مركز الملك عبدالله للدراسات والبحوث البترولية
King Abdullah Petroleum Studies and Research Center

Discussion Paper

Alternative Fuels and Processes for Saudi Construction Materials Companies

Walid Matar, Sid Ahmed Hamdani, and Faris Aljamed

February 2025 | Doi: 10.30573/KS--2025-DP05

About KAPSARC

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

This publication is also available in Arabic.

Legal Notice

Summary

Producing construction materials requires a great amount of energy, and in Saudi Arabia, this production currently entails the use of substantial amounts of liquid fuels. Liquid fuels are mostly sold at below-market prices domestically, and thus result in large opportunity costs for the government. Saudi Arabia's interests reside in displacing higher-value liquid fuels with more appropriate alternatives. The Saudi government plans to encourage the displacement of oil by reforming the below-market oil prices. Alternatives could include other fuels and more energy-efficient manufacturing processes. This paper investigates, the cost implications of switching existing fuels or processes for individual firms and the government.

We focus on firms that produce ceramic tiles, float glass, and red bricks. Two policy instruments are considered: the speed of energy price adjustments and whether the government covers half of a firms' capital expenses when purchasing alternate manufacturing units. Switching to natural gas and keeping the existing process is generally found to be the least costly option for both stakeholders. However, the capital subsidy can make alternative manufacturing units attractive, especially when natural gas is used. This is the case for the examined float glass firm, where oxyfuel regenerative furnaces become the preferred option. Similarly, vertical shaft brick kilns would be the cost-minimizing option for a red bricks firm when the subsidy is applied. The main finding is that switching from oil products to natural gas would be the most economical option.

1. Introduction

According to the Saudi Industrial Center, the domestic market for construction materials was valued at 22.1 billion Saudi Arabian riyals (SAR) in 2021 (IC 2024). These materials consist of cement or cement derivatives, ceramics, glass, bricks, and lime. The Saudi General Authority for Statistics (GASTAT 2024a) shows that production in this industry rose by 29% in August 2024 compared to 2021. This growth is expected to continue, as the construction materials industry is projected to contribute 53 billion SAR to the national gross domestic product by 2035 (IC 2024). The fuel use data available to us show that local firms producing construction materials use substantial amounts of liquid fuels that are sold at below-market prices. In aggregate, GASTATs (2024b) input-output table of the Saudi economy in 2021 indicates that 7.67 billion SAR worth of refined oil products were used by this industry.

Local fuel sales by Saudi Aramco at below-market domestic prices impose a cost for the Saudi government. The government compensates Aramco for any forgone revenues that result from the sales. The forgone revenues are essentially calculated using the gaps between market and domestic prices multiplied by quantities of consumption.[1] Saudi Aramco (2024) disclosed that the compensation totaled 203.1 billion SAR in 2023. Although domestic fuel prices were raised in 2024, the gap between domestic and market prices is still sizeable. Domestic prices of major industrial fuels in 2023 and 2024 are shown in Table 1.

Table 1. Select fuel prices in Saudi Arabia in 2023 and 2024 (in U.S. dollars)

	2023	2024
Arabian Light crude oil	$6.35/barrel	$14.90/barrel
Fuel oil (380 centiStokes)	$3.80/barrel	$8.30/barrel
Diesel	$23.81/barrel	$36.51/barrel
Natural gas	$1.25/mmBtu	$1.75/mmBtu

Source: Aljazira Capital (2024); Riyad Capital (2024).Source: Aljazira Capital (2024); Riyad Capital (2024).

As part of its Fiscal Balance Program (2019), the Saudi government intends to improve the allocation efficiency of fuels by setting them at reference prices (Kingdom of Saudi Arabia 2019). Reference prices either mean international market prices in the case of liquid fuels or some price that is linked to domestic production costs in the case of gaseous fuels. Furthermore, the Saudi government has the ambition to displace liquid fuels from the domestic energy mix. The liquid fuel displacement program aims to displace around 1 million barrels a day that could have more valuable uses and reduce greenhouse gas (GHG) emissions in Saudi Arabia (United Nations Framework Convention on Climate Change 2024).

In this context, it is important to assess the possibilities of fuel switching in the construction material industry and the associated costs of adopting alternative options on both the industrial facilities and the government. The cost for the government is of interest, especially when considering the pace of implementing domestic energy price reforms and the option to grant capital subsidies to support companies in changing their processes and switching to alternative fuels.

We develop and apply a techno-economic tool that covers ceramic tiles, red bricks, and float glass. Using the tool, this study investigates the incremental costs associated with switching fuels and manufacturing units in the three sectors. Both private and public costs are considered in our analysis. Private costs consist of any investment and operational costs incurred by the firms. Public costs primarily consider the forgone revenues for which the Saudi government must compensate Saudi Aramco. The effects of government support for any investment required by the firms are also analyzed.

Several studies have been carried out on the future of fuel use in the Saudi petrochemical, fertilizer, steel, and cement industries. Alshammari (2021) estimates energy use to generate heat for SABIC, a Saudi chemicals company: he considers that SABIC mainly uses natural gas, and his assumptions yield a linear rise in projected natural gas use by the company. Looking into the prospects of fuel substitution, Matar et al. (2015), Matar and Anwer (2017), Matar and Elshurafa (2017), Matar and Filali (2022), and Matar, Mansouri, and Umeozor (2024) show that if domestic fuel prices are raised to their market-equivalent values, liquid fuels used by Saudi electricity and water utilities as well as large industry will be replaced by natural gas and renewable technologies. However, they do not incorporate smaller industrial sectors like those of the construction materials industry, and they also do not consider individual firms in their analyses as they use an energy systems model for the broader economy. Less attention in the literature has been paid to local, smaller, fragmented industrial energy consumers in Saudi Arabia, and so our study will look at smaller firms in the construction materials industry.

In the following sections, the literature on the construction materials sectors and how it has shaped our tool's development are reviewed. Then, the methods and data used in the assessment are described, and the examined policy scenarios and the tool's output are discussed.

2. Fuel Use and Manufacturing Processes in the Construction Materials Industry

The energy performance of the construction material industry has attracted attention in the literature, notably because of its role in GHG emissions in the life cycle of many products and in final energy use, as well as the significant potential for its improvement. According to the International Energy Agency (IEA 2023), the energy used in the construction material industry is responsible for about 7% of the total final energy demand in 2022.

Feeding into our study, energy efficiency in the construction materials industry has been pervasively supported by government-led energy efficiency programs. The United States's "Energy Star" program supported the development of energy guidelines for plant managers for cement, glass, and concrete products (Kermeli et al. 2011; Worrell et al. 2008; Worrell, Kermeli, and Galitsky 2013). Likewise, the European Commission released *Reference Documents for the Best Available Techniques (BAT) to Save Energy in Cement, Lime, Ceramics and Glass* (Schorcht et al. 2013; European Commission 2007; Scalet et al. 2013; Lecomte et al. 2017). Shen, Price, and Lu (2012) highlighted that mandatory energy audits imposed by the Chinese government have not only supported companies in identifying opportunities to save energy but have also enhanced management practices, including through improved analysis of energy use data.

Companies in the construction materials sector utilize processing units similar to those in any other industry. Energy intensive units encompass steam or thermal boilers, furnaces, and kilns. If existing units are not changed and only fuel substitution is considered, a simple fuel burner change may be required within the existing units. The Department for Business, Energy & Industrial Strategy (2022) estimates that burner costs are 30% of a complete boiler set up. For a 25-MWth boiler, for example, the price comes out under $175,000. We incorporate this burner cost-to-boiler relationship for all firing units. We also take into account electric boilers as an option to replace fuel-operated variants, as although they require more capital, they are more energy efficient than their fuel-based counterparts (Zuberi, Hasanbeigi, and Morrow 2021). As two sectors that require the use of steam boilers, we integrate the boiler costs in the cement board and concrete blocks industries based on the estimate of the Department for Business, Energy & Industrial Strategy (2022) and Zuberi, Hasanbeigi, and Morrow (2021). Further, the energy used for the steam-curing of concrete blocks is parameterized using the Concrete Block Association (2013).

Ceramics manufacturing is primarily classified into two main categories: tiles and sanitary ware. Ceramic tiles are less energy intensive compared with sanitary ware. Ceramics use kilns as the foundational process that may be electrified. Electric kilns exhibit lower energy use compared to fuel-operated tunnel kilns (European Commission 2007). Waste heat recovery also has large potential in the manufacturing of ceramics. Monteiro, Cruz, and Moura (2022) illustrate heat recovery strategies where the exhaust gases from the kiln are recirculated back to the kiln using an intermediate heat exchange. Those strategies lower fuel use by up to a third. Oliviera, Iten, and Matos (2021) also highlight the significant potential of waste heat recovery in improving efficiency in the ceramic industry; however, they caution against its use due to the corrosive nature of certain exhaust components.

Furthermore, glassmaking is diverse but can be categorized in container and flat varieties. Within flat glass, float glass is manufactured on a line where molten glass is floated over a bed of molten tin. Energy use and manufacturing line lifetimes differ between the two categories. Even within the same category and the same units, energy use can vary based on whether the glass is laminated or processed further downstream (Institute for Prospective Technological Studies 2013). Worrell et al. (2008) detail the furnaces and cooling units used to manufacture glass. Regenerative furnaces are the predominant technology used in the process. Oxy-fuel furnaces are less energy intensive and have a similar capital cost to regenerative furnaces. They burn fuel with oxygen gas rather than air. Thus, their operational costs are higher as the oxygen gas is purchased from a third-party supplier or sourced from an on-site air separator. The oxygen gas supply options typically depend on the amounts of oxygen needed by the factory (Zier et al. 2021). There are also electric boosters for fuel-based furnaces. Those boosters may be equipped to lower fuel use for glassmaking. We will examine the costs of electricity compared to other fuels in Saudi Arabia.

Zier et al. (2021) review options for decarbonizing glass manufacturing. They claim that future glass manufacturing will rely on oxy-fuel furnaces and use hydrogen gas and electricity as energy carriers. Griffin, Hammond, and McKenna (2021) discuss fuel switching as one of the broad interventions for decarbonizing the glass sector in the United Kingdom. Glass Futures, an initiative funded by the UK Research and Innovation Energy Programme, is supposed to have completed a research facility by now to investigate switching from coal to mainly biofuels and further electrification but also, potentially, hydrogen gas.

Although heat recovery is already built into glass furnaces (Sissa et al. 2013), Zier et al. (2021) state that waste heat recovery has potential in this industry but can be technically challenging. It has rarely been applied due to operational issues, such as equipment fouling or the distance between the heat recovery equipment and the furnace in the glassmaking facility. Zier et al. (2021) caution that full electrification or using state-of-the-air fuels like hydrogen gas to make glass is not generally cost-competitive.

Moving on to bricks, there are broadly two types: (1) cured bricks that do not require firing, and (2) burnt bricks. We assess both types in the form of cured concrete blocks and red bricks. Concrete blocks are made by mixing cement, aggregates, and water, and then blowing the mixture into molds, with the molded blocks then cured using steam in a kiln (Shakir and Mohammad 2013). We include fuel- or electricity-based steam-curing kilns for concrete block companies. There is also potential here for advanced technologies, like those for CO_2-cured concrete blocks. Shi et al. (2012) state that energy use for CO_2 curing is about one fifth of the energy used for steam curing. However, we will only explore mature technologies.

When it comes to red bricks, several kiln technologies are used to manufacture them. Kilns, or any other firing equipment, may be classified as intermittent or continuous. Continuous kilns offer constant and simultaneous firing and cooling. Their exhaust gases are used for drying purposes. Continuous kilns offer improved flame control and higher energy efficiency over intermittent kilns, and they thus dominate the class of technologies used in the red bricks sector (Heierli and Maithel 2008). Heierli and Maithel (2008) additionally show that within the continuous class of kilns, vertical shaft brick kilns (VSBK) exhibit the least amount of energy per unit mass of fired bricks. This is followed closely by modern tunnel kilns and fixed chimney bull's trench kilns. In our analysis, we incorporate these three kiln technologies for red bricks manufacturing.

In terms of other literature, Felea et al. (2021) perform an energy audit on a brick manufacturing unit that uses a tunnel kiln process, and they found that optimizing the load (the volume of bricks produced per day) can substantially improve energy performance. The relationship between the energy consumed and the load is modeled as a concave function. The Shakti Sustainable Energy Foundation (2012), meanwhile, also brings up zigzag kilns, which are named because of a meandering firing path. Abbas et al. (2021) assess the long-term impact of switching processes in the brickmaking industry in India, which is dominated by the energy-intensive fixed chimney bull's trench kiln, finding that switching to a VSBK or zig-zag kiln can reduce fuel demand, and they recommend adopting zig-zag kilns because of their similarity in design and operations. We did not include zig-zag kilns in our tool as the Saudi industry does not use bull's trench technology.

Previous quantitative studies for Saudi Arabia have been conducted in the context of examining alternative fuels and processes for the local cement sector (Matar and Elshurafa 2017; Matar and Filali 2022), and these studies, which raise projected energy prices, favor natural gas use and either upgrading or rebuilding all of the cement manufacturing lines with preheating and pre-calcination. Cement manufacturing takes the costs and unit characteristics from these studies. An industry expert was interviewed during the development of the tool and corroborated their estimates.

The process of making lime is like that of cement. The European Lime Association (EuLA 2014) summarizes the energy use of various kiln technologies to produce quicklime, an intermediate product used to make lime. In addition to conventional rotary kilns, a key technology that we add in the tool for the lime kiln is the parallel flow regenerative kiln. Finally, we rely on Venta, Glaser & Associates (1997) to parameterize the calcination kettles for making plasterboard.

3. Methods and Data

We devise a tool to evaluate individual firms in multiple construction materials sectors. The tool adopts a techno-economic approach, which in general integrates various technical and economic analyses, including process design, equipment sizing, capital and operational cost estimates, and cash-flow analysis to determine the economic performance and cost-effectiveness of technologies and processes (Chai et al. 2022). This study focuses on the cost assessment part of the techno-economic analysis by estimating the incremental costs of various processes using alternative fuels compared to a company's current operations. These incremental costs represent the cost of switching to alternative fuels.

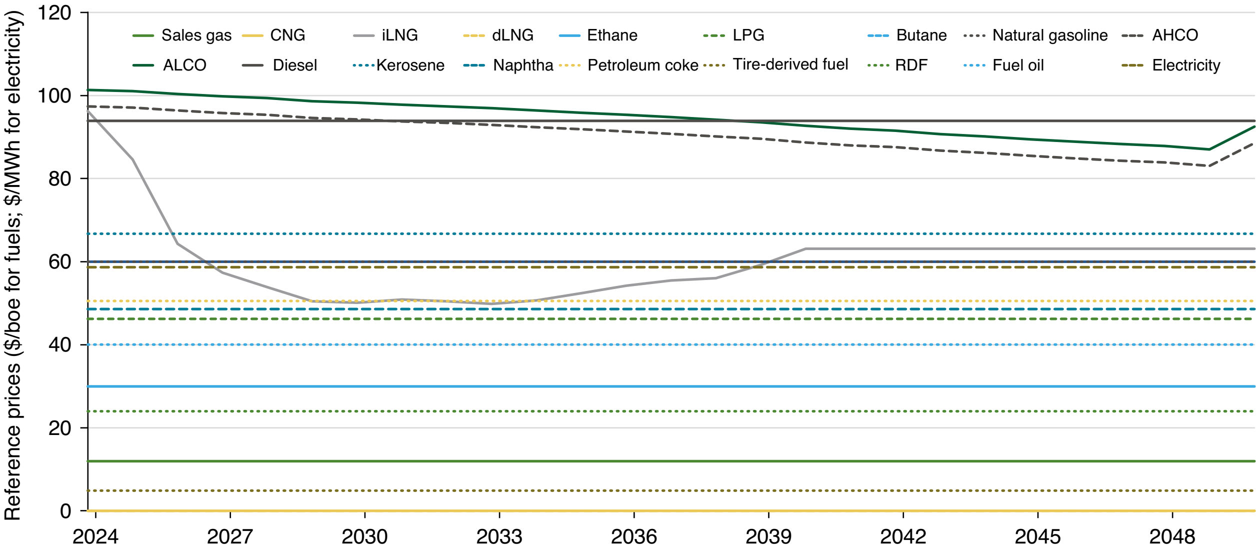
Companies within these sectors are characterized by manufacturing processes, for which we focus on energy intensive production units. In the tool, we assess numerous alternative fuel and/or process options for any one company, and then rank them from private and public perspectives. For each option, the assessment considers any capital costs, non-fuel variable and fixed operational costs, and fuel costs for private and public stakeholders. The ranking is performed by comparing the costs of the alternative options to the costs of existing operations using the 2024 domestic fuel prices. The tool may be used to indirectly find the least-cost option(s) based on those perspectives. It allows the user to view all options' costs rather than that of the optimal solution only. The approach is further detailed in the Appendix.

The sectors covered in our analysis are ceramic tiles, red bricks, and float glass. Fuel options generally span the following:

- dry natural gas, or sales gas
- compressed natural gas (CNG)
- imported liquefied natural gas (iLNG)
- domestically sourced LNG (dLNG)
- liquefied petroleum gases (LPG)
- butane
- natural gasoline
- Arabian Heavy crude oil (AHCO)
- Arabian Light crude oil (ALCO)
- diesel
- kerosene
- nnaphtha
- petroleum coke
- tire-derived fuel (TDF)
- refuse-derived fuel (RDF)
- fuel oil

In the tool, LNG may be imported through Yanbu (western Saudi Arabia) or Ras Tanura (in eastern Saudi Arabia). It may also be domestically sourced by liquefying domestic natural gas supply. Estimated reference prices of the fuels are shown in Figure 1. The domestic prices of LNG imports or LPG are always estimated to equal reference prices. The 2024 domestic prices for other fuels are partially shown in Table 1. We consider the costs of regassification at the port and delivering the fuel as dry gas to the company.

Figure 1. Reference prices of fuels used in our assessment from 2024 until 2050.



Source: Authors.

Aside from the general description in the Appendix, several manufacturing processes in each sector are considered. For those sectors, we evaluate and summarize the list of manufacturing units in our tool and their corresponding specific energy use measures that we incorporate in the tool in Table 2. We define energy use in barrels of oil equivalent (boe).

Table 2. Manufacturing processes by sector in the tool.

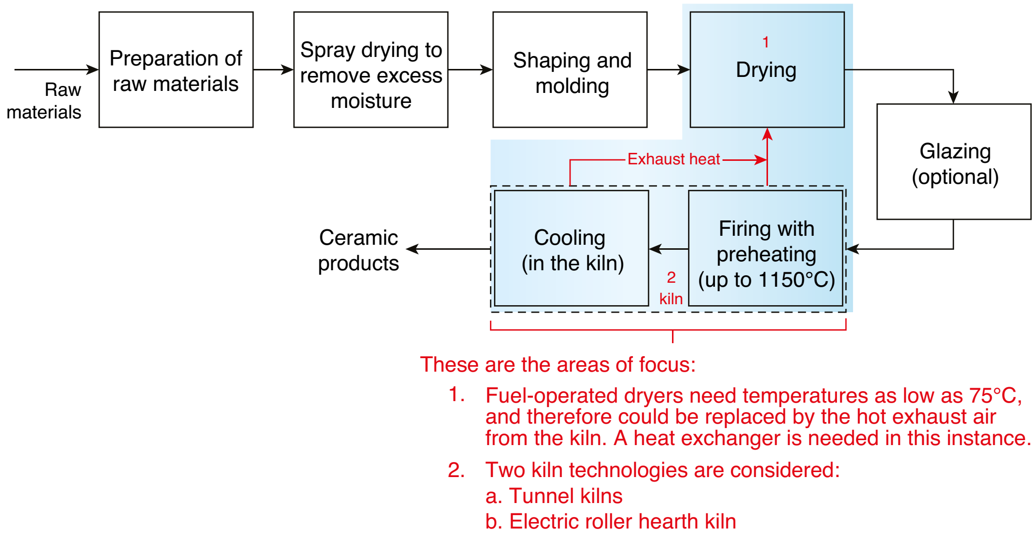
Sector	Process or unit	Specific energy use (boe/metric ton)
Ceramic tiles	Tunnel kiln for ceramics	0.665
	Electric roller hearth kiln	0.461
	Fuel-operated dryer	0.109
Float glass	Regenerative furnace	1.169
	Recuperative furnace	1.308
	Electric booster for a regenerative furnace	Reduces fuel use by 17%, and raises electricity use by 0.08 boe/metric ton
	Oxy-fuel furnace	0.785
	Fuel-operated lehr	0.067
	Electric lehr	0.072
Red bricks	Fixed chimney bull's trench kiln	0.222
	Vertical shaft brick kiln	0.136
	Tunnel kiln for red bricks	0.256

Source: European Commission (2007); Heierli and Maithel (2008); Worrell et al. (2008); Mezquita et al. (2014); Fadel et al. (2023).

3.1 Ceramic Tiles

The ceramic tiles manufacturing process represented in the tool is illustrated in Figure 2. We focus on two energy intensive units: the kiln and the dryers. For the kiln, we consider tunnel kilns and electrified kilns. For drying, we only consider fuel-operated dryers and waste heat recovery as process options. Recovering waste heat imposes no energy use but requires additional investment to transfer the heat produced by the kiln. Some of that heat would be lost in the heat exchanger (Fakheri 2007; Monteiro, Cruz, and Moura 2022). All units are characterized by their capital costs, non-fuel, and non-raw material operational costs – such as labor and maintenance costs, and the energy intensities presented in Table 2. The units' capital costs are annualized over a design lifetime of 25 years.

Figure 2. Ceramics manufacturing process.

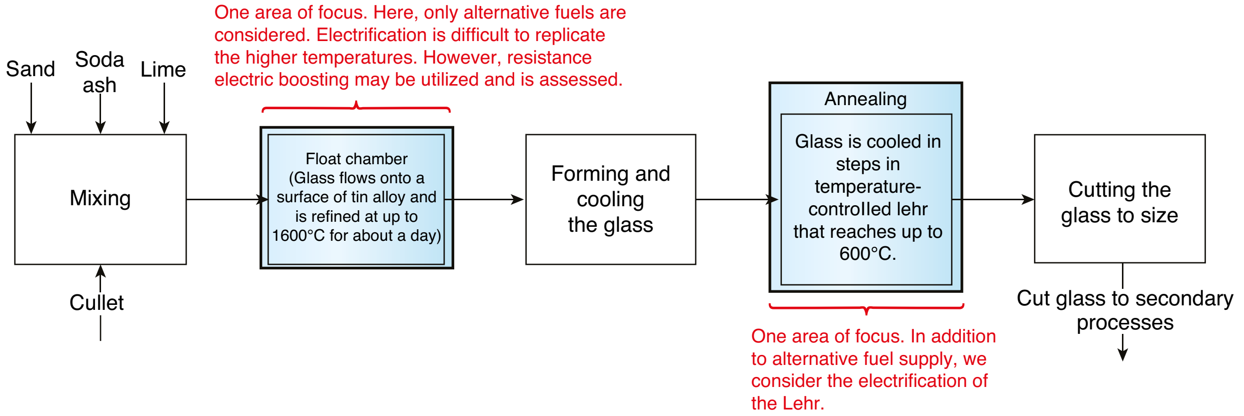


Source: Authors.

3.2 Float Glass

Our tool covers container and float glass products. We thus opted to analyze a float glass company, and the overall process flow for float glass is depicted in Figure 3. After several raw materials are mixed, the prepared batch is fed into a chamber in which it floats on a liquid tin surface. Although pure electrification is currently difficult at large production scales (Furszyfer Del Rio et al. 2022), the float chamber may be equipped with electric boosters. Electric boosting can shave off around 20% of energy used by the float glass plant, and even more for container glass plants. The other focus of a float glass plant is annealing. The annealing unit, called the lehr, cools down the intermediate glass product in a controlled manner.

Figure 3. Float glass manufacturing process.



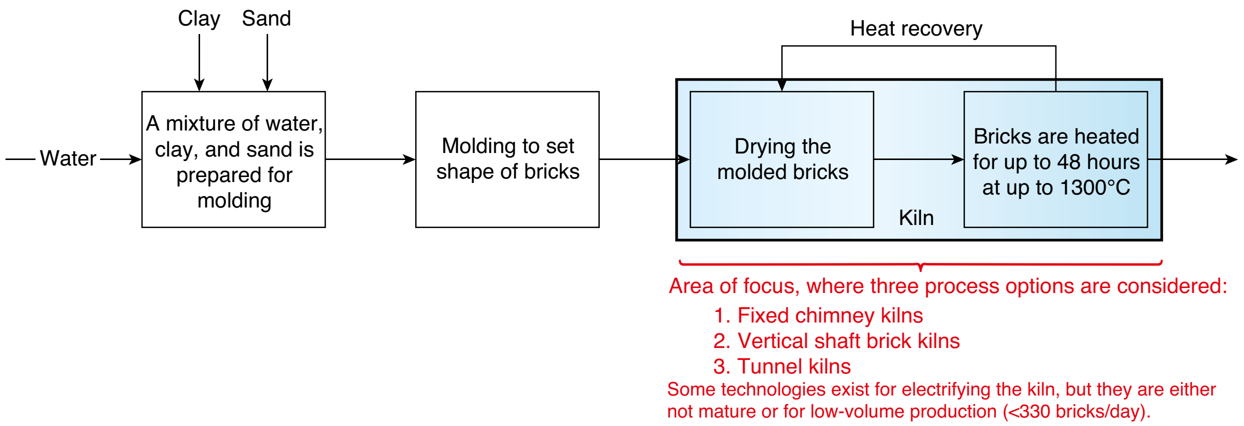
Source: Authors.

After discussions with an industry expert, it transpires that float glass plants have a shorter lifetime than other sectors of about 18 years, and it was also determined that production units are predominantly retrofitted only for fuel burners. Otherwise, production units and lines are almost always rebuilt. Worrell et al. (2008) also stress temperature stability to minimize manufacturing defects and increase yields. We deem that tire derived fuels (TDF) and refuse derived fuels (RDF) are not suitable for this sector, as they offer a less controllable flame.

3.3 Red Bricks

Red bricks are produced using the simplified schematic illustrated in Figure 4. Whereas previous sectors consist of multiple units for which we consider alternatives, we only focus on the kiln for red bricks. Three options are considered for the kiln: a fixed chimney bull's trench kiln, a VSBK, and a tunnel kiln. As shown in Table 2, the VSBK is the most energy efficient of the three options. It is unclear in the literature if red bricks kilns have electrified variants. For example, Heierli and Maithel (2008), Shmidt (2013), Martínez-González and Jiménez-Islas (2014), Rahman and Kazi (2019), and Yüksek, Öztaş, and Tahtalı (2020) all make no mention of electric kilns for brickmaking. Yet, small electric tunnel kilns are available, as seen on listings by Alibaba (2024). We want to evaluate firms whose operation qualifies as large-scale (i.e., 1,000 kg per day or more). Therefore, we do not consider electrification of the kiln.

Figure 4. Manufacturing process for red bricks.



Source: Authors.

A unique factor that differentiates red bricks from ceramic tiles or float glass in our analysis is that TDF and RDF may be used. Aside from the discussion on glass in the last section, we do not prefer using these two fuels in the process of making ceramic tiles due to lower temperature requirements in the kiln. For red bricks, we allow 30% of TDF and RDF to be part of the fuel mix due to environmental limitation (Usón et al. 2013). Taken from Worrell, Kermeli, and Galitsky (2013), the cost of installing a system that feeds tires to the kiln is set at $1 per metric ton of bricks.

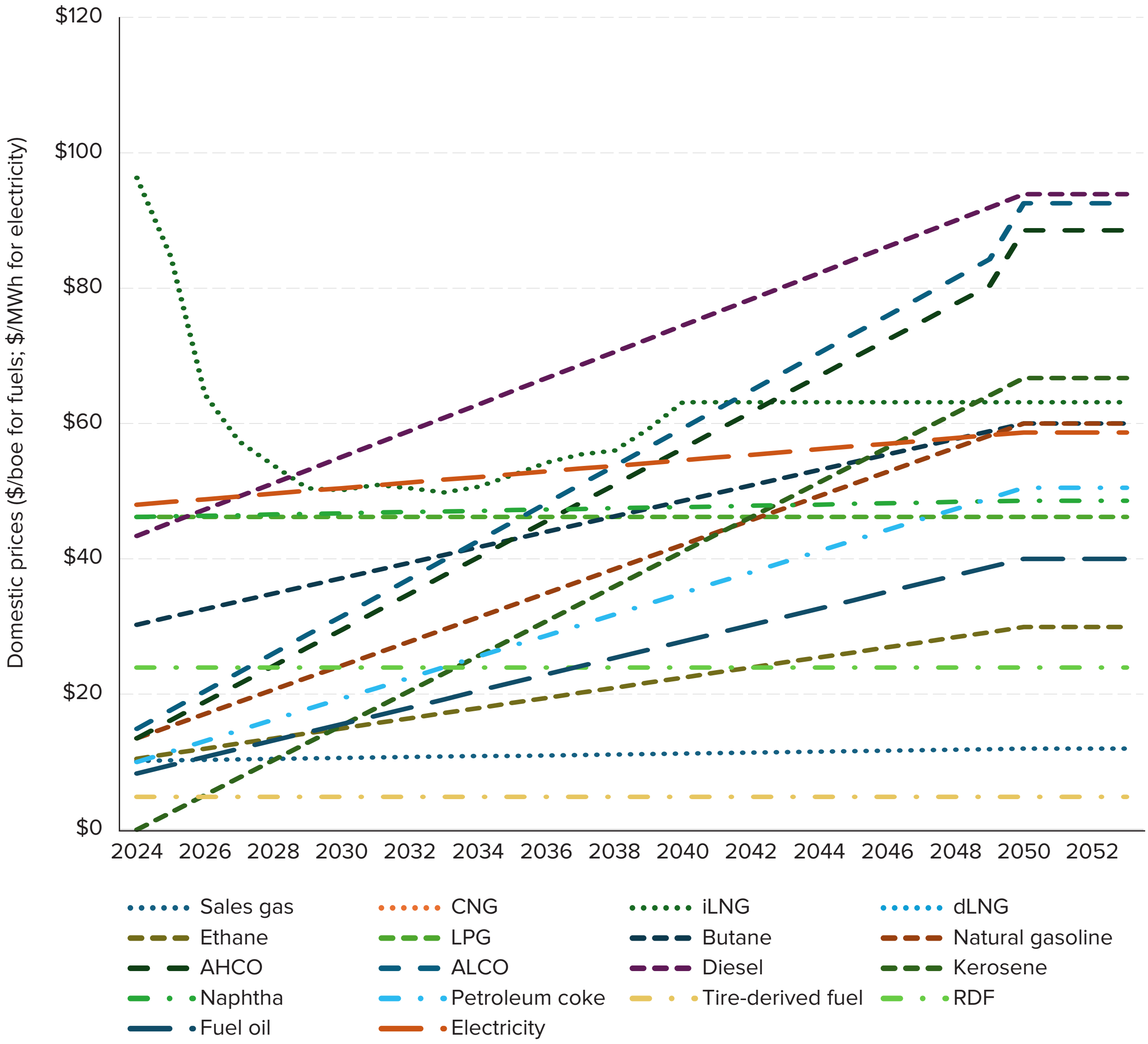
4. Policy Scenarios

The two policy levers of interest deal with energy pricing and government subsidy for private firms for their capital expenses. Historically, energy prices in Saudi Arabia have been well below international market prices. As referenced in Table 1, they were most recently adjusted in January 2024 (Aljazira Capital 2024). Two pathways for energy prices are considered. The Relaxed pathway specifies that domestic energy prices reach the reference prices shown in Figure 1 by 2050 in a linear fashion, and this is shown in Figure 5. The Accelerated pathway brings forward the year for reaching reference prices to 2030. Imported LNG prices are the same in both price reform cases, and these prices are taken from the reference scenario of Nexant's World Gas Model.

Moreover, investments in new production units may be financially untenable for small local companies that might not have the means to purchase new equipment. In this case, the government may choose to provide subsidies for capital expenditures. The capital subsidies entail shifting a portion of the firm's investment cost to the government. In our analysis, these subsidies are only applied to new production units that are listed in Table 2. Switching fuel burners is relatively less costly, and may thus be shouldered by the private firms. The associated fixed operational costs of the equipment are not supported.

Subsidizing capital equipment is not without its challenges. It would raise the costs for the Saudi government, which is already anticipating rising fiscal deficits in the coming few years (Ministry of Finance 2024). However, a capital subsidy that results in benefits that exceed the cost of implementation may be worthwhile. The benefits would come in the form of fuel savings. In other words, there would be lower fuel subsidies in the form of lower forgone revenues, as discussed in the Introduction.

Figure 5. Domestic energy prices in the relaxed energy pricing pathway.



Sources: 2024 prices from Aljazira Capital (2024) and Riyad Capital (2024).

As summarized in Table 3, the consideration of these two policy levers allows us to define four scenarios as follows:

1. **Relaxed energy price reforms without public support (Relaxed-None)**: This scenario assumes that the domestic prices of all fuels will reach reference prices by 2050, reflecting a relaxed implementation of the price reforms. In this scenario, no public investment support is assumed.
2. **Relaxed energy price reforms with capital subsidy (Relaxed-Support)**: This scenario keeps the same pace of price reforms of the previous scenario, but it considers the government subsidizing 50% of the total investment cost of switching to alternative options.
3. **Accelerated energy price reforms without public support (Accelerated-None)**: This scenario factors in more accelerated price reforms, where domestic energy prices are set to reach reference prices by 2030. No public investment support is assumed.

Table 3. Policy scenarios applied to the three industrial sectors.

Scenario name	Year all fuels' domestic prices reach reference levels	Public support for investments
Relaxed energy price reforms without public support **(Relaxed-None)**	2050	No capital subsidy
Relaxed energy price reforms with capital subsidy **(Relaxed-Support)**	2050	Capital subsidy of 50%
Accelerated energy price reforms without public support **(Accelerated-None)**	2030	No capital subsidy
Accelerated energy price reforms with capital subsidy **(Accelerated-Support)**	2030	Capital subsidy of 50%

4. **Accelerated energy price reforms with capital subsidy (Accelerated-Support)**: This scenario assumes a combination of accelerated price reforms and capital subsidies, marking a substantial policy effort of the government to push for alternative options.

The changes in costs compared to current operations are then estimated in the four scenarios by considering both private and public perspectives. For visualization purposes, the annualized cost change is plotted along two axes. Private cost changes are represented on the vertical axis and their public counterparts are shown on the horizontal axis. In addition to visualizing the changes in the costs for the four scenarios, the top options will be ranked.

5. Results and Discussion

The following sub-sections detail the findings for firms in the ceramic tiles, float glass, and red bricks sectors. In general, the most favorable option for the private firms and the government is to use natural gas with the existing process. However, the government support scenarios can occasionally make other manufacturing processes more attractive to the firm.

5.1 Ceramic Tiles

A company that is located in Yanbu is chosen as a case study for the ceramic tiles sector. This company presently uses mostly diesel, some natural gasoline, and electricity to operate its equipment. The company discloses that its capacity to produce ceramic tiles is 200,000 square meters (m^2) per year. We estimate, based on the resulting energy intensity figures, that the plant uses a tunnel kiln and a fuel-operated dryer. From here, we investigate the cost implications of adopting different fuels and manufacturing processes. Table 4 lists the operational options we explore.

Using the options' acronyms in Table 4, Figures 6 to 9 visualize the changes in costs for the company as well as the government compared to the fuel use and energy prices in 2024. Figures 6 and 7 show the results if no capital support is provided and if domestic energy prices are reformed. Figures 8 and 9 show the relaxed and accelerated energy price reform results for a scenario where 50% of capital costs are covered by the government. Figure 10 shows the variations in cost changes between the various scenarios considered.

All alternative options result in lower government costs compared to the status quo for this firm. In general, switching to natural gas and keeping the existing process results in the highest cost savings for the firm. When the fuel price scenarios are applied, firms are expected to spend substantially more on fuels compared to the 2024 prices, especially if fuel use remains the same.

By switching the firm's fuel use to domestically sourced natural gas from the status quo and maintaining manufacturing processes, the Saudi government is expected to save $9 million in the Relaxed cases and $9.8 million when prices are more rapidly raised. For the same option, the company saves $4.2 million per year in the Relaxed fuel price case. This is compared to $3.7 million in the Accelerated cases. Both the Relaxed and the Accelerated cases presume fuel prices are also raised if current operations are kept. The domestic natural gas option also yields close to the highest cost savings from the government perspective. This option is generally the most favorable when the interests of both the firm and the government are considered.

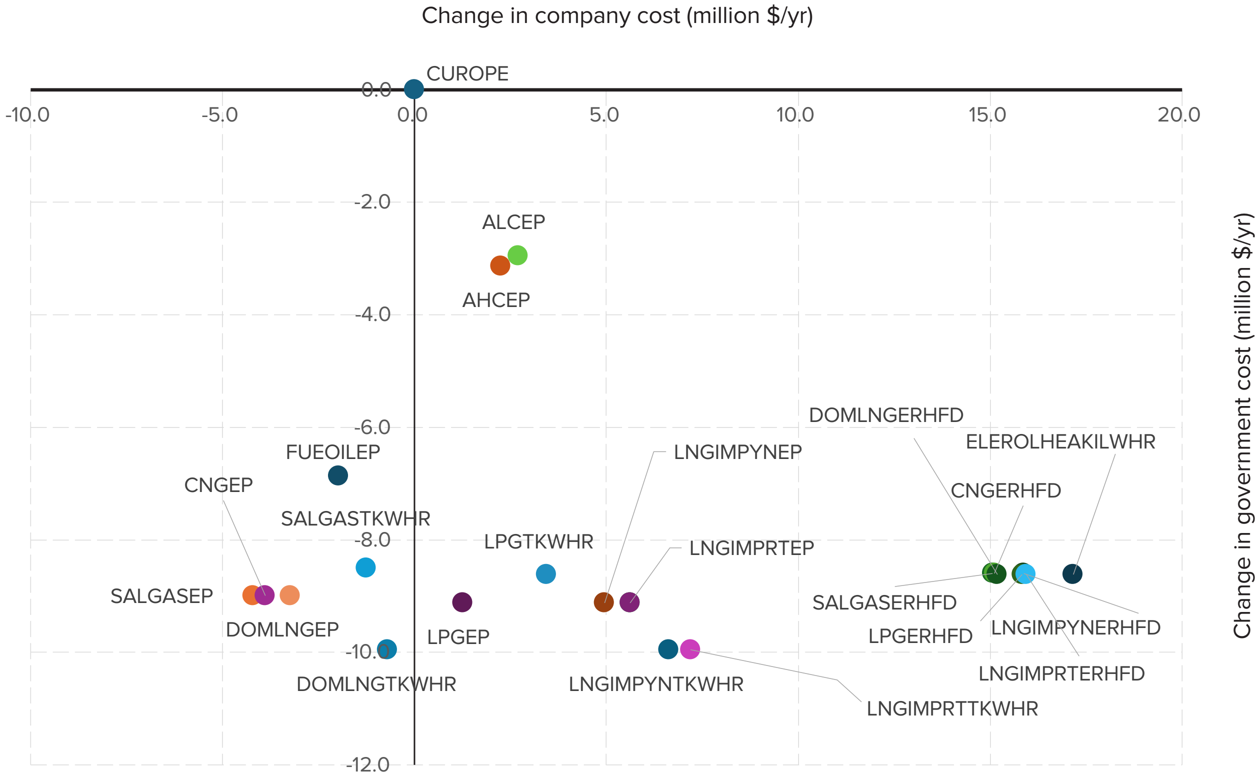
The options that result in higher government savings are those where the fuel's domestic price equals its market price (i.e. LNG imports). Importing LNG through Yanbu saves the Saudi government $9.1 million per year in the Relaxed case, which is a slightly higher saving than occurs when using domestic natural gas. However, the costs for the firm rise by $5 million dollars per year. As shown in Figure 5, internationally sourced LNG has a higher average price over the next 30 years than diesel and natural gasoline.

Table 4. List of operational options considered in the tool for ceramic tiles.

Operations options	Acronym
Current operation	CUROPE
Sales gas with existing process	SALGASEP
Sales gas with electric roller hearth kiln and fuel-operated dryer	SALGASERHFD
Sales gas with tunnel kiln for ceramics and waste heat recovery	SALGASTKWHR
CNG with existing process	CNGEP
CNG with electric roller hearth kiln and fuel-operated dryer	CNGERHFD
Electric roller hearth kiln and waste heat recovery	ELEROLHEAKILWHR
LNG imports via Yanbu with existing process	LNGIMPYNEP
LNG imports via Yanbu with electric roller hearth kiln and fuel-operated dryer	LNGIMPYNERHFD
LNG imports via Yanbu with tunnel kiln for ceramics and waste heat recovery	LNGIMPYNTKWHR
LPG with existing process	LPGEP
LPG with electric roller hearth kiln and fuel-operated dryer	LPGERHFD
LPG with tunnel kiln for ceramics and waste heat recovery	LPGTKWHR
Domestic LNG supply with existing process	DOMLNGEP
Domestic LNG with electric roller hearth kiln and fuel-operated dryer	DOMLNGERHFD
Domestic LNG with tunnel kiln for ceramics and waste heat recovery	DOMLNGTKWHR
LNG imports via Ras Tanura with existing process	LNGIMPRTEP
LNG imports via Ras Tanura with electric roller hearth kiln and fuel-operated dryer	LNGIMPRTERHFD
LNG imports via Ras Tanura with tunnel kiln for ceramics and waste heat recovery	LNGIMPRTTKWHR
ALCO with existing process	ALCEP
Fuel oil with existing process	FUEOILEP
AHCO with existing process	AHCEP

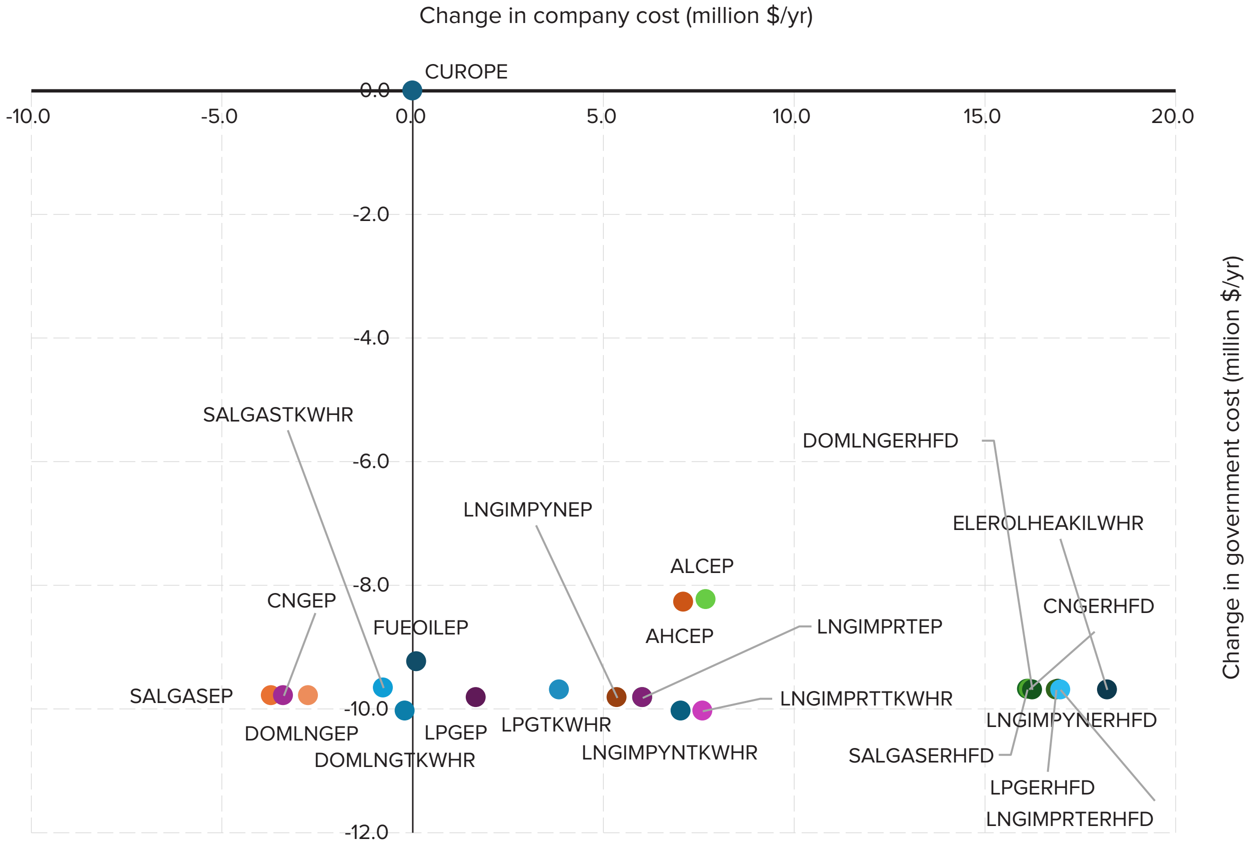
Source: Authors.

Figure 6. Changes in a ceramics tiles company and government costs relative to existing operations in ***Relaxed-None***.



Source: Model results.

Figure 7. Changes in a ceramics tiles company and government costs relative to existing operations in ***Accelerated-None***.

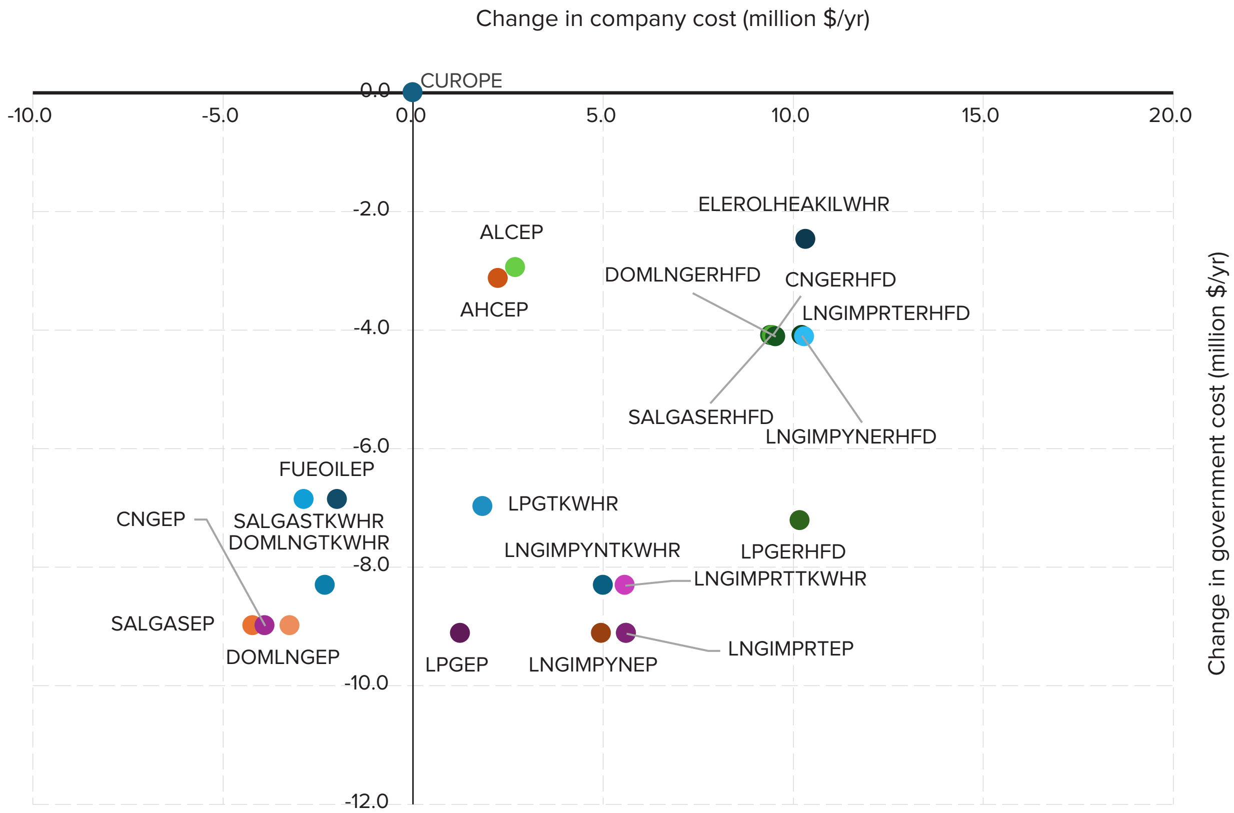


Source: Model results.

The only options that use domestically sourced natural gas (CNG, LNG, and waste heat recovery) result in cost savings for the private firm without public subsidy. Capital subsidy lowers the costs of the firms but raises the costs for the government for options with the alternative process units. The most favorable option with capital support is adopting natural gas and waste heat recovery. This option increases the firm's costs by $1.3 million per year and raises the government costs by $2.1 million per year compared to natural gas without changing the manufacturing process. For this Yanbu-based ceramics tiles company, the subsidy does not change the fact that existing processes are still preferred for the private firm and the government. Electrifying the hearth raises the costs of the firm even with the capital subsidy provided.

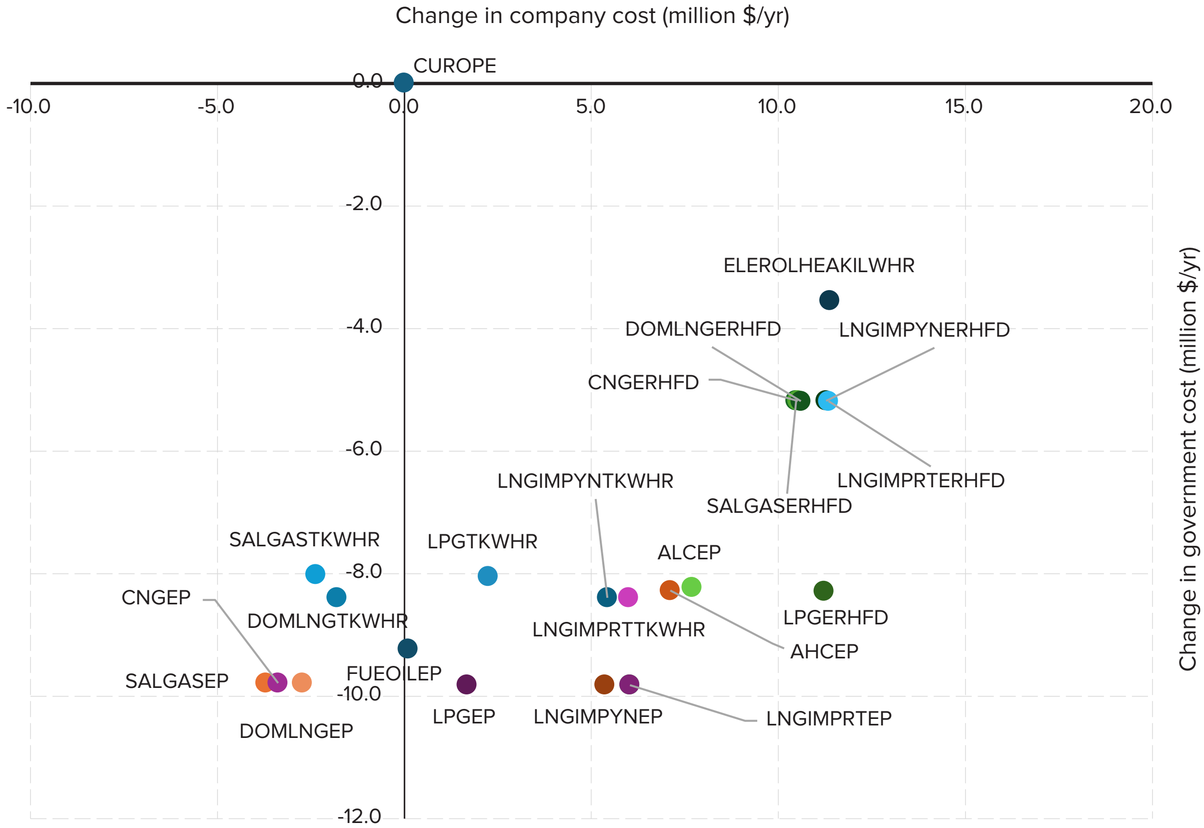
Looking at the variations in cost changes in different scenarios (Figure 10), it is possible to note that repurposing the existing process to allow the utilization of domestic natural gas (either sales gas, CNG, or domestic LNG) enables cost savings in all scenarios for both the company and the government. For these solutions, accelerated price reforms will reduce the company's cost savings compared to the relaxed reform (Relaxed-None) scenario by $500,000 a year while increasing the government's cost savings by more than $700,000 annually. Since the company is making significant cost savings by switching to natural gas, it is not recommended for the government to grant capital subsidies to it.

Figure 8. Changes in a ceramics tiles company and government costs relative to existing operations in ***Relaxed-Support***.



Source: Model results.

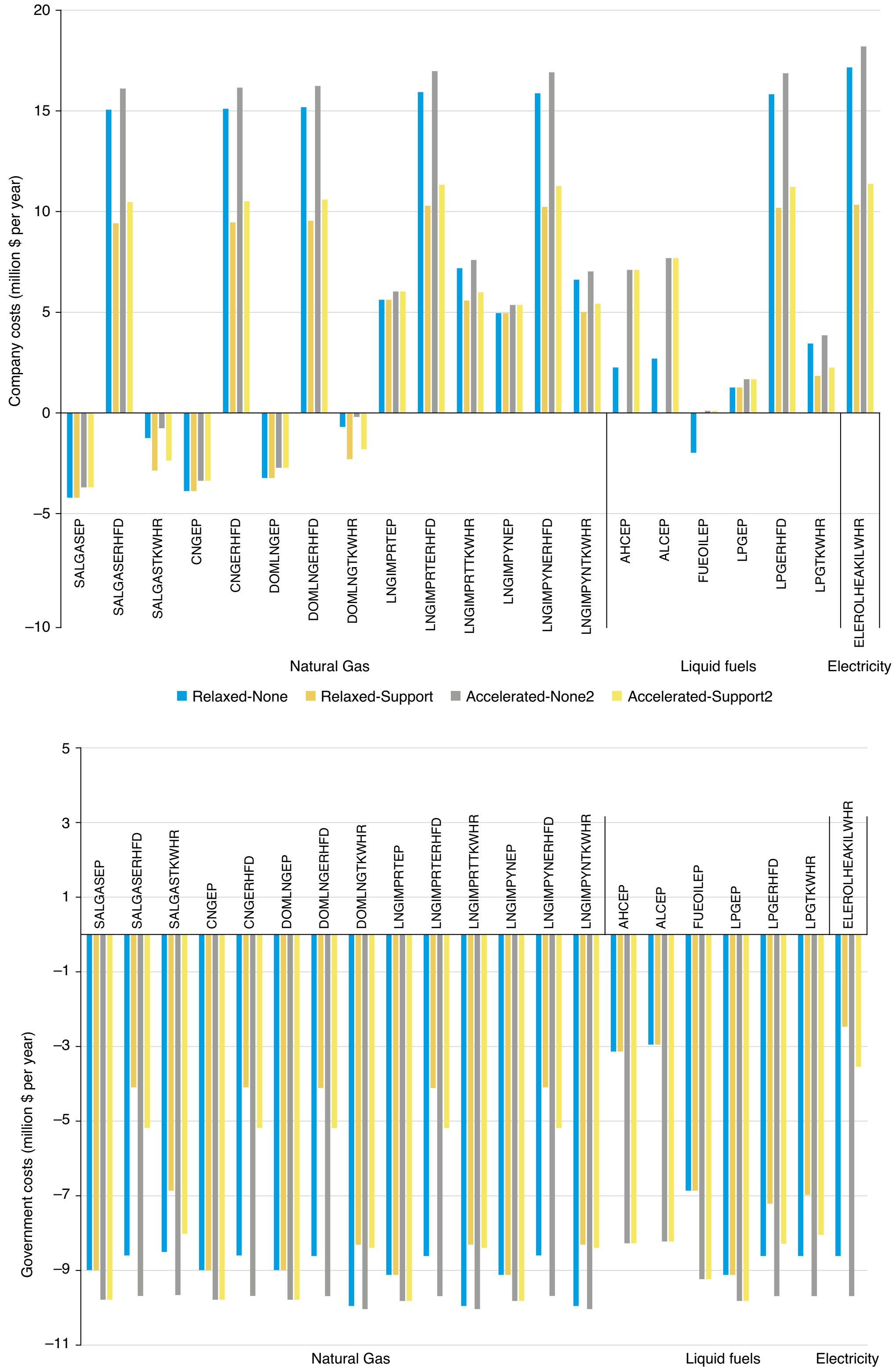
Figure 9. Changes in a ceramics tiles company and government costs relative to existing operations in ***Accelerated-Support***.



Source: Model results.

An alternative process based on electrifying the kiln will substantially increase the company's cost, adding between $15 million to $17 million a year to the cost of the current operations, and this cost is exacerbated in the case of accelerated price reforms, which impose more than $1 million of additional fuel expenses on the company. Capital subsidies will be critical in reducing the cost burdens in this situation. The government might consider these subsidies under a policy supporting electrification and emissions mitigation.

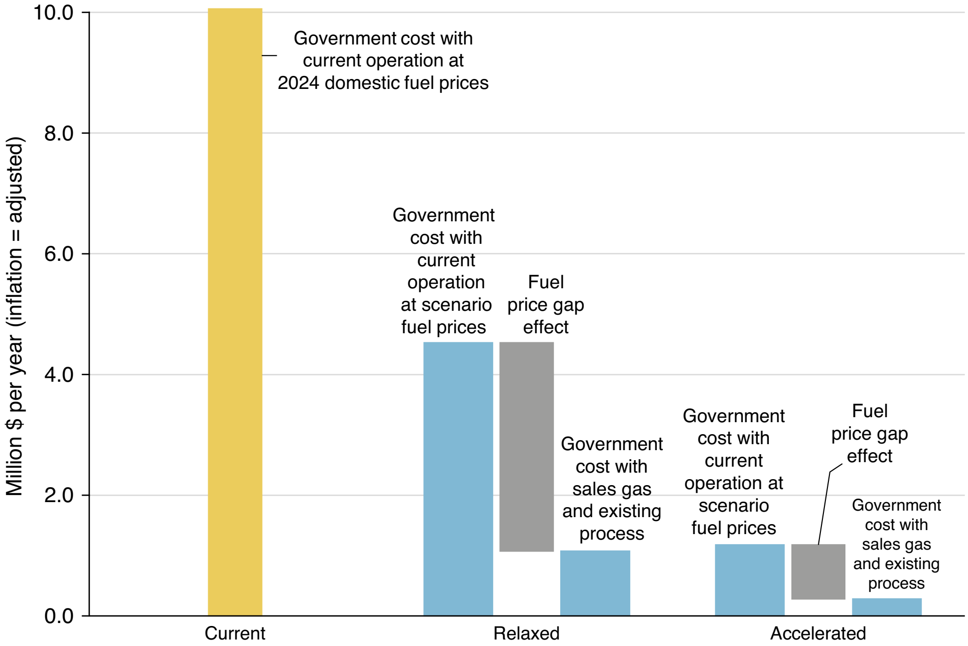
Figure 10. Changes in a ceramics tiles company costs (top) and government costs (bottom) relative to existing operations in all the scenarios (in million U.S. dollars per year).



Source: Model results.

Figure 11 focuses on the change in government costs by adopting sales gas with the existing process. By using diesel and natural gasoline, the firm imposes a current cost for the government of $10 million a year. Naturally, an accelerated fuel price adjustment results in the highest cost savings for the government for sales gas substitution compared to a relaxed adjustment.

Figure 11. Government costs for the assessed ceramic tiles company in the relaxed and accelerated cases.



Source: Authors.

We must use the same reference case when comparing the accelerated and relaxed price reforms. If fuel prices in the Relaxed cases were applied to current fuel use and fuel switching to only sales gas, we would observe $3.5 million lower costs per year for the government. If fuel prices in the Accelerated cases were applied to both options instead, the cost savings would be smaller at $0.9 million dollars per year. The fuel cost savings in the accelerated cases would be lower, but the initial condition in each case is different.

5.2 Float Glass

We input current operational data for a company located in Jubail, an industrial city in eastern Saudi Arabia. Its existing process is a regenerative furnace and a fuel-operated lehr. The production capacity is disclosed as 146,000 metric tons of glass per year. About half of the company's fuel use is natural gas while the other is diesel. A key differentiator for float glass is that we have two production units that may be substituted, in addition to the multitude of fuel options. Table 5 lists the options that we consider in the tool for the sector. There are options that only substitute the fuels, some that only change the furnace, and others that also electrify the lehr.

Table 5. List of operational options considered in the tool for float glass.

Operations options	Acronym
Current operation	CUROPE
Sales gas with existing process	SALGASEP
Sales gas with oxy-fuel furnace and fuel-operated lehr	SALGASO2FFUL
Sales gas with oxy-fuel furnace and electric lehr	SALGASO2FELL
CNG with existing process	CNGEP
CNG with oxy-fuel furnace and fuel-operated lehr	CNGO2FFUL
CNG with oxy-fuel furnace and electric lehr	CNGO2FELL
LNG imports via Yanbu with existing process	LNGIMPYNEP
LNG imports via Yanbu with oxy-fuel furnace and fuel-operated lehr	LNGIMPYNO2FFUL
LNG imports via Yanbu with oxy-fuel furnace and electric lehr	LNGIMPYNO2FELL
LPG with existing process	LPGEP
LPG with oxy-fuel furnace and fuel-operated lehr	LPGO2FFUL
LPG with oxy-fuel furnace and electric lehr	LPGO2FELL
Domestic LNG supply with existing process	DOMLNGEP
Domestic LNG with oxy-fuel furnace and fuel-operated lehr	DOMLNGO2FFUL
Domestic LNG with oxy-fuel furnace and electric lehr	DOMLNGO2FELL
LNG imports via Ras Tanura with existing process	LNGIMPRTEP
LNG imports via Ras Tanura with oxy-fuel furnace and fuel-operated lehr	LNGIMPRTO2FFUL
LNG imports via Ras Tanura with oxy-fuel furnace and electric lehr	LNGIMPRTO2FELL
Sales gas with electric boosting in regenerative furnace and fuel-operated lehr	SALGASELEBOOINREGFUL
LPG with electric boosting in regenerative furnace and fuel-operated lehr	LPGELEBOOINREGFUL
Fuel oil with electric boosting in regenerative furnace and fuel-operated lehr	FUEOILELEBOOINREGFUL
ALCO with existing process	ALCEP

Source: Authors.

Figures 12 to 15 illustrate the cost changes to the private float glass firm and the government for the four policy scenarios. Complementing the figures, the top four options from the company or the government perspectives are summarized in Table 6. If no capital subsidy is provided, dry natural gas with the existing process is the preferred option for both stakeholders. This option allows the firm to realize $3.9 million dollars per year in savings compared to the current operation when the energy price reform path is relaxed. The savings slightly differ when the price reform path is accelerated, reaching $3.6 million dollars per year. This is followed by the existing process coupled with CNG and domestically sourced LNG. The fourth best option is sales gas with electric boosters installed on a re-built regenerative furnace.

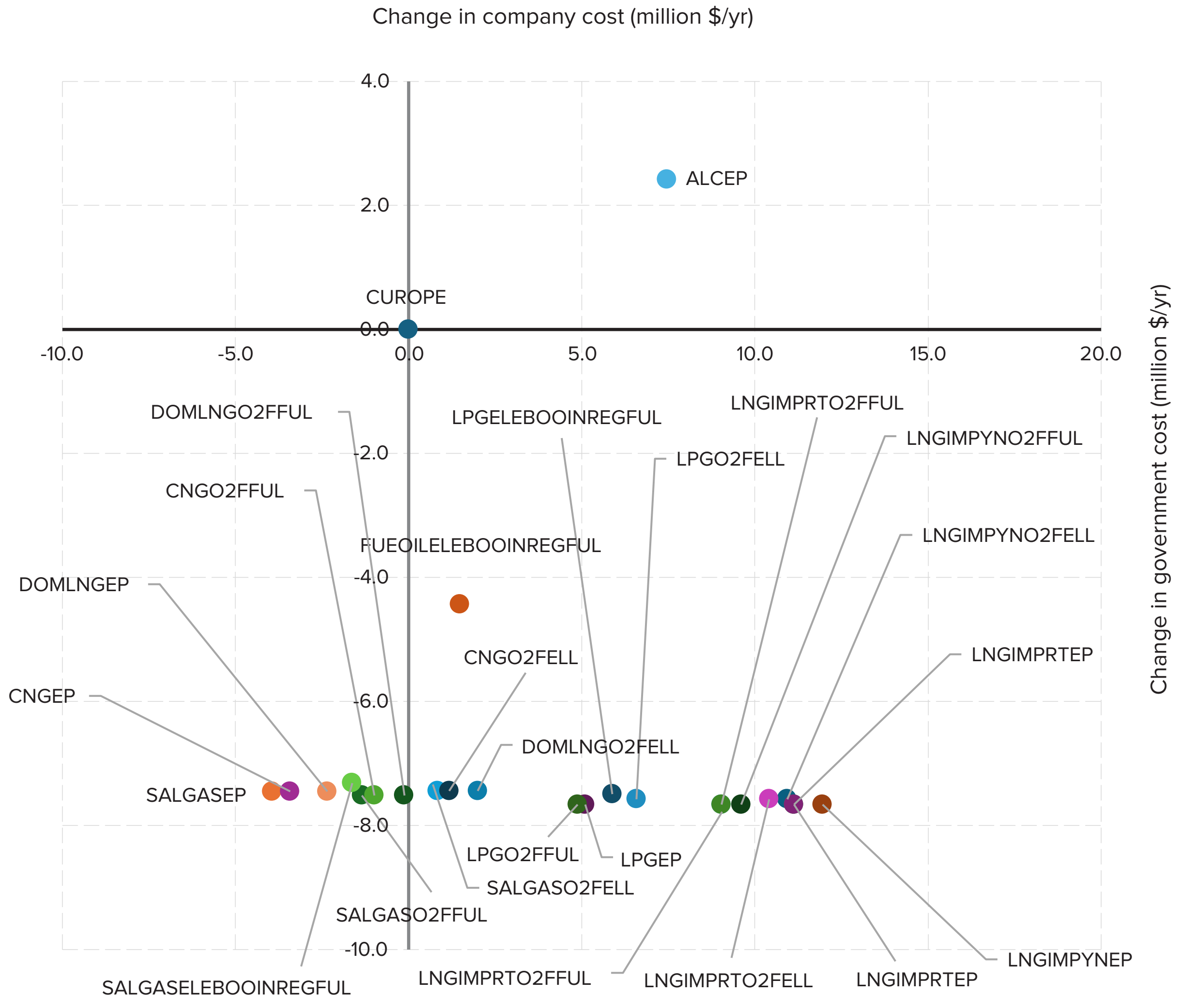
Installing and operating an electric lehr is more expensive for the company than using the existing fuel-operated lehr. Without the capital subsidy, the electric lehr is $2.2 million per year more expensive than maintaining the fuel-operated unit.

Table 6. Top four options in the float glass sector whether fuel prices gradually reach reference prices in 2023 or 2050.

	Without capital subsidy		With capital subsidy	
Change in costs for:	**Own company**	**Own company and government**	**Own company**	**Own company and government**
1	Sales gas with existing process		Sales gas with oxy-fuel furnace and fuel-operated lehr	
2	CNG with existing process		Sales gas with existing process	
3	Domestic LNG supply with existing process		CNG with oxy-fuel furnace and fuel-operated lehr	
4	Sales gas with electric boosting in regenerative furnace and fuel-operated lehr		CNG with existing process	

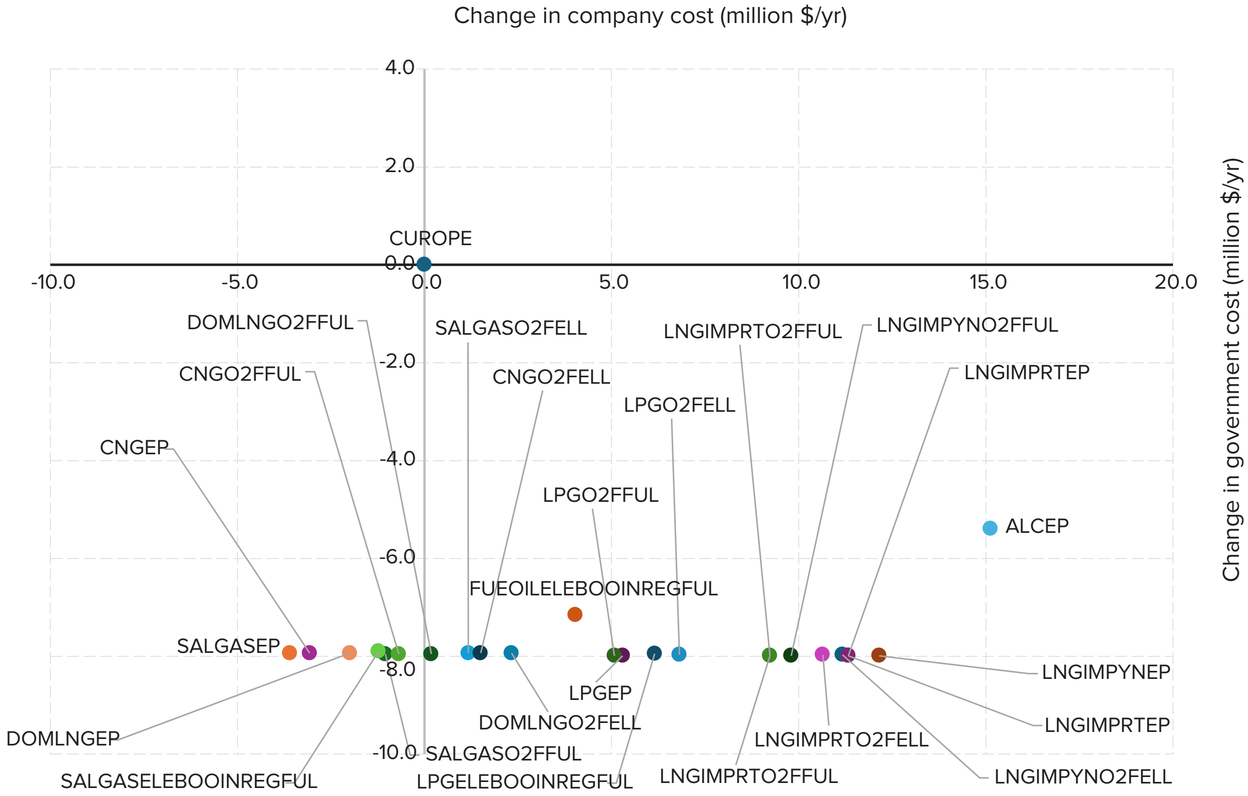
Even with the higher operational costs related to sourcing oxygen gas, the 50% capital subsidy allows the firm to experience higher cost savings by using natural gas and installing an oxy-fuel furnace with a fuel-operated lehr compared to the existing option. The firm's cost savings are $4.1 million a year in this case in the relaxed energy price reform case, surpassing that of natural gas substitution only. Similar behavior is observed whether energy prices match reference prices in a relaxed or accelerated timeframe. However, the government would have higher costs than it could experience with the existing process due to the capital expense and insufficient fuel savings. In this situation, the capital subsidy would not be recommended. Moreover, installing an electric lehr will significantly increase the company's cost even when using gas as an alternative fuel. Electricity is substantially more expensive in energy terms than domestically sourced natural gas.

Figure 12. Changes in a float glass company and government costs relative to existing operations in ***Relaxed-None***.



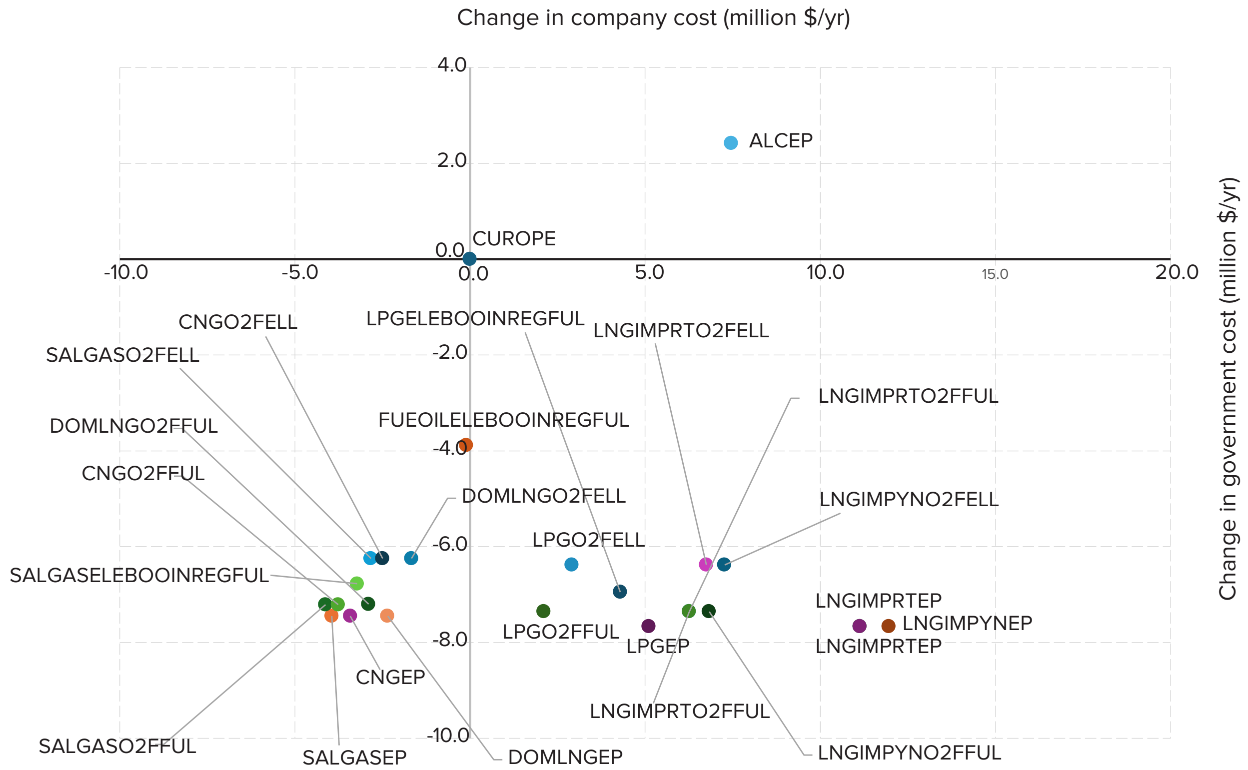
Source: Model results.

Figure 13. Changes in a float glass company and government costs relative to existing operations in ***Accelerated-None***.



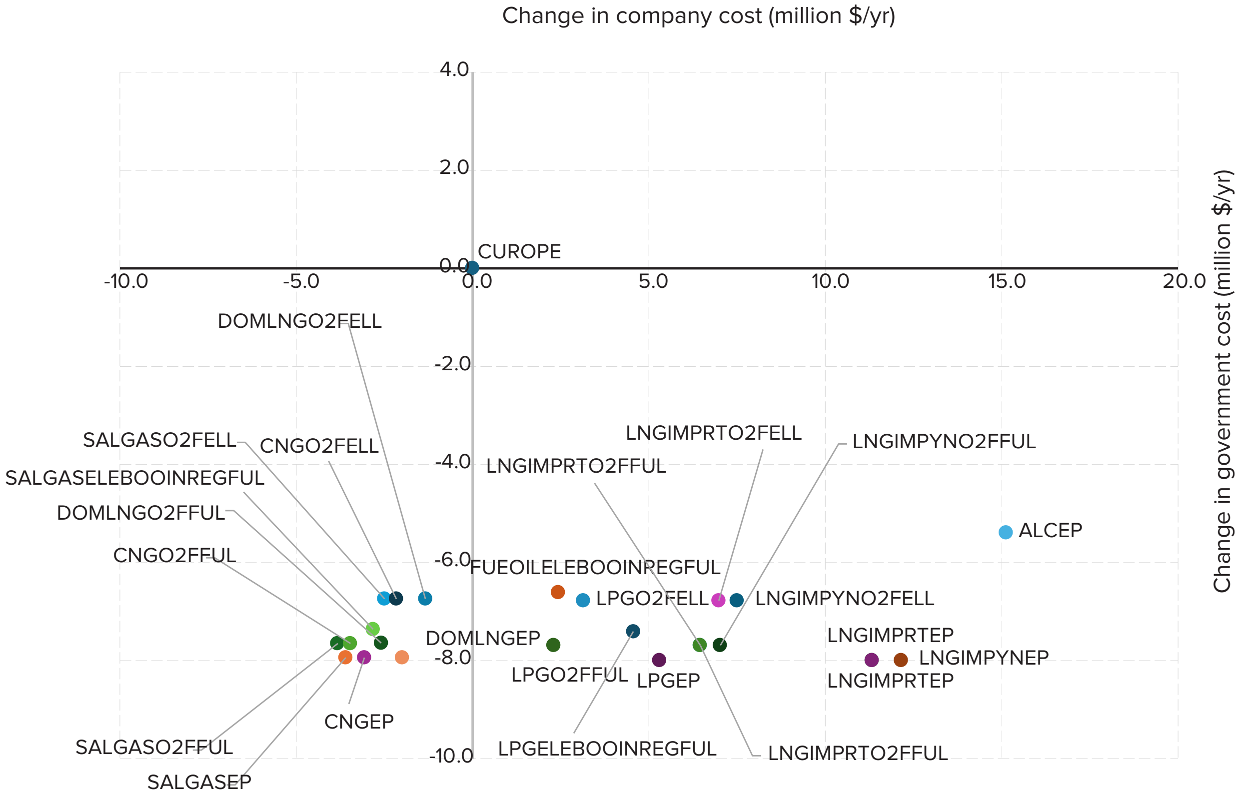
Source: Model results.

Figure 14. Changes in a float glass company and government costs relative to existing operations in ***Relaxed-Support***.



Source: Model results.

Figure 15. Changes in a float glass company and government costs relative to existing operations in ***Accelerated-Support***.

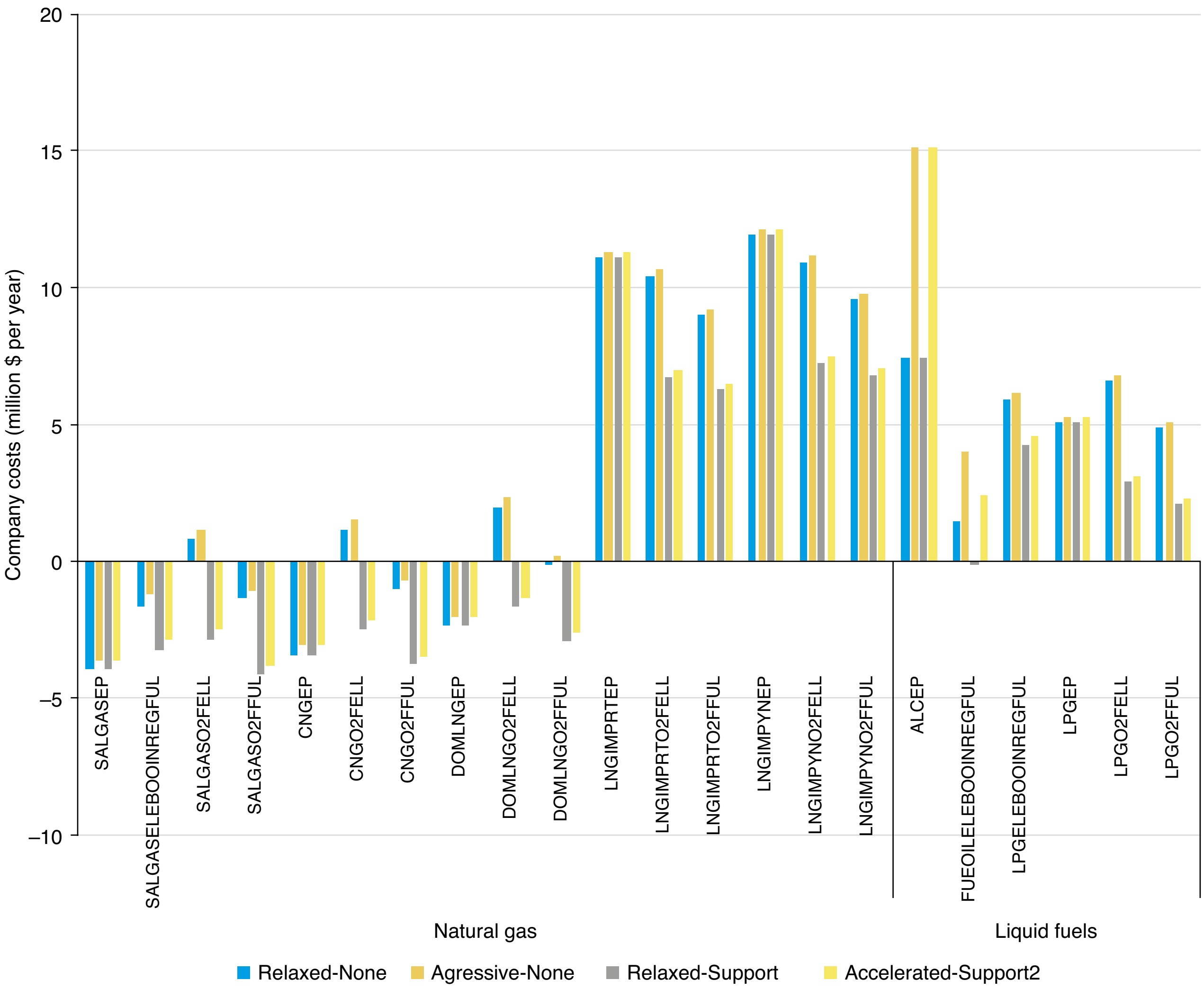


Source: Model results.

As depicted in Figure 16, installing an electric lehr will significantly increase the company's cost even when using gas as an alternative fuel. The electrification of the lehr imposes additional costs that require some capital support from the government to reduce its impact on the company's cost competitiveness.

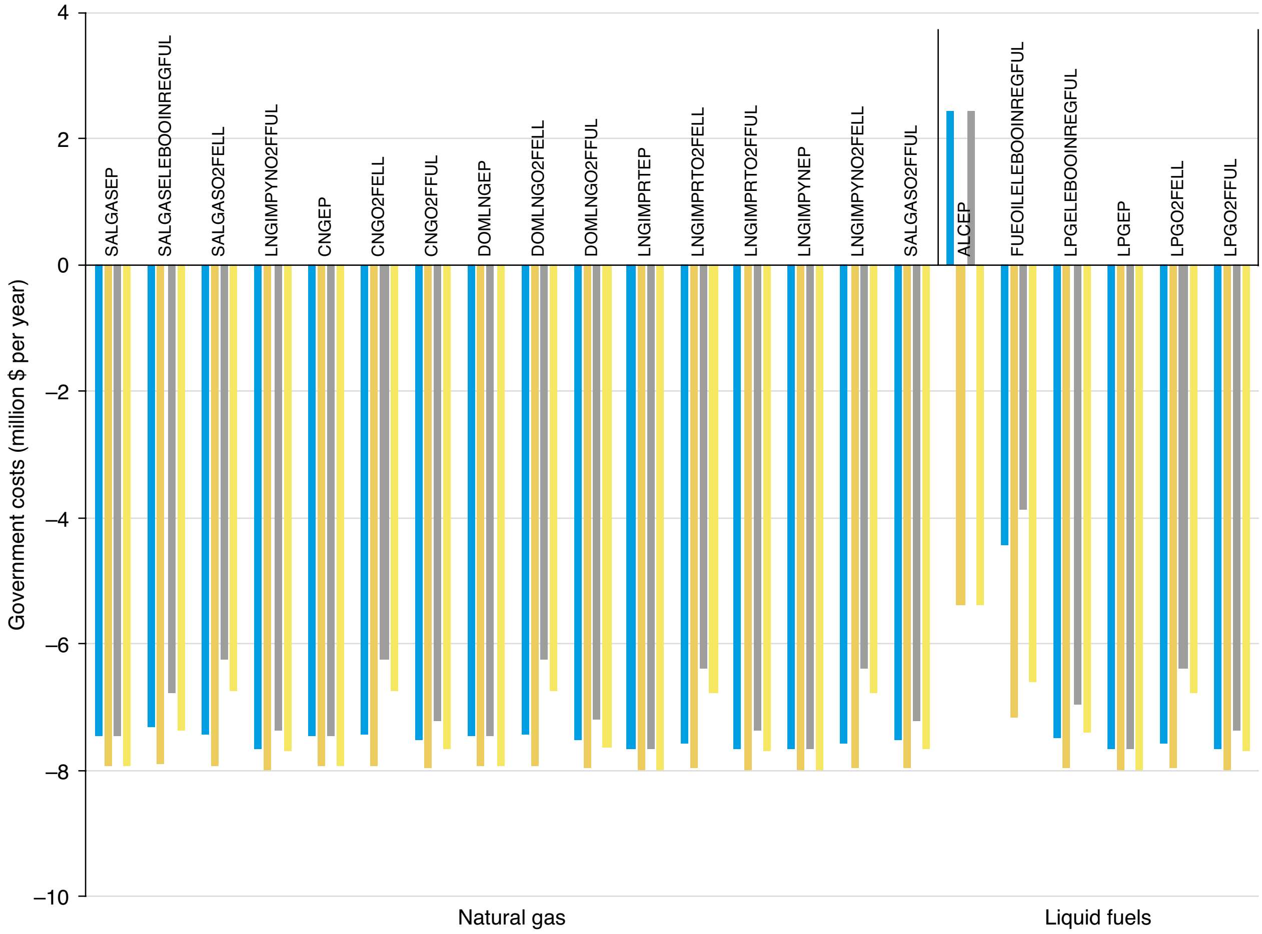
Furthermore, using ALCO as an alternative fuel is unsuitable for the government since it would add more than $2 million a year compared to the current operations in the case of relaxed price reforms.

Figure 16. Changes in a float glass company costs (top) and government costs (bottom) relative to existing operations in all the scenarios (in million U.S. dollars per year).



(continues)

Figure 16. (continued)



Source: Model results.

5.3 Red Bricks

We analyzed a red bricks company located in Madinah, Saudi Arabia. Its production capacity is 1 million tons of bricks annually. A total of 84% of its fuel use is fuel oil and the rest is diesel. The baseline manufacturing process uses a tunnel kiln. Based on the energy intensity of a tunnel kiln, we approximated the company is producing at about half of its capacity. Table 7 lists the options we assessed for any red brick firm. In addition to a limited set of fuels, we assessed the existing process and, if not already installed, a VSBK.

Table 7. List of operational options considered in the tool for red bricks.

Operations options	Acronym
Current operation	CUROPE
Sales gas with existing process	SALGASEP
Sales gas with vertical shaft brick kiln	SALGASVSBK
CNG with existing process	CNGEP
CNG with vertical shaft brick kiln	CNGVSBK
LNG imports via Yanbu with existing process	LNGIMPYNEP
LNG imports via Yanbu with vertical shaft brick kiln	LNGIMPYNVSBK
Petroleum coke with existing process	PETCOKEP
Petroleum coke with vertical shaft brick kiln	PETCOKVSBK
30% tire-derived fuel with existing process (and fuel oil)	30%TIRFUEEPFUEOIL
30% tire-derived fuel and vertical shaft brick kiln (and fuel oil)	30%TIRFUEVSBKFUEOIL
AHCO with existing process	AHCEP
AHCO with vertical shaft brick kiln	AHCVSBK
ALCO with existing process	ALCEP
ALCO with vertical shaft brick kiln	ALCVSBK
LPG with existing process	LPGEP
LPG with vertical shaft brick kiln	LPGVSBK
Domestic LNG supply with existing process	DOMLNGEP
Domestic LNG supply with vertical shaft brick kiln	DOMLNGVSBK
30% RDF with existing process with fuel oil	30%RDFEPFUEOIL
30% RDF and vertical shaft brick kiln with fuel oil	30%RDFVSBKFUEOIL
LNG imports via Ras Tanura with existing process	LNGIMPRTEP
LNG imports via Ras Tanura with vertical shaft brick kiln	LNGIMPRTVSBK

Source: Authors.

Figures 17 to 20 show the resulting cost changes for the company itself and for the government. Figure 21 highlights these changes under various policy and investment support scenarios. A key difference between relaxed and accelerated price adjustments is the placement of the crude oils with the existing process options. In the Relaxed cases, those options result in higher government costs compared to the base case (see Figure 21). Conversely, they yield lower costs when energy prices are more rapidly raised. This happens because fuel oil is sold domestically at a fraction of its reference price, causing a large fuel subsidy. Crude oils are also so heavily subsidized that it makes a large difference between the average 30-year-ahead prices between the Relaxed and Accelerated scenarios. For instance, the average price for Arabian Light crude oil over the next 30 years is $55 per boe in the relaxed scenarios, whereas it is $84 per boe in the Accelerated ones. The difference between the status quo with fuel oil and $55/boe or $84/boe causes this interspersed placement.

The consideration of RDF as an alternative option in this company for red bricks will drive a lower cost increase compared to the utilization of liquid fuels. The government can envisage these options as part of a strategy to monetize waste, but a capital subsidy can be a relevant option to reduce the company's cost burdens.

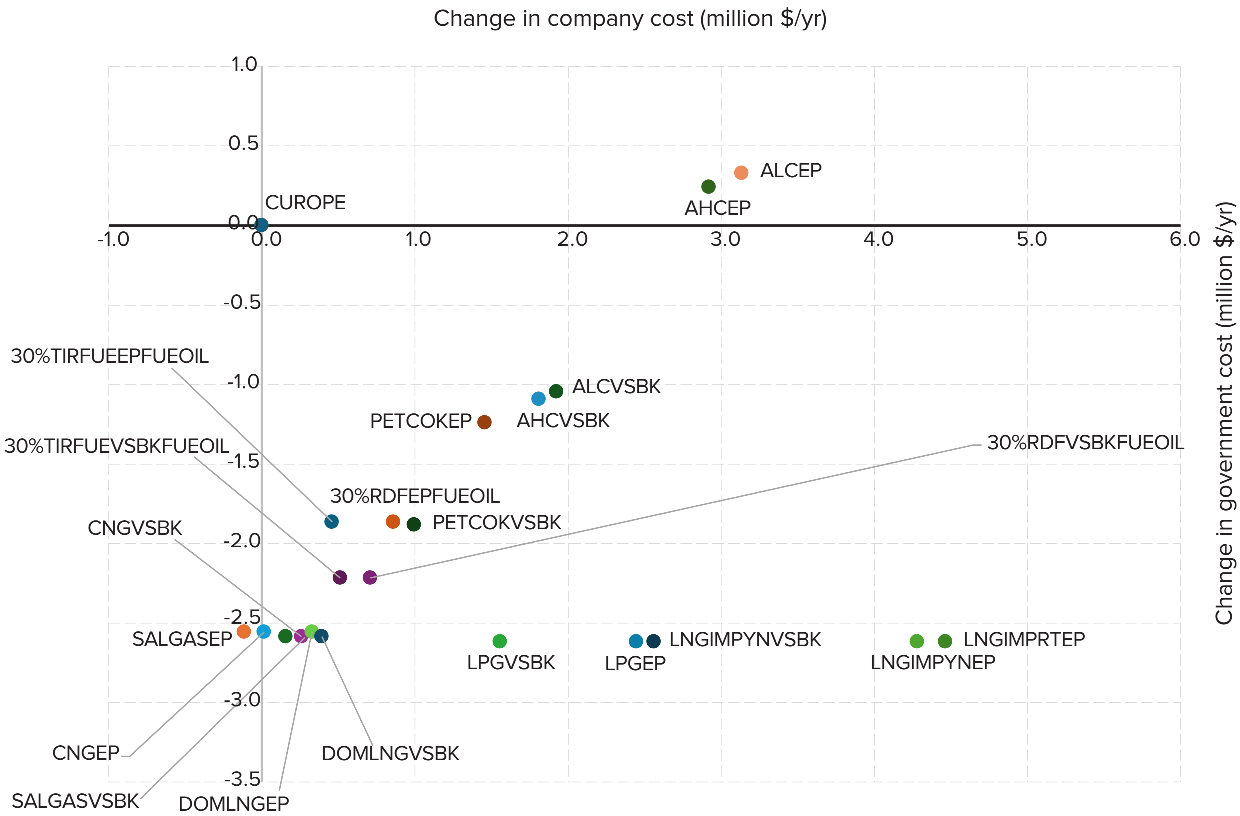
Table 8 shows the best four options, as extracted from Figures 17 to 20. Without capital support, sales gas with the existing process is the sole option that lowers the company's costs. Capital subsidy brings alternate manufacturing processes into the discussion. Sales gas with VSBK takes the top spot for the company itself with $ 0.2 million per year savings for the Relaxed cases, but results in higher costs for the government than a case without the capital subsidy. For instance, government cost savings when natural gas with VSBK is implemented amount to $2.2 million a year with capital subsidy versus $2.6 million a year without the subsidy. The capital subsidy would not make sense for this process option.

As shown in Table 8, the accelerated path to energy price reforms switches between the second- and third-best options when capital subsidy is provided to the red bricks company. This switch indicates that sales gas with the existing process and CNG with VSBK exhibit similar cost changes when the capital subsidy is offered.

Table 8. Top four options in the red bricks sector based on whether fuel prices gradually reach reference prices in 2023 or 2050.

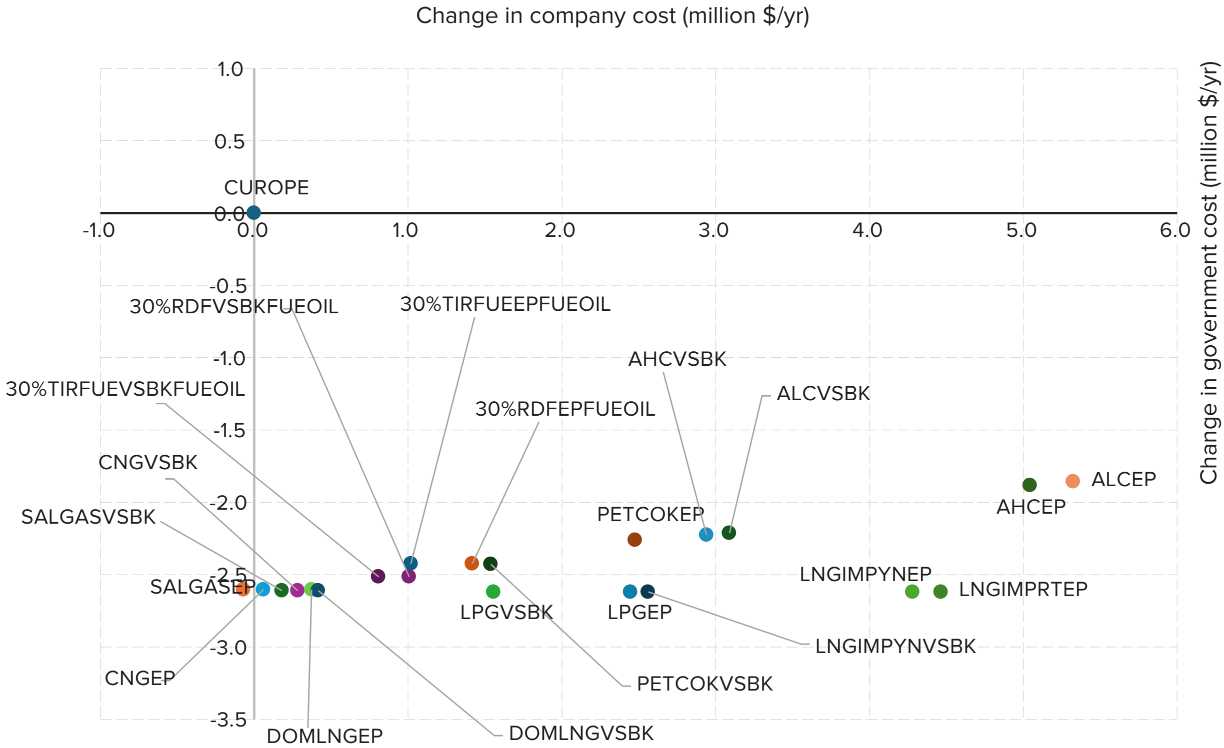
Scenario:	**Without capital subsidy**		**With capital subsidy**		
Change in costs for:	**Own company (both energy price scenarios)**	**Own company and government (both energy price scenarios)**	**Own company (relaxed energy prices)**	**Own company (accelerated energy prices)**	**Own company and government (both energy price scenarios)**
1	Sales gas with existing process		Sales gas with vertical shaft brick kiln		Sales gas with existing process
2	Current operation	CNG with existing process	CNG with vertical shaft brick kiln	Sales gas with existing process	CNG with existing process
3	CNG with existing process	Sales gas with vertical shaft brick kiln	Sales gas with existing process	CNG with vertical shaft brick kiln	Sales gas with vertical shaft brick kiln
4	Sales gas with vertical shaft brick kiln	CNG with vertical shaft brick kiln	Current operation		Domestic LNG supply with existing process

Figure 17. Changes in a red bricks company and government costs relative to existing operations in ***Relaxed-None***.



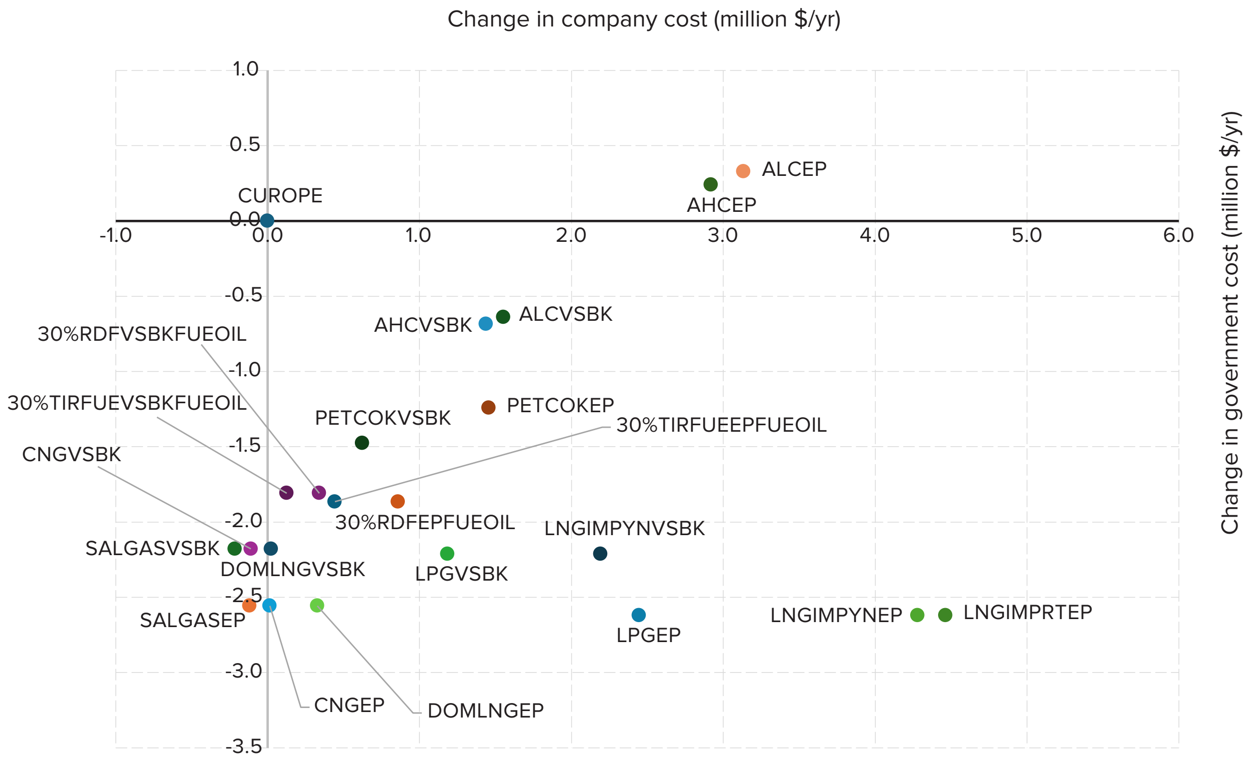
Source: Model results.

Figure 18. Changes in a red bricks company and government costs relative to existing operations in ***Accelerated-None***.



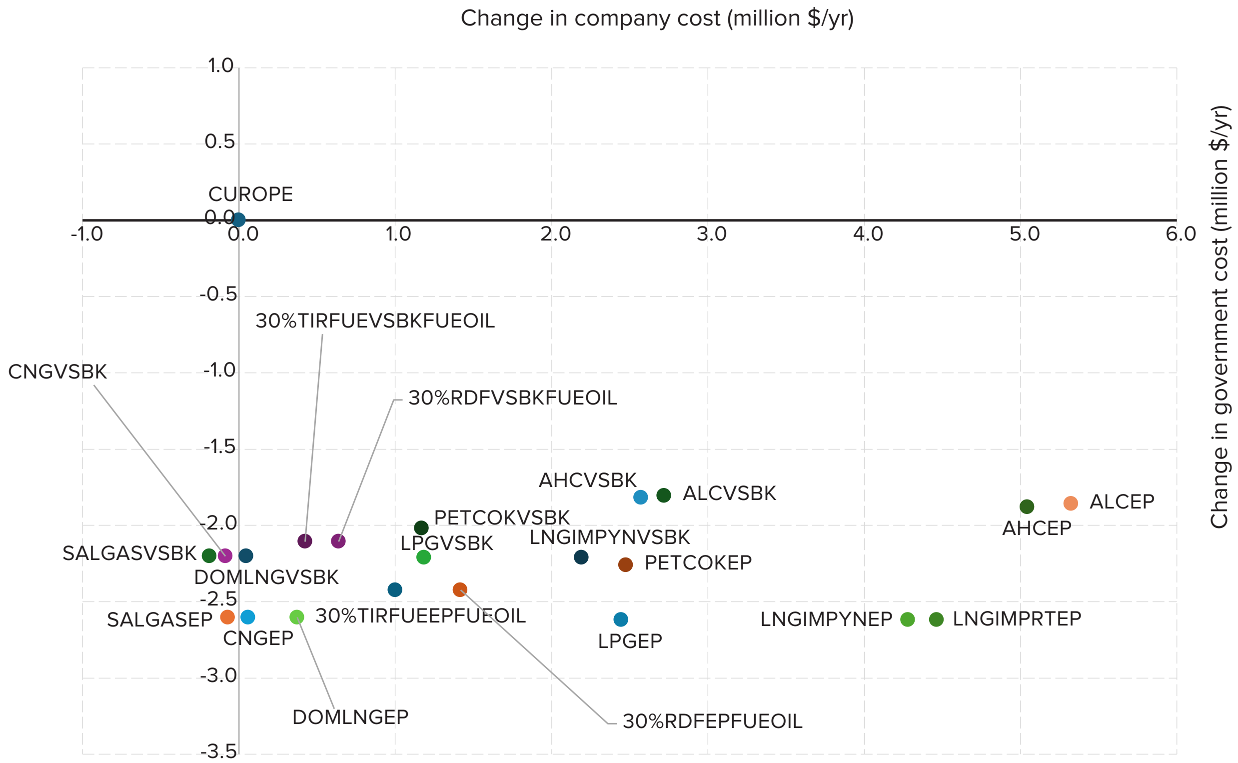
Source: Model results.

Figure 19. Changes in a red bricks company and government costs relative to existing operations in ***Relaxed-Support***.



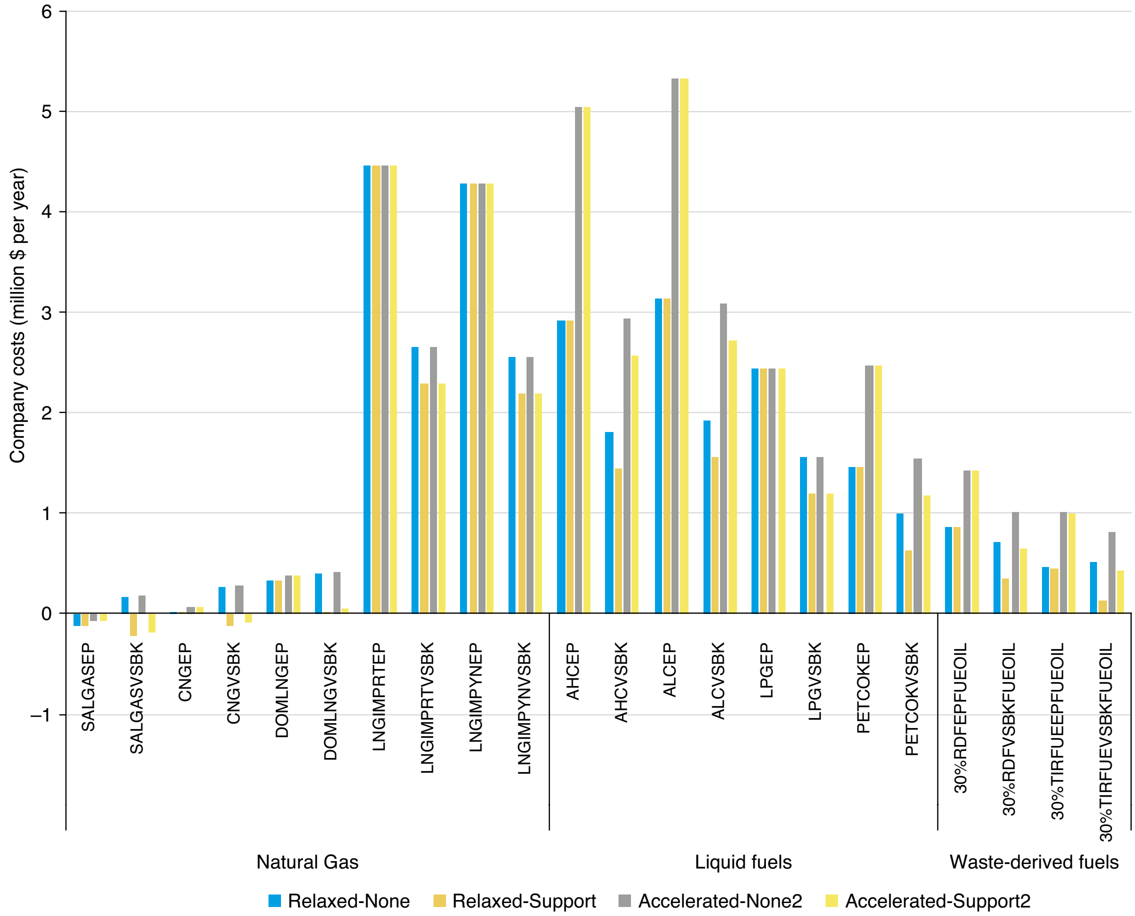
Source: Model results.

Figure 20. Changes in a red bricks company and government costs relative to existing operations in ***Accelerated-Support***.



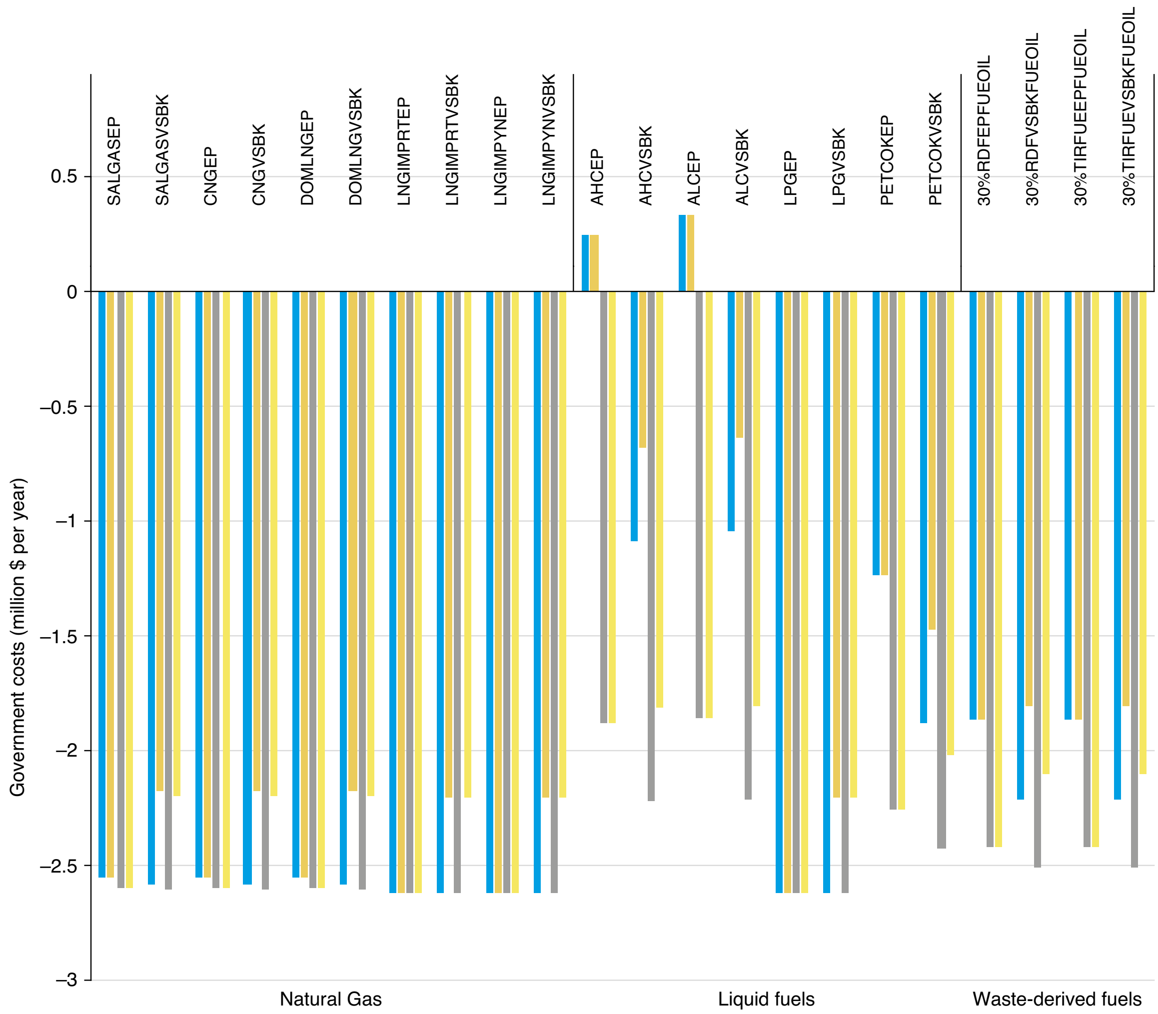
Source: Model results.

Figure 21. Changes in a red bricks company costs (top) and government costs (bottom) relative to existing operations in all the scenarios (in million U.S. dollars per year).



(continues)

Figure 21. (continued)



Source: Model results.

6. Conclusion

The construction materials sector is sizable in Saudi Arabia. Yet, little attention has been paid to fuel use and manufacturing process options in this segment locally. The manufacturing of construction materials will play a key role as Saudi Arabia looks to improve the allocation efficiency of its resources and reduce the fuel costs on the government. This paper fills a gap in the literature about Saudi industry.

Specifically, firms in the ceramics tiles, float glass, and red bricks sectors were examined. These sectors were chosen because firms within them predominantly use oil products. The cost changes for the firm and the government by switching from liquid fuels and/or manufacturing units were assessed using two policy instruments: (1) the rate at which domestic energy prices reach their market-level prices, and (2) the offer of capital subsidy to firms. Energy price reform considerations saw domestic prices gradually reaching some reference or market-equivalent prices by 2030 or 2050. In the analysis, half of the investment costs in more energy efficient manufacturing units were covered by the government in the event that a capital subsidy was provided.

To do this, a techno-economic tool that includes those three sectors was developed and included as a supplementary material. There are six other sectors in the supplementary tool. These six are cement, cement board, concrete blocks, plasterboard, lime, and container glass. The changes in private and government costs were estimated for broad sets of fuels and manufacturing units. Then, the results were plotted and ranked from best, or least costly, to worst for the firm and for the government.

Without capital subsidy, sales gas with the existing process was found to be the best option for both the government and the private firm. This is the case whether energy prices are reformed by 2030 (Accelerated) or 2050 (Relaxed) and for the three sectors. To elaborate, the difference in government costs in both energy price scenarios was found to be small. Domestic energy prices that reach market prices in 2050 would save the Saudi government $9 million per year, and such savings only slightly increase to $9.8 million dollars per year if the energy price reforms are completed by 2030. As another example, the government saving for the float glass company was $7.4 million per year in the Relaxed cases, whereas it was $7.9 million per year in the Accelerated cases. For the red bricks company, the government savings would differ by only 2% between the Relaxed and the Accelerated cases. Small cost differences were also observed for private firms. It may behoove the government to implement a more relaxed energy price reform rather than pursue a more drastic approach.

In general, the capital subsidies assessed were not found to be economically beneficial for both stakeholders. Even when the subsidies lower the costs for the firms, any fuel savings stemming from new manufacturing equipment would be insufficient to recover the subsidy cost. For instance, the analysis of the red bricks company shows that while the capital subsidy induces higher cost savings for the firm, government cost savings would fall from $2.6 million a year without the subsidy to $2.2 million a year with capital subsidy.

The analysis consists of companies that currently use oil products that would benefit by switching to alternative fuels. The government also benefits by lowering the use of oil products for manufacturing construction materials. The use of oil may be better directed at other activities in the Saudi economy, the simplest of which is international export. Other activities using oil may be in the form of producing plastics or specialty chemicals.

Endnotes

[1] Koplow (2009) discusses the price-gap method applied to energy products.

[2] See https://www.gem.wiki/MGS_III_Gas_Pipelines.

References

Abbas, Akhtar, Muhammad Bilal Sajid, Muhammad Asaad Iftikhar, Asif Hussain Khoja, Muhammad Muneeb Ahmad, Muhammad Shahid, and Kafait Ullah. 2021. "Assessment of Long-Term Energy and Environmental Impacts of the Cleaner Technologies for Brick Production." *Energy Reports* 7 (November): 7157–7169. https://doi.org/10.1016/j.egyr.2021.10.072.

Alibaba. 2024. "China's Advanced Small Electric Rotary Mobile Brick Burning Tunnel Kiln." https://www.alibaba.com/product-detail/China--s--advanced--small--electric--rotary_1601134617835.html.

Aljazira Capital. 2024. *Impacts of Feedstock Price Hikes on Petrochemical & Cement Industries: Thematic Report I January 2024*. https://argaamplus.s3.amazonaws.com/acf37816-5efc-417e-a37f-f244da353b50.pdf.

Alshammari, Yousef M. 2021. "Scenario Analysis for Energy Transition in the Chemical Industry: An Industrial Case Study in Saudi Arabia." *Energy Policy* 150 (March): 112128. https://doi.org/10.1016/j.enpol.2020.112128.

Chai, Slyvester Yew Wang, Frederick Jit Fook Phang, Lip Siang Yeo, Lock Hei Ngu, and Bing Shen How. 2022. "Future Era of Techno-Economic Analysis: Insights from Review." *Frontiers in Sustainability* 3: 924047. https://doi.org/10.3389/frsus.2022.924047.

Concrete Block Association. 2013. Aggregate Concrete Blocks: Aggregate Block Sustainability. https://www.thenbs.com/PublicationIndex/documents/details?Pub=CBA&DocId=323032.

Department for Business, Energy & Industrial Strategy. 2022. *Industrial Boilers: Study to Develop Cost and Stock Assumptions for Options to Enable or Require Hydrogen-Ready Industrial Boilers*. https://www.h2knowledgecentre.com/content/government4234.

EIA (U.S. Energy Information Administration). 2024. "Spot Prices (Crude Oil in Dollars per Barrel, Products in Dollars per Gallon)." https://www.eia.gov/dnav/pet/pet_pri_spt_s1_a.htm.

European Commission. 2007. *Reference Document on Best Available Techniques in the Ceramic Manufacturing Industry*. August. https://www.academia.edu/32947890/EUROPEAN_COMMISSION_Ceramic_Manufacturing_Industry.

European Lime Association (EuLA). 2014. *A Competitive and Efficiency Lime Industry: Cornerstone for a Sustainable Europe*. July. https://www.eula.eu/wp-content/uploads/2019/02/A-Competitive-and-Efficient-Lime-Industry-Technical-report-by-Ecofys_0.pdf.

Fadel, Ahmed, Abd Elrahman Lotfy Kalil, Amr Hassan El-Nawagy, Ahmed Mohamed Fetoh, and Mahmoud Abdelhakem Amer. 2023. Design of Industrial Furnace (End Port Glass Type). July. https://www.researchgate.net/publication/372526128_Design_of_Industrial_Furnace_End_Port_Glass_Type.

Fakheri, Ahmad. 2007. "Heat Exchanger Efficiency." *ASME Journal of Heat and Mass Transfer* 129 (9): 1268–1276. https://doi.org/10.1115/1.2739620.

Felea, I., G. Bendea, N. Rancov, D. Albuț-dana, V. Moldovan, and D. Meianu. 2021. "Energy Performance Level Analysis of a Brick Manufacturing Process." *Journal of Sustainable Energy* 12, no. 1 (June): 40–51. https://energy-cie.ro/archives/2021/nr_1/v12-n1-5.pdf.

Furszyfer Del Rio, Dylan D., Benjamin K. Sovacool, Aoife M. Foley, Steve Griffiths, Morgan Bazilian, Jinsoo Kim, and David Rooney. 2022. "Decarbonizing the Glass Industry: A Critical and Systematic Review of Developments, Sociotechnical Systems and Policy Options." *Renewable and Sustainable Energy Reviews* (March) 155: 111885. https://doi.org/10.1016/j.rser.2021.111885.

Gasim, Anwar A., and Walid Matar. 2023. "Revisiting Energy Subsidy Calculations: A Focus on Saudi Arabia." *The Energy Journal* 44 (1): 245–276. https://doi.org/10.5547/01956574.44.1.agas.

General Authority for Statistics (GASTAT). 2024a. “Industrial Production Index, August 2024.”

General Authority for Statistics (GASTAT). 2024b. “Supply and Use & Input-Output Tables 2021.”

Griffin, Paul W., Geoffrey P. Hammond, and Russell C. McKenna. 2021. “Industrial Energy Use and Decarbonisation in the Glass Sector: A UK Perspective.” *Advances in Applied Energy* 3 (August): 100037. https://doi.org/10.1016/j.adapen.2021.100037.

Heierli, Urs, and Sameer Maithel. 2008. *Brick by Brick: The Herculean Task of Cleaning up the Asian Brick Industry*. Berne: Swiss Agency for Development and Cooperation (SOC), Natural Resources and Environment Division

Industrial Center (IC). 2024. “Building Materials: Overview.” https://www.ic.gov.sa/industries-building-materials/.

Institute for Prospective Technological Studies (Joint Research Centre). 2013. Best Available Techniques (BAT) Reference Document for the Manufacture of Glass. Industrial Missions Directive 2010/75/EU: Integrated Pollution Prevention and Control. European Union. [Aivi Querol Sissa, Luis Delgado Sancho, Serge Roudier, Bianca Maria Scalet, Marcos Garcia Muñoz et al.] https://data.europa.eu/doi/10.2791/70161.

International Energy Agency (IEA). 2014. “ETSAP: Electricity Transmission and Distribution.” https://iea-etsap.org/E-TechDS/PDF/E12_el-t&d_KV_Apr2014_GSOK.pdf.

International Energy Agency (IEA). 2023. “Final Energy Consumption of Buildings Relative to Other Sectors, 2022.” https://www.iea.org/data-and-statistics/charts/final-energy-consumption-of-buildings-relative-to-other-sectors-2022.

KAPSARC. 2016. The KAPSARC Energy Model for Saudi Arabia: Documentation of the model build called “KEM-SA_v9.16”. Riyadh: King Abullah Petroleum Studies and Research Center (KAPSARC). https://www.kapsarc.org/wp-content/uploads/2016/11/KEM-SA_documentation_v9.16.pdf.

Kermeli, Katerina, Ernst Worrell, and Eric Masanet. 2011. “Energy Efficiency Improvement and Cost Saving Opportunities for the Concrete Industry: An ENERGY STAR® Guide for Energy and Plant Managers.” Lawrence Berkeley National Laboratory, LBNL-5342E. https://www.scribd.com/doc/160705792/Concrete-Industry.

Kingdom of Saudi Arabia. *Fiscal Balance Program 2019 Update*. Riyadh. https://www.mof.gov.sa/en/budget/2019/Documents/Fiscal%20Balance%20Program.pdf.

Koplow, Doug. 2009. “Measuring Energy Subsidies Using the Price-Gap Approach: What Does It Leave Out.” IISD, Winnipeg, Canada. https://www.iisd.org/publications/report/measuring-energy-subsidies-using-price-gap-approach-what-does-it-leave-out.

Lecomte, Thierry, Jose Felix Ferreria de La Fuente, Frederik Neuwahl, Michele Canova, Antoine Pinasseau, Ivan Jankov, Thomas Brinkmann, Serge Roudier, and Luis Delgado Sancho. 2017. *Best Available Techniques (BAT) Reference Document for Large Combustion Plants*. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control). No. JRC107769. Joint Research Centre (JRC) Science for Policy Report. https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/JRC_107769_LCPBref_2017.pdf.

Martínez-González, G. M., and H. Jiménez-Islas. 2014. “Experimental Study of the Firing of Red Clay Bricks Using Liquefied Petroleum Gas.” *Journal of Scientific & Industrial Research* 73 (October): 661–666. https://nopr.niscpr.res.in/bitstream/123456789/29451/1/JSIR%2073%2810%29%20661-666.pdf.

Matar, Walid, and Murad Anwer. 2017. “Jointly Reforming the Prices of Industrial Fuels and Residential Electricity in Saudi Arabia.” *Energy Policy* 109 (October): 747–756. https://doi.org/10.1016/j.enpol.2017.07.060.

Matar, Walid, and Amro M. Elshurafa. 2017. “Striking a Balance Between Profit and Carbon Dioxide Emissions in the Saudi Cement Industry.” *International Journal of Greenhouse Gas Control* 61 (June): 111–123. https://doi.org/10.1016/j.ijggc.2017.03.031.

Matar, Walid, and Doaa K. Filali. 2022. “Alternative Fuels for Saudi Cement Manufacturing with Time-Varying Carbon Pricing.” Riyadh: King Abdullah Petroleum Studies and Research Center (KAPSARC). https://www.doi.org/10.30573/KS--2022-DP12.

Matar, Walid, Noura Y. Mansouri, and Evar Umeozor. 2024. “Energy Policy Pathways to Inform Climate Policy in Saudi Arabia.” *Journal of Cleaner Production* 445 (March): 141190. https://doi.org/10.1016/j.jclepro.2024.141190.

Matar, Walid, Frederic Murphy, Axel Pierru, and Bertrand Rioux. 2015. “Lowering Saudi Arabia’s Fuel Consumption and Energy System Costs Without Increasing End Consumer Prices.” *Energy Economics* 49 (May): 558–569. https://doi.org/10.1016/j.eneco.2015.03.019.

Mezquita, Ana, Juan Boix, Eliseo Monfort, and Gustavo Mallol. 2014. “Energy Saving in Ceramic Tile Kilns: Cooling Gas Heat Recovery.” *Applied Thermal Engineering* 65, Issues 1–2 (April): 102–110. https://doi.org/10.1016/j.applthermaleng.2014.01.002.

Ministry of Finance. 2024. *Budget Statement: FY 2025. 2025 Saudi Arabia – Budget*. https://www.mof.gov.sa/en/budget/2025/Documents/Bud-E%202025-251124-V8-Fin.pdf.

Monteiro, Helena, Pedro L. Cruz, and Bruna Moura. 2022. “Integrated Environmental and Economic Life Cycle Assessment of Improvement Strategies for a Ceramic Industry.” *Journal of Cleaner Production* 345 (April): 131173. https://doi.org/10.1016/j.jclepro.2022.131173.

Oliveira, Miguel Castro, Muriel Iten, and Henrique A. Matos. 2021. “Assessment of Energy Efficiency Improvement in Ceramic Industry Through Waste Heat Recovery Modelling.” Computer Aided Chemical Engineering 50: 1653–1658. https://doi.org/10.1016/B978-0-323-88506-5.50256-4.

Rahman, Shayemur, and Shahed Mohammad Kazi. 2019. “Assessment of Brick Kiln Technologies of Bangladesh.” A Thesis Submitted to the Institute of Appropriate Technology (IAT), Bangladesh University of Engineering and Technology (BUET) in Partial Fulfillment of the Requirements for the Degree of Master of Science in Management of Technology (MoT). March. http://lib.buet.ac.bd:8080/xmlui/handle/123456789/5418.

Riyad Capital. 2024. “Saudi Arabian Equities: Energy Price Update.” January 7. https://www.riyadcapital.com/documents/671358/3985789/Energy%20Price%20Update_Jan%202024.pdf/7269cf4b-f79f-640c-c643-ebe66a68a901.

Saudi Aramco. 2024. *Saudi Aramco Annual Report 2023*. https://www.aramco.com/-/media/publications/corporate-reports/annual-reports/saudi-aramco-ara-2023-english.pdf.

Saudi Electricity Company (SEC). 2019. “Saudi Electricity Company (‘SEC’): Financial Results for Fiscal Year Ended 31 December 2018.” https://www.se.com.sa/-/media/sec/Investors/Earning-Reports/FY2018-Earnings_Release_final.ashx.

Scalet, Bianca Maria, Marcos Garcia Muñoz, Aivi Querol Sissa, Serge Roudier, Luis Delgado Sancho. 2013. *Best Available Techniques (BAT) Reference Document for the Manufacture of Glass*. Industrial Emissions Directive 2010/75/EU: Integrated Pollution Prevention and Control. Joint Research Center (JRC). https://data.europa.eu/doi/10.2791/70161.

Schmidt, Charles W. 2013. “Modernizing Artisanal Brick Kilns: A Global Need.” *Environmental Health Perspectives* 121 (8): a242-a249. https://doi.org/10.1289/ehp.121-a242.

Schorcht, Frauke, Ioanna Kourti, Bianca Maria Scalet, Serge Roudier, and L. Delgado Sancho. 2013. “Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide.” Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control). European Commission Joint Research Centre Institute for Prospective Technological Studies. https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/CLM_Published_def_0.pdf.

Shakir, Alaa A., and Ali Ahmed Mohammed. 2013. “Manufacturing of Bricks in the Past, in the Present and in the Future: A State of the Art Review.” *International Journal of Advances in Applied Sciences (IJAAS)* 2 (3): 145–156. 10.11591/ijaas.v2i3.1751.

Shakti Sustainable Energy Foundation. 2012. *Brick Kilns Performance Assessment: A Roadmap for Cleaner Brick Production in India*. April. https://cdn.catf.us/wp-content/uploads/2019/10/21093607/Brick_Kilns_Performance_Assessment.pdf?_gl=1*16d43ru*_ga*MTI5MDI4NjI5NS4xNzM2NDA2MzE0*_ga_88025VJ2M0*MTczNjQwNjMxMy4xLjAuMTczNjQwNjMxNS4wLjAuODE0NTMyNzUx*_fplc*dXRCZyUyRlNBS3R1em50VVdiVmFLNHNQclFmVGt0UkZRTEVWUnhRc05wY1JSeEdIMEc2OGU3OWszYkdMTjBWb0J1a0RCWUxpdEZQMDBLeVQxVXB5QXhiTFpIRTV1WXBPNnk2MDIsV3RNMGN0b1ZjWHU4SmhUTndnTm52MHRRZ3clM0QlM0Q.*_gcl_au*MTkxNTQ5NDgzNS4xNzM2NDA2MzE1.

Shen, Bo, Lynn Price, and Hongyou Lu. 2012. "Energy Audit Practices in China: National and Local Experiences and Issues." *Energy Policy* 46 (July): 346–358. https://doi.org/10.1016/j.enpol.2012.03.069.

Shi, Caijun, Dehui Wang, Fuqiang He, and Meng Liu. 2012. "Weathering Properties of CO_2-Cured Concrete Blocks." *Resources, Conservation and Recycling* 65 (August): 11–17. https://doi.org/10.1016/j.resconrec.2012.04.005.

SIRC. 2023. "Targeted Liquid Displacement Program Regions Alterative Fuel Utilization Assessment." December.

Sissa, Aivi Querol, Luis Delgado Sancho, Serge Roudier, Bianca Maria Scalet, and Marcos Garcia Muñoz. 2013. Best Available Techniques (BAT) Reference Document for the Manufacture of Glass. European Commission, Institute for Prospective Technological Studies (Joint Research Centre). https://doi.org/10.2791/69502.

United Nations Framework Convention on Climate Change. 2024. *Kingdom of Saudi Arabia: The Second Biennial Update Report (BUR2)*. March.https://unfccc.int/sites/default/files/resource/Kingdom%20of%20Saudi%20Arabia%C2%A0Bur2.pdf.

Usón, A. A., A. M. López-Sabirón, G. Ferreira, and E. Llera-Sastresa. 2013. "Uses of Alternative Fuels and Raw Materials in the Cement Industry as Sustainable Waste Management Options." *Renewable and Sustainable Energy Reviews* 23 (July): 242–260. https://doi.org/10.1016/j.rser.2013.02.024.

Venta, Glaser & Associates. 1997. *Life Cycle Analysis of Gypsum Board and Associated Finishing Products*. The Athena Sustainable Materials Institute. March. https://calculatelca.com/wp-content/themes/athenasmisoftware/images/LCA%20Reports/Gypsum_Wallboard.pdf.

Worrell, Enrst, Christina Galitsky, Eric Masanet, and Wina Graus. 2008. "Energy Efficiency Improvement and Cost Saving Opportunities for the Glass Industry." Lawrence Berkeley National Laboratory, University of California. https://escholarship.org/uc/item/21n0z94m.

Worrell, Ernst, Katerina Kermeli, and Christina Galitsky. 2013. "Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making: An ENERGY STAR® Guide for Energy and Plant Managers." Lawrence Berkeley National Laboratory, University of California. https://escholarship.org/uc/item/8wm6q3v3.

Yüksek, İzzet, Saniye Karaman Öztaş, and Gürhan Tahtalı. 2020. "The Evaluation of Fired Clay Brick Production in Terms of Energy Efficiency: A Case Study in Turkey." *Energy Efficiency* 13 (October): 1473–1483. https://doi.org/10.1007/s12053-020-09896-y.

Zier, Michael, Peter Stenzel, Leander Kotzur, and Detlef Stolten. 2021. "A Review of Decarbonization Options for the Glass Industry." *Energy Conversion and Management: X* 10 (June): 100083. https://doi.org/10.1016/j.ecmx.2021.100083.

Zuberi, Jibran, Ali Hasanbeigi, and William R. Morrow. 2021. *Electrification of Boilers in U.S. Manufacturing*. Lawrence Berkeley National Laboratory, University of California. LBNL-2001436. https://static1.squarespace.com/static/5877e86f9de4bb8bce72105c/t/62fb89dfb827c92c3340eed9/1660652049933/Boiler+Electrification-final+Rev2.pdf.

Appendix – Tool Overview

Our tool measures the net change in the annual costs of alternative energy use and process options compared with current operations at domestic fuel prices. In this way, we do not consider the costs that are the same in all options and of which we have no knowledge. For instance, we do not consider the costs of raw materials or shares of scraps that would be required or unchanged in all scenarios. The objective of the tool is to balance the additional costs or savings between a company, other companies in the supply chain, and the government.

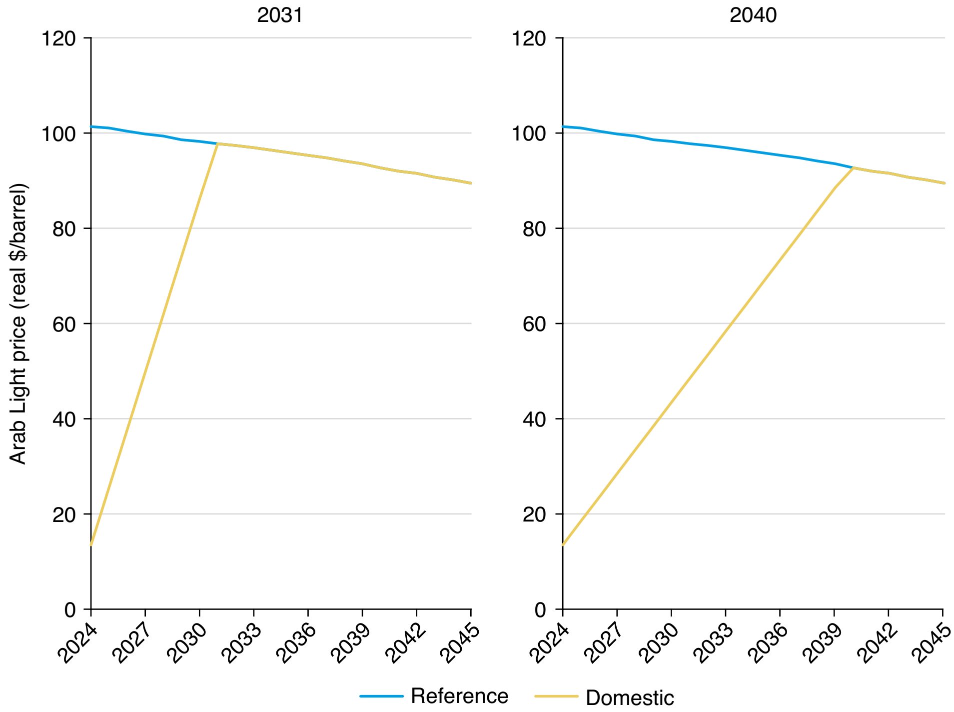
Fuel costs are distinguished by the company itself, the government, and other companies that are part of the fuels' supply chains. The costs for the company itself are the sum product of the fuels used and their prices. The cost to the government is primarily taken as an opportunity cost – in other words, the forgone revenues that are associated with maintaining energy subsidies. This cost is essentially the price gap between a reference price and the domestic price multiplied by the quantity of the fuel. In the scenarios that call for the government to support private companies in their investment, we add on those costs to the fuel costs. The costs of other companies include operational and investment costs to deliver fuel or electricity to the company.

A spreadsheet contains all the data on capital and operational costs, and energy use and prices. The tool allows the user to either input the domestic energy prices in 2024 or energy price reform. The energy price reform option allows the user to input any year between 2025 and 2050 that domestic prices reach reference prices.

Although Gasim and Matar (2023) show that the forgone revenues associated with Saudi oil use should be based on a reference price that is lower than the market price, we consider reference prices that are projected as market prices for simplicity. Reference price projections are based on Enerdata for crude oil and diesel prices, the KAPSARC Energy Model for marginal costs of other refined oil products (KAPSARC 2016), estimated average cost pricing for domestic natural gas, Nexant's World Gas Model for global LNG prices, and the U.S. Energy Information Administration (EIA 2024) for LPG, the Saudi Investment Recycling Company (SIRC 2023) for the cost of RDF, and cost estimations based on the Saudi Electricity Company (SEC 2019) for electricity.

For example, Figure A1 shows the domestic prices of Arab Light crude oil if the user inputs 2031 and 2040 as that reference-price year. The input equation estimates energy prices to rise linearly from 2024 to that end year. Domestic prices equal reference prices after that year. Of course, the user may enter custom energy prices.

Figure A1. Domestic and reference price relationship example for an end year of 2031 and 2040.



Source: Authors' calculations in the tool.

Location is one input in the tool that can have significant implications on some fuel options. The impact of location is mostly felt when estimating the costs for other companies, like those that supply energy. The incremental investment cost to deliver gaseous fuels is differentiated by location. In addition, the costs for transporting liquefied or liquid fuels are highly location dependent.

Investments made in natural gas infrastructure may be made to supply gas to firms that are analyzed. Pipelines may be built in large capacities that serve many customers. We are interested in the cost of the infrastructure that can be attributed to a single customer. For this, we convert the unit cost of pipelines in $ per unit length per unit diameter to $ per unit length per unit energy flow using the corresponding diameter size and volumetric flow rate of capacity for MGS-3.[2] MGS-3 is a new natural gas project being constructed in Saudi Arabia. Required investment in electricity distribution lines is also considered for other private firms. Investment costs are obtained from the IEA (2014).

Annual costs involve annualizing the capital costs of process units. This makes the capital and operational costs comparable when combined. Alternative process options that replace the existing process must also consider the residual value of the existing process. If some equipment is to be replaced, its remaining life may still hold value to the company. The residual value of the existing process is added to the change in company costs for the alternative options. The procedure entails inputting when the equipment was installed. Then, we scale the annualized capital costs of the existing process by how many years it has left in its design life. The residual value is highest if the equipment was recently installed and declines the longer it has been in service. If the existing units are past their design life or there is no information about the units' installation time, their residual value is 0.

New investment proposals by companies are examined in the same framework. The proposed process is considered as the "existing process." A year equal to the present year or later is input as the year of installation – only in this case, the full annualized capital cost of the proposed process is subtracted from that of alternative options.

We have a separate sheet for each sub-sector. Each sheet consists of sections for inputs, calculations, and outputs. The inputs are:

- Quantities of fuels used by the facility for process heat or electricity generation purposes annually in barrels of oil equivalent (boe annually).
- Quantity of electricity purchased from the grid annually in megawatt-hours (MWh annually).
- Process(es) currently installed in the facility.
- Production capacity by finished product in the facility in metric tons (tons annually).
- Actual production of finished product at the facility in metric tons (tons annually).
- Approximate location of the facility.
- Year of commencing operations, if known.

Finally, the top four options for each sector from three different perspectives are tabulated: the own-company costs, total private costs (own-company plus other companies), and combined government and own-company costs. The first two perspectives take a straightforward approach where the summed costs are ranked from lowest (best) to highest (worst). For ranking the options based on combined company and government costs, however, we adopt an approach that considers both the direction and the magnitude of the cost changes. We first stipulate that any alternative option that maximizes cost savings for both the company and the government equally is desired. It would therefore lie on an axis that is 45 degrees between the negative horizontal and negative vertical axes in the graphs embedded in the sectors' sheets. This axis is our reference, where a point that lies on it is given maximum value. The greater a point's direction deviates from the reference axis, the lower its value. By taking this value for direction and the distance of the point from the origin, we rank the options using the highest values of Equation A1, and the product in Equation A1 ranges from -1 to 1:

$$R = \left[\frac{2\left(\theta - \theta_{max}\right)}{-\theta_{max}} - 1 \right] \cdot \frac{\left(M - M_{min}\right)}{M_{max} - M_{min}} \qquad \text{(A1)}$$

where:

R = overall ranking of options between –1 and 1

θ = angle of point relative to the reference axis

M = magnitude of the point relative to the origin

About the Authors

Walid Matar

Walid is a Principal Fellow at KAPSARC working on energy systems models. Ongoing work includes the KAPSARC Energy Model and satellite projects, such as modeling residential electricity use and the distribution of refined products in Saudi Arabia. Walid holds a Ph.D. in economics from the University of Portsmouth, a Master of Science degree in mechanical engineering from North Carolina State University, and a Bachelor of Science degree in the same field from the University of South Carolina.

Sid Ahmed Hamdani

Sid Ahmed is a Principal Fellow in KAPSARC's Oil & Gas program, and has almost two decades of experience in the oil and gas industry. Before joining KAPSARC, he worked as an Energy Policy and Environment Analyst at the Gas Exporting Countries Forum. He has monitored energy policies and environmental developments worldwide and evaluated their impacts on energy prospects. He also worked at a major national oil company, delivering strategic analyses and insights, evaluating business opportunities and supporting the company's strategic planning process. Sid Ahmed's areas of expertise include gas market developments, energy modeling, assessing policy impacts, strategic analyses and business evaluations for oil and gas projects. Among his interests is assessing energy market developments and the role of hydrocarbons in the energy transition. He holds an Industrial Engineering degree and a Master's in Energy Economics. He also has an MBA in Energy and Sustainability.

Faris Aljamed

Faris is an Energy Consulting Associate at KAPSARC, with experience in assessing alternative fuels across industrial sectors, direct air capture of CO_2, and emission trading schemes. He holds a Master of Science in Electrical and Computer Engineering from KAUST and a Bachelor of Science in Electrical Engineering from Boston University. His work has focused on researching the production processes of various industrial sectors, evaluating alternative fuels for industrial applications, and identifying electricity key performance indicators relevant to Saudi Arabia's power sector. He has also contributed to evaluating renewable energy integration costs and analyzing policies to enhance cybersecurity in the energy sector.

About the Project

We developed the KAPSARC Energy Model (KEM) for Saudi Arabia to understand the dynamics of the country's energy system. It is a partial equilibrium model formulated as a mixed complementarity problem to capture the administered prices that permeate the local economy. KEM has been previously used to study the impacts of various industrial fuel pricing policies, improved residential energy efficiency on the energy economy, the feasibility of deploying power plant technologies in Saudi Arabia, natural gas storage, and a way to computationally analyze residential electricity prices. This analysis is a precursor to expanding the industrial sectors' representation in KEM.