0$) because we subtract the load to be shifted. It is positive in winter months (i.e., $SL_j>0$) because we add the shifted load to the load in these months.

$$SL_i = LS_i - IL_i$$
$$SL_j = LS_j - IL_j$$

Figure A illustrates the monthly loads before and after the load shifting using this procedure. The load shifts for the months in sets i and j are bordered in red and in green, respectively. SL_i and SL_j are illustrated in Figure A by the gaps between the actual and shifted loads for February (a) and June (b), respectively.

Figure A. Industrial monthly observed loads and loads with shifting, at a 25% shift potential.



Source: Saudi Electricity Company.

Note: The load levels are hidden to avoid revealing commercial data.

Once we derive the total shifted load for each month, we compute the corresponding loads to be shifted by period. In other words, we compute the hours for which the load is to be increased (P_i) or decreased (P_j) in each month. The number of hours (n) with load shifting depends on the targeted hours in each of the three variants (i.e., *All-day*, *Half-day* and *Peak-summer*). For instance, May 2018 included 23 working days (recall that working days in the Kingdom are Sunday to Thursday). Thus, n equals 552 in *All-day*, 276 in *Half-day* and 115 in *Peak-summer*.

$$SL_i' = \frac{SL_i}{\sum_{h=1}^{n} P_{n,i}}$$

$$SL_j' = \frac{SL_j}{\sum_{h=1}^{n} P_{n,j}}$$

The hourly variations, SL_i' and SL_j', are then weighted by the regional industrial load shares presented in Table 2. Finally, the total regional load profile (TL), which is an input in the KAPSARC power model, is incremented by the net shifted industrial loads by region.

$$TL'_{i,r} = TL_{i,r} + SL'_{i,r}$$

$$TL'_{j,r} = TL_{j,r} + SL'_{i,r}$$

TL' is the updated total regional load after load shifting, and r refers to the region, where r = COA,EOA,SOA,WOA,NWOA,NEOA.

Notes

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About the Authors

Salaheddine Soummane

Salaheddine is a Research Associate at KAPSARC, where he is leading research on the Saudi electricity market. His main research topics cover power sector modeling, demand-side management, and regulatory frameworks. Prior to joining KAPSARC, Salaheddine worked as a research associate for CIRED (a CNRS lab) in Paris on macroeconomic modeling. He also worked as researcher for EDF R&D (Paris), within the Energy Markets and Environmental Regulation department. Salaheddine holds a Ph.D. in Economics from Paris-Saclay University in France.

Amro Elshurafa

Amro is a Research Fellow at KAPSARC with nearly 20 years of experience in the fields of energy and technology in three continents. His research interests lie in renewable energy policy, power systems modeling, and hybrid microgrid design and optimization. He has led and executed several national modeling initiatives both on distributed- and utility-scale projects. Credited with 40+ papers and several patents, Amro holds a Ph.D. in electrical engineering and an MBA in finance.

Hatem Alatwi

Hatem is a senior research analyst at KAPSARC. He holds a master's degree in power system economics with a focus on electricity markets from the KTH Royal Institute of Technology, Sweden. He also holds a bachelor's degree in electrical engineering from the University of Idaho. Before joining KAPSARC, Hatem worked within various industries. He interned at ABB Västerås in Sweden, where he worked on electric vehicle asset management under the Swedish transport administration's electric road systems project. Hatem also worked at Schweitzer Engineering Laboratories in Washington state, where he modeled speed governors and prime movers for hydro and gas turbines.

Frank Felder

Frank is an engineer, energy policy analyst, and Program Director for the Energy Transitions and Electric Power program at KAPSARC. Prior to joining KAPSARC, Frank was a Research Professor at the School of Planning and Public Policy at Rutgers University and Director of the Rutgers Energy Institute. He has conducted original and applied research in the areas of electric power system modeling, clean energy policies, and climate change for government agencies, energy companies and research institutions. He has also worked as an economic consultant and nuclear engineer. He earned his doctorate from the Massachusetts Institute of Technology.

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