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Modeling final energy demand and the impacts of energy price reform in Saudi Arabia

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ABSTRACT

We model energy demand across five end-use sectors and 15 energy products in Saudi Arabia, generating comprehensive price and income elasticity estimates. Using the Structural Time Series Model, we demonstrate that the trends underlying energy demand are generally stochastic, underscoring the importance of using such models for estimating unbiased elasticities. Our estimates reveal that energy demand in Saudi Arabia is price inelastic in all cases and income inelastic in most cases, with industrial natural gas and electricity being the only exceptions. Nevertheless, we find extensive variation in the elasticities across sectors and energy products, highlighting the importance of using sector- and product-specific elasticity values and not assuming they are similar in the same country. We then use our estimated elasticities to conduct a welfare analysis of the energy price reforms implemented in 2016 and 2018. Our analysis reveals that the 2016 reform delivered a total annual welfare gain of 11.6 billion 2010 United States Dollars (USD) in 2016. Following the 2018 reform, the annual welfare gain increased to 17.0 billion 2010 USD in 2018. We also estimate the cumulative carbon dioxide emissions avoided between 2016 and 2018 due to energy price reform at 164 million tonnes.

1. Introduction

The Kingdom of Saudi Arabia is a leading oil and natural gas producer and one of the largest energy consumers in the Middle East (BP, 2020). Between 1970 and 2018, Saudi primary energy consumption grew from 23 to 259 million tonnes of oil equivalent (Mtoe), while energy-related carbon dioxide (CO_2) emissions grew from 67 to 571 million tonnes (BP, 2020). Extensive economic development, rapid population growth, and low energy prices appear to have contributed to the tenfold increase in Saudi energy consumption and emissions over the past five decades. Between 1970 and 2018, real Saudi gross domestic product (GDP) increased from 129 to 700 billion 2010 United States Dollars (USD) (SAMA, 2020), while the population grew from 5.8 to 33.7 million (World Bank, 2020). During this period, domestic energy prices were regulated, which likely contributed to both high consumption and low levels of energy efficiency, particularly in the absence of energy efficiency regulations before 2010.

Not only do low energy prices lead to concerns over resource sustainability (Lahn and Stevens, 2011), but they have also strained the Saudi government's fiscal position, particularly following the fall in international oil prices towards the end of 2014. These concerns have prompted the government to reform energy prices (Fiscal Balance Program, 2016).

However, implementing energy price reform can be difficult, as there are many barriers, and research is needed to support policymakers in implementing such reforms (IMF, 2013). First, policymakers need an understanding of how consumers may respond to price changes. Price and income elasticities can provide policymakers with crucial insights into the demand response. However, while some price elasticity estimates exist for gasoline and residential electricity in Saudi Arabia (Aldubyan and Gasim, 2021), price elasticity estimates for many other critical energy products are strikingly missing. Second, policymakers need an understanding of the potential economic, fiscal, and environmental impacts of energy price reform, but few studies have quantified these impacts for Saudi Arabia (Atalla et al., 2018; Aldubyan and Gasim, 2021).

This paper has three objectives. First, it estimates price and income elasticities for all energy products in Saudi Arabia across all five end-use

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sectors: transport, residential, commercial and governmental, industrial, and non-energy use (i.e., feedstock). Estimation is performed using the Harvey (1990) Structural Time Series Model (STSM). Second, this paper explores the trends underlying energy demand for each energy product in each sector, demonstrating the important influence of exogenous factors such as energy efficiency, behavioural change, and urban sprawl on energy demand. Third, it uses the estimated elasticities to measure energy price reform's economic, environmental, and welfare impacts across all energy products and sectors. This paper is structured as follows. Section 2 provides a background on Saudi Arabia's energy demand, domestic energy pricing policy, and recent attempts to reform energy prices. Section 3 presents a literature review on energy demand modeling and the welfare impacts of energy price reform. Section 4 describes the methods and data used in this study. Section 5 presents and discusses the results, while Section 6 concludes.

2. Background

2.1. Saudi final energy demand

Final energy consumption in Saudi Arabia has increased from 30.7 Mtoe in 1986 to 148.0 Mtoe in 2018 (IEA, 2021), as shown in Fig. 1, which breaks down final consumption by sector and energy product. Consumption grew rapidly up to 2015, before decreasing between 2015 and 2018, a decline likely driven by the energy efficiency regulations launched in the 2010s, reduced government spending caused by the collapse in international oil prices in late 2014, and energy price reforms (Aldubyan and Gasim, 2021). In 2018, the industrial and transport sectors accounted for the largest shares of final energy consumption, around 33% and 31%, respectively. They were followed by the non-energy use (20%), residential (9%), and commercial and governmental (7%) sectors.[1]

Each end-use sector consumes a different combination of energy products (IEA, 2021). The Saudi industrial sector consumes natural gas, fuel oil, diesel, crude oil, and electricity to manufacture a wide range of goods, with petrochemicals, cement, and iron and steel manufacturing accounting for the lion's share of the sector's consumption (SEEC, 2021a). The Saudi transport sector consumes three fuels: gasoline, which is used in passenger cars; diesel, which is primarily used in trucks to move freight; and kerosene, which is used for domestic aviation. The non-energy use sector's consumption consists almost entirely of feedstocks such as natural gas (i.e., methane), ethane, liquefied petroleum gas (LPG), and naphtha, all of which are used by the petrochemical subsector. The petrochemical subsector uses methane to produce fertilizers, while it uses ethane, LPG, and naphtha to produce petrochemicals such as ethylene, propylene, butadiene, and benzene, which are then used to produce chemical, plastic, and rubber products (IHS Markit, 2021). The Saudi residential sector consumes mainly electricity, with small amounts of LPG for cooking, in addition to tiny amounts of kerosene, charcoal, and solid biofuels. In contrast to the other sectors, the commercial and governmental sector consumes only electricity.

2.2. Saudi energy pricing policy and price reform

The Saudi government has been regulating domestic energy prices for decades (WTO, 2005), but recent concerns over resource and fiscal sustainability have prompted two waves of energy price reform. The first wave of energy price reform was implemented on January 1, 2016, resulting in substantial increases in fuel, electricity, and water prices for industry and households. The second wave was subsequently implemented on January 1, 2018, focusing on a smaller subset of fuels. The 2018 wave was implemented alongside the introduction of a 5% value-added tax (VAT) on all goods and services. These initiatives were part of the Fiscal Balance Program (2016), suggesting that fiscal sustainability was a key reason why these reforms were launched (Saudi Vision 2030, 2016, 2023).[2] Table 1 shows domestic energy prices in 2015, after the 2016 reform, and after the 2018 reform. Most of the domestic energy prices in 2015 had been nominally fixed at those levels for at least a decade, as the Saudi government did not revise domestic energy prices frequently. The percentage changes in Table 1 highlight the considerable increases that have been implemented over the 2015–2018 period. Nonetheless, although the reforms in 2016 and 2018 were extensive, there remains further scope for reform, as demonstrated in Table 1, which also shows what domestic energy prices would have been in 2018 if they were fully reformed and set equal to reference prices.[3]

Although domestic energy prices in Saudi Arabia reached new levels in nominal terms following the reforms (e.g., in the case of gasoline, its price had never previously crossed the 1.0 Saudi Riyal (SR) per liter threshold prior to 2018), it is useful to see how they compare to past prices in real terms, given that some prices were fixed in nominal terms for almost a decade or longer. Fig. 2 illustrates the evolution of real energy prices between 2000 and 2018, demonstrating that, in most cases, reformed energy prices in 2018 were higher than prices in 2000 in real terms. However, for some fuels, such as diesel for transport, the real price in 2018 was slightly lower than the real price in 2000, despite its doubling in nominal terms during the recent reforms.

Since energy provides households with fundamental services such as lighting, heating, and cooling, energy price reform can have detrimental impacts on the welfare of households, affecting their living standards and quality of life. To mitigate the negative impacts of price reform and the VAT on lower- and middle-income households, the Saudi government launched the Citizen's Account in 2018, a compensation scheme that compensates households for higher energy prices through monthly cash transfers (Arab News, 2017; Fiscal Balance Program, 2018).

Since 2018, the Saudi government has not implemented further significant energy price increases. However, there have been changes to its gasoline pricing policy (Gasim and Aldubyan, 2020). In 2019, Saudi Arabia linked its domestic gasoline price to global prices, adjusting the domestic price every quarter. In 2020, it tightened this link as it started adjusting domestic gasoline prices every month. However, in 2021, the Saudi government placed a cap on domestic gasoline prices, as crude oil prices reached multi-year highs (Arab News, 2021a). Prices of other energy products have remained at their 2018 levels, albeit slightly higher following the VAT increase from 5% to 15% in the middle of 2020 (Alarabiya, 2020). More recently, the Saudi government has implemented minor gradual increases in the price of diesel for the transport sector (Saudi Aramco, 2023), and has also announced that fuel and feedstock prices would be adjusted from the fourth quarter of 2023 onwards (Arab News, 2022), indicating a potential third wave of energy price reform.

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[1] We also refer to the non-energy use sector as the feedstock sector.

[2] The original Fiscal Balance Program (2016) is part of SaudiSaudi Vision 2030, 2016, a plan launched in 2016 that targets social and economic reform. Saudi Vision 2030 incorporates around a dozen "Vision Realization Programs", including the Fiscal Balance Program (2016), which aims to achieve fiscal sustainability. The Fiscal Balance Program is made up of several initiatives, among the most important of which are energy price reform and the introduction of the VAT. The Fiscal Balance Program has recently been renamed as the Fiscal Sustainability Program Saudi Vision 2030 (2023).

[3] We quantify the existence of further scope for reform by comparing domestic energy prices to reference prices using the price-gap method (Koplow, 2009). For traded energy products such as gasoline, international market prices are used as reference prices. For (largely) non-traded energy products such as electricity, domestic production costs are used as reference prices.

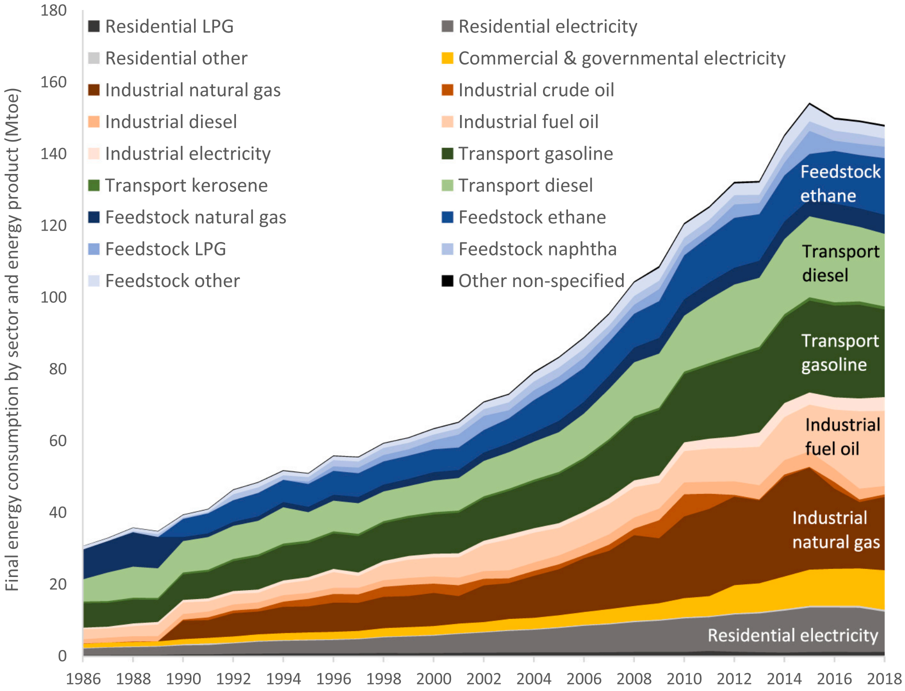

Fig. 1. Breakdown of final energy consumption in Saudi Arabia. Source: IEA (2021).

3. Literature review

3.1. Econometric modeling of energy demand

There exists an extensive array of econometric studies on energy demand, and given the large range of estimated values for its elasticities, several attempts have been made to summarize them into a single value through meta-analysis (Dahl, 1986; Dahl and Sterner, 1991; Epsey, 1998; Epsey and Epsey, 2004; Brons et al., 2008; Havranek et al., 2012; Labandeira et al., 2017). Most of these meta-analyses have focused on gasoline or electricity demand. However, Labandeira et al. (2017) extended their meta-analysis to cover most major energy products, estimating the average energy price elasticity in the empirical literature to be around −0.21 in the short run and −0.59 in the long run.

In the case of Saudi Arabia, while published elasticity estimates exist for some energy products (such as gasoline and residential electricity), elasticity estimates for other energy products are scarce. Furthermore, many of these published estimates are likely to be outdated, having been obtained using data only up to the 1990s. Table 2 summarizes the results from published studies that found statistically significant price or income elasticities for Saudi Arabia. It shows that gasoline demand in Saudi Arabia is generally both price and income inelastic. Gasoline demand models have been estimated for a range of time horizons using various methods, from simple partial adjustment models estimated by ordinary least squares to cointegration-based error-correction models to STSMs. Electricity demand has also been analyzed with some depth, but existing studies are scattered in terms of sectoral focus, with recent studies focusing on residential electricity demand, which is found to be both price and income inelastic. For all other energy products in Saudi Arabia, there are still many gaps in terms of empirical evidence, so it is difficult to draw conclusions regarding demand responses. Therefore, we aim in this paper to fill these gaps by providing a comprehensive estimation of price and income elasticities for all energy products across all five end-use sectors in Saudi Arabia.

3.2. Welfare analysis of energy price reform

Setting domestic energy prices below private costs leads to ‘waste’ that is made up of two components: deadweight loss and external costs. Deadweight loss occurs because low domestic energy prices encourage consumers to purchase energy even though their willingness-to-pay is below private cost (Davis, 2017). Low domestic energy prices also produce excessive external costs, such as air pollution and CO_2 emissions. In theory, reforming energy prices (i.e., raising energy prices) leads to a net welfare gain by reducing deadweight loss and external costs. The net welfare gain of reform is thus calculated as the benefits from higher revenues (for producers and the government) minus the consumer surplus losses plus the benefits from lower external costs (Coady et al., 2015; Davis, 2017; Coady et al., 2019). This calculation reflects a partial equilibrium welfare analysis of energy price reform.

Most studies on the welfare impacts of energy price reform have a global focus. In the absence of detailed price elasticity estimates for all countries and energy products, these studies apply a single elasticity value across countries to conduct the welfare calculations. Coady et al. (2015) and Coady et al. (2018) estimated the global welfare gain from eliminating post-tax energy subsidies to be 1.4 trillion USD in 2013, roughly 2% of global GDP in that year. Coady et al. (2018) broke down this global welfare gain by region, showing that the Middle East, North Africa, Afghanistan, and Pakistan region, which includes Saudi Arabia, accounts for almost 200 billion USD of the total global welfare gain. These studies highlight the potentially enormous welfare benefits from energy price reform, although they make strong assumptions regarding the size of the price elasticities in their calculations.

Some studies on the welfare impacts of energy price reform have been country-specific, and a few have focused on Saudi Arabia. Atalla et al. (2018) used their estimated gasoline demand model to measure the welfare changes from the 2016 wave of gasoline price reform in Saudi Arabia. They measured the welfare gain to be up to 1.7 billion 2010 USD. Aldubyan and Gasim (2021) quantified the welfare changes that resulted from the 2018 wave of price reform (excluding the impact of the 2016 wave) to be 2.3 billion USD for gasoline and 1.0 billion USD for residential electricity.

However, there are no studies that estimate the welfare impacts of energy price reform in Saudi Arabia for energy products other than gasoline and residential electricity. Additionally, no study yet looks at the combined economy-wide welfare changes across all energy

Table 1

Nominal energy prices in Saudi Arabia between 2015 and 2018. The last column shows how high prices would have been if they were fully reformed in 2018. All 2018 prices include the then newly introduced 5% VAT. Sources: Aleqt (2015), Alriyadh (2015), Alyousef and Stevens (2011), Akhbaar24 (2015), CEIC (2021), ECRA (2013, 2019), EIA (2021a, 2021b), Gasim and Matar (2023), Matar et al. (2015), Matar and Anwer (2017), SAMA (2020), SPA (2017), and WTO (2005). Notes: [a] Residential and commercial electricity prices vary by consumption segment. [b] The reference price for both grades of gasoline in Saudi Arabia is set to the spot price for 'conventional' gasoline in the US, which may have a different octane number. Abbreviations: SR = Saudi Riyal; USD = United States Dollar; L = Liter; LPG = Liquified Petroleum Gas; bbl = Barrel; mmBtu = Million British Thermal Units; VAT = Value Added Tax; kWh = Kilowatt-Hour; RON = Research Octane Number.

End-use sector: Energy product	Units	Prices before 1st wave of reform (2015)	Prices after 1st wave of reform (2016–2017)	1st wave % change	Prices after 2nd wave of reform (2018)	2nd wave % change	Fully reformed prices for comparison (2018)
Transport:							
91 RON Gasoline	SR/L	0.45	0.75	67%	1.37	83%	2.00[b]
95 RON Gasoline	SR/L	0.60	0.90	50%	2.04	127%	2.00[b]
Diesel	SR/L	0.25	0.45	80%	0.47	5%	2.12
Kerosene	SR/L	0.44	0.61	39%	0.64	5%	2.10
Residential[a]:							
Electricity: 0–2000 kWh	SR/kWh	0.05	0.05	0%	0.19	278%	0.31
Electricity: 2001–4000 kWh	SR/kWh	0.10	0.10	0%	0.19	89%	0.31
Electricity: 4001–6000 kWh	SR/kWh	0.12	0.20	67%	0.19	−6%	0.31
Electricity: 6001+ kWh	SR/kWh	0.15 to 0.26	0.30	N/A	0.32	5%	0.31
LPG	SR/L	0.72	0.72	0%	0.75	5%	0.91
Commercial & Governmental[a]:							
Electricity: commercial	SR/kWh	0.12 to 0.26	0.16 to 0.30	N/A	0.21 to 0.32	N/A	0.31
Electricity: governmental	SR/kWh	0.26	0.32	23%	0.34	5%	0.31
Industry & Non-Energy Use:							
Electricity	SR/kWh	0.14	0.18	29%	0.19	5%	0.31
Natural gas	USD/mmBtu	0.75	1.25	67%	1.31	5%	4.20
Ethane	USD/mmBtu	0.75	1.75	133%	1.84	5%	4.73
Arab light crude oil	USD/bbl	4.24	6.35	50%	6.67	5%	74.12
Arab heavy crude oil	USD/bbl	2.67	4.40	65%	4.62	5%	71.97
Diesel	USD/bbl	9.12	14.00	54%	16.03	14%	89.86
Heavy fuel oil	USD/bbl	2.08	3.80	83%	3.99	5%	64.52
Propane, butane, naphtha	% of reference price	72% of naphtha's cost + insurance + freight price in Japan	80% of each fuel's Ras Tanura export price to Japan	N/A	80% of each fuel's Ras Tanura export price to Japan +5% VAT	N/A	100% of each fuel's export price +5% VAT

products. One possible reason behind this gap in the literature is the lack of price elasticity estimates for all energy products in Saudi Arabia. These price elasticities are a necessary input for conducting a welfare analysis that avoids strong assumptions about these fundamental parameters. In this paper, we fill this gap by utilizing our estimated elasticities to conduct a comprehensive welfare analysis of the consequences of energy price reform across all energy products and end-use sectors in Saudi Arabia. Moreover, we quantify the welfare impacts of further potential energy price reforms that might be enacted in the future.

The published empirical studies on energy price reform agree on its positive welfare impacts, in line with economic theory, but it is also useful to explore how these welfare gains may be affected by potentially large general equilibrium effects. General equilibrium models can extend the analysis to incorporate these wider economic effects. However, general equilibrium models also require massive amounts of data, and the welfare results can be sensitive to a much wider range of parameters. In a review of both partial and general equilibrium empirical studies of energy price reform, Ellis (2010) found that the general equilibrium models "reached somewhat similar conclusions with regard to the economic, environmental and social impacts of fossil-fuel subsidy reform." For example, all six of the multi-region multi-fuel general equilibrium studies reviewed by Ellis (2010) found "overall increases in real income or GDP". Burniaux and Chateau (2014) used a global general equilibrium model and showed that if "each non-OECD country were to remove its fossil-fuel subsidies unilaterally, it would generally record welfare gains, in line with what is suggested by the theory." These welfare gains stem from energy subsidy reform leading to a more efficient allocation of resources across each country's economic sectors. However, in the case of multilateral energy price reform, Burniaux and Chateau (2014) found that oil-exporting countries' welfare gains could decline because of multilateral energy price reform reducing international oil prices. Nevertheless, Burniaux and Chateau (2014) showed that even in this scenario, oil-exporting countries as a whole "do not incur any real income loss as the GDP loss resulting from reduced oil extraction is compensated by the relatively large welfare gains from the subsidy removal."

Looking beyond these general equilibrium studies, there are other factors that could influence the welfare outcome of energy price reform. For example, consumers may have certain expectations regarding the level of energy prices, and increases in those prices could lead to protests, social unrest, and political instability. Natalini et al. (2020) explored how energy price reform, although welfare-enhancing in economic theory, can lead to social unrest, thereby producing negative welfare outcomes. They found that higher international oil prices were likely to increase 'fuel riots', and that wealthier countries were less likely to suffer from fuel riots following energy price reform. Therefore, attempts by countries to reform energy prices should ideally be accompanied by mitigation measures, such as a compensation scheme that minimizes the negative impacts on lower-income households and reduces the likelihood of social unrest. This remains an area that requires further research to better understand the factors that can cause energy price reform to fail and produce negative

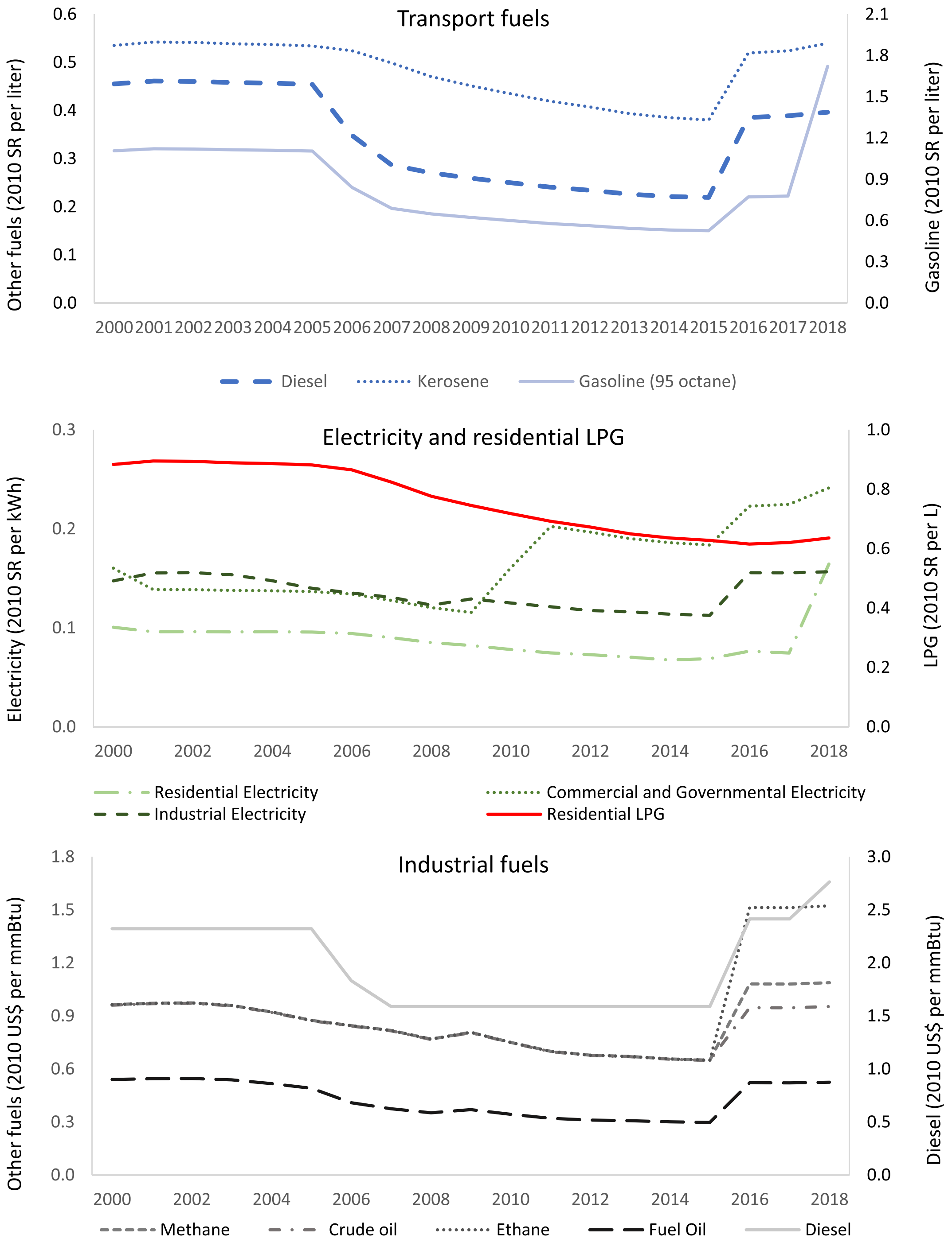

Fig. 2. Real energy prices in Saudi Arabia between 2000 and 2018 (electricity prices averaged). Abbreviations: SR = Saudi Riyal; US$ = United States Dollar; mmBtu = Million British Thermal Units; L = Liter; kWh = Kilowatt-Hour.

Table 2

Price and income elasticities from the literature from studies that modelled energy demand in Saudi Arabia using econometric methods. Notes: [n] Estimated coefficient not statistically significant. Abbreviations: DOLS = Dynamic Ordinary Least Squares; ECM = Error-Correction Model; LPG = Liquified Petroleum Gas; LR = Long Run; OLS = Ordinary Least Squares; PAM = Partial Adjustment Model; N/A = Not Available; SR = Short Run; STSM = Structural Time Series Model; TVC = Time-Varying Coefficient.

Study	Energy Product	Estimation Period	Estimation Method	Price Elasticities		Income Elasticities		Notes
				SR	LR	SR	LR	
Al-Sahlawi (1988)	Gasoline	1970–1985	OLS/PAM	−0.08	−0.67	0.11	0.92	Given the end of the estimation period, the estimated coefficients may not reflect current demand responses.
Al-Sahlawi (1990)	Total electricity	1970–1985	OLS/PAM	N/A	N/A	0.37	1.21	May not reflect current demand responses. No price variable included.
Al-Faris (1992)	Gasoline	1970–1990	OLS/PAM	−0.08	−0.30	0.02	0.07	May not reflect current demand responses.
Al-Faris (1997)	Gasoline	1970–1991	OLS/PAM	−0.09	−0.32	0.03	0.11	Monetary variables expressed in nominal rather than real terms. No trend included. May not reflect current demand responses.
	LPG	1970–1991	OLS/PAM	−0.22	−0.85	0.12	0.46	
	Jet fuel	1970–1991	OLS/PAM	−0.20	−0.43	0.26	0.57	
	Diesel	1970–1991	OLS/PAM	−0.37	−2.47	0.18	1.20	
	Fuel oil	1970–1991	OLS/PAM	−0.26	−0.68	0.09	0.24	
Al-Sahlawi (1997)	Gasoline	1971–1995	OLS/PAM	−0.16	−0.80	0.30	1.50	No trend included. May not reflect current demand responses.
	Diesel	1971–1995	OLS/PAM	−0.09	−0.26	0.29	0.83	
	Jet fuel	1971–1995	OLS/PAM	−0.51	−1.00	0.45	0.88	
	Total	1971–1995	OLS/PAM	−0.27	−3.00	0.18	2.00	
Al-Sahlawi (1999)	Average electricity	1975–1996	OLS/PAM	−0.06	−0.46	0.21	1.62	One of the few studies that includes a deterministic linear time trend. May not reflect current demand responses.
	Residential electricity	1975–1996	OLS/PAM	−0.10	−0.50	0.13	0.65	
	Industrial electricity	1975–1996	OLS/PAM	N/A	N/A	0.08	0.67	
Chakravorty et al. (2000)	Gasoline	1972–1992	OLS/PAM	−0.08[n]	−0.52[n]	0.10[n]	0.66[n]	No trend included. Many of the coefficients with unexpected signs or not statistically significant. May not reflect current demand responses.
	LPG	1972–1992	OLS/PAM	−0.24	−0.55	−0.44[n]	−1.01[n]	
	Jet fuel	1972–1992	OLS/PAM	0.36	0.71	0.37	0.74	
	Diesel	1972–1992	OLS/PAM	−0.39	−2.63	0.01[n]	0.06[n]	
	Fuel oil	1972–1992	OLS/PAM	−0.12[n]	−0.35[n]	0.50[n]	1.48[n]	
Al-Faris (2002)	Total electricity	1970–1997	Cointegration ECM	−0.04	−1.24	0.05	1.65	One of the few studies to include a cross-price variable (the price of LPG). May not reflect current demand responses.
Al Yousef (2013)	Gasoline	1980–2007	DOLS cointegration	N/A	−0.28	N/A	0.55	Short-run elasticity estimates were not presented. Price coefficient for diesel was not statistically significant. May not reflect current demand responses.
	Diesel	1980–2007	DOLS cointegration	N/A	0.13[n]	N/A	0.35	
	Kerosene	1980–2007	DOLS cointegration	N/A	−0.96	N/A	1.54	
	Total	1980–2007	DOLS cointegration	N/A	N/A	N/A	0.58	
Atalla and Hunt (2016)	Residential electricity	1985–2012	STSM	−0.16	−0.16	N/A	0.48	The final model for Saudi Arabia does not pass serial correlation test.
Atalla et al. (2018)	Gasoline	1981–2015	STSM	−0.10	−0.15	N/A	0.15	Their results using real GDP per capita as the income variable are presented here.
Mikayilov et al. (2019)	Gasoline	1980–2017	TVC	−0.13	−0.05 to −0.31	N/A	smaller than 0.15	Elasticities grew larger towards the end of the period, during which price reforms were implemented.
Alarenan et al. (2020)	Industrial total energy	1986–2016	STSM	−0.18	−0.34	0.60	0.60	Estimation period incorporates only one wave of price reform.
Mikayilov et al. (2020a)	Regional total electricity	1990–2016	Cointegration techniques	−0.01 to −0.27	−0.06 to −0.63	0.05 to 0.47	0.10 to 0.93	Models estimated for four regions of KSA.
Mikayilov et al. (2020b)	Regional residential electricity	1990–2018	STSM	−0.10 to -0.15	−0.20 to -0.46	0.14 to 0.43	0.27 to 1.02	Models estimated for four regions of KSA.
Aldubyan and Gasim (2021)	Gasoline	1981–2018	STSM	−0.09	−0.13	0.10	0.15	Estimation period incorporates both waves of price reform.
	Residential electricity	1985–2018	STSM	−0.09	−0.09	0.22	0.22	

welfare outcomes, and the factors that can contribute to successful reforms that unlock welfare gains for the economy.

4. Methods and data

4.1. Econometric modeling of energy demand

In many energy demand equations that attempt to estimate price and income elasticities, deterministic trends are added to capture the impact of exogenous factors such as energy efficiency or technical progress. Hunt et al. (2003a) demonstrated how the exclusion of simple linear trends can bias the energy price elasticity upwards (over-estimate) or downwards (under-estimate), depending on the direction of the trend. Hunt et al. (2003b) went on to argue that elasticities could still be biased if deterministic trends do not adequately capture the shape of the true trend, which is likely to be non-linear. Hunt et al. (2003b) estimated these biases for energy demand equations for the UK whole economy, residential, manufacturing, and transportation sectors. Hunt et al. (2003a, 2003b) concluded that the use of stochastic trends is best for estimating unbiased price and income elasticities.[4] Agnolucci (2010) supported their recommendation after comparing several econometric methods, adding that: “as STSMs have not been applied very often in the literature, future studies would benefit from implementing these models.” We therefore employ the STSM with the goal of estimating unbiased price and income elasticities, which are essential inputs for analyzing the economic, environmental, and welfare impacts of energy price reform.

The STSM, also known as the unobserved components model, is a state space model that allows users to model a dependent variable as the sum of components, such as a stochastic trend and an irregular. It also allows users to include explanatory variables and lagged dependent variables. Using the STSM, we model the demand for each energy product, or aggregate sectoral energy demand, as a function of the energy price, income/economic activity, and the stochastic trend, which for energy demand models is generally referred to as the underlying energy demand trend (UEDT). In some cases, additional explanatory variables are added to the models. For building electricity demand models, a cooling degree days (CDDs) variable is added, while a structural variable is added to the industrial sector models to capture the effect of changes in the energy intensity of manufacturing.[5]

We use the general-to-specific approach to obtain final energy demand models, starting from a general unrestricted model (GUM), given by Eq. (1). Starting from the GUM, we test down by dropping insignificant right-hand side variables and adding significant interventions (i.e., dummy variables). Interventions are added based on an analysis of the time series data, residual diagnostic testing, and visual inspection of the residuals. We run this general-to-specific testing down process while monitoring an array of summary statistics and diagnostic tests, until a final parsimonious model is found that passes all the tests. When multiple final models are found that pass the tests, the information criteria and prediction error variance are used to select the ‘best’ model.

The monitored tests and statistics during the general-to-specific testing down procedure include the coefficient of determination, the coefficient of determination based on differences, the prediction error variance, and the Akaike information criterion. The diagnostic tests include the heteroscedasticity test, the normality tests for the residuals and auxiliary residuals, and the residual autocorrelation coefficients at multiple lags. The residual diagnostic tests also include the Durbin-Watson statistic, which is relevant for models without a lagged dependent variable, and the Box-Ljung statistic, which is relevant for all models. The diagnostic tests also include the predictive failure test for the last eight years of the estimation period, which checks for model stability and forecasting ability. We set 10% as the maximum significance level for rejecting the null hypothesis for interventions, diagnostic tests, and estimated coefficients.

Eq. (1) shows the GUM based on the autoregressive distributed lag specification[6]:

$$e_t^{\,j} = \alpha_1^{\,j} e_{t-1} + \alpha_2^{\,j} e_{t-2} + \beta_0^{\,j} p_t + \beta_1^{\,j} p_{t-1} + \beta_2^{\,j} p_{t-2} + \gamma_0^{\,j} y_t + \gamma_1^{\,j} y_{t-1} + \gamma_2^{\,j} y_{t-2} + \delta_0^{\,j} z_t + \delta_1^{\,j} z_{t-1} + \delta_2^{\,j} z_{t-2} + UEDT_t^{\,j} + \varepsilon_t^{\,j} \tag{1}$$

where variables e_t, p_t, and y_t denote the natural logarithms of energy demand, real energy prices, and real income or economic activity, respectively. ε_t is the irregular component or random error term that is normally distributed, with variance σ_ε^2. z_t denotes an additional sector-specific variable (i.e., other than price and income). The subscript t denotes the year, while the superscript j denotes a specific energy product in a specific sector. Additional sector-specific variables include CDDs, which capture the impact of warm weather on cooling requirements in buildings, and the structural factor, which captures the energy intensity (or structure) of manufacturing in Saudi Arabia. The structural factor is measured as the ratio of energy-intensive manufacturing exports to total manufacturing exports. Table 3 lists all the independent variables in the GUM for each energy product.[7] The coefficients β_0 and γ_0 in Eq. (1) are respectively the short-run price and income elasticities. The long-run price (Β) and income (Γ) elasticities are respectively calculated as $\mathrm{B} = \frac{\beta_0+\beta_1+\beta_2}{1-\alpha_1-\alpha_2}$ and $\Gamma = \frac{\gamma_0+\gamma_1+\gamma_2}{1-\alpha_1-\alpha_2}$, and the long-run coefficient for the variable z_t is also calculated in the same manner.

The stochastic trend of the STSM consists of a stochastic level μ_t and a stochastic slope ρ_t, which are modelled as follows (Harvey and Shephard, 1993):

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

$$\rho_t = \rho_{t-1} + \xi_t; \qquad \xi_t \sim NID\left(0, \sigma_\xi^2\right) \tag{3}$$

where η_t and ξ_t are zero-mean random error terms, assumed to be mutually uncorrelated, with variances denoted by σ_η^2 and σ_ξ^2, respectively. If both variances are found to be zero, the stochastic trend collapses into a deterministic linear trend.

As noted by Dilaver and Hunt (2011), the added interventions are incorporated into and affect the shape of the UEDT. The irregular intervention has a transient effect on the trend, while the level and slope interventions have permanent effects on the level and slope components of the trend, respectively. Interventions are generally added to help maintain the normality of the auxiliary residuals, as they can explain data breaks and major events, trends, or structural changes that influenced energy demand during the estimation period (Harvey and Koopman, 1992). When no interventions are added, the UEDT is given by μ_t, as shown in Eq. (2). However, when interventions are added, the UEDT is given by the following equation:

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[4] Although there are studies that compared bias between the STSM and other methods, there appear to be no studies that compared the STSM’s efficiency relative to other methods. This appears to be a gap that requires further research.

[5] For many energy products, there were no clear substitutes to include in their energy demand equations. For example, all passenger cars in Saudi Arabia run on gasoline only, while diesel is mainly used in heavy-duty vehicles such as trucks, so both fuels are not substitutes. There may be some substitutability between certain industrial fuels and feedstocks, but we found no evidence of this in our regressions, so variables for substitutes were dropped from the energy demand equations.

[6] Similar to Atalla and Hunt (2016), Atalla et al. (2018), and Aldubyan and Gasim (2021), we use two lags in the GUM given the roughly three-decade time horizon for most energy demand models.

[7] For the feedstock models, different economic activity variables were tested, and the variable that produced the best fit was used to obtain the final models.

Table 3
Independent variables in the general unrestricted model for each energy product in each end-use sector. For certain energy products, the required data was not available, so estimation was not possible.

End-use sector: Energy product	Price variable (p_t)	Income or economic activity variable (y_t)	Additional variable (z_t)	Estimation period
Transport:				
Gasoline	Real gasoline price	Real GDP		1986–2018
Diesel	Real diesel for transport price	Real GDP		1986–2018
Kerosene	Real kerosene price	Real GDP		1986–2018
Residential:				
LPG	Real LPG price	Real GDP		1986–2018
Electricity	Real residential electricity price	Real GDP	CDD	1986–2018
Other				1986–2018
Total	Real weighted average price	Real GDP	CDD	1986–2018
Commercial & governmental:				
Electricity	Real weighted average price	Real GDP	CDD	1986–2018
Industrial:				
Natural gas	Real methane price	Real MVA	Structural factor	1992–2018
Fuel oil	Real fuel oil price	Real MVA	Structural factor	1992–2018
Crude oil	Real crude oil price	Real MVA	Structural factor	1992–2018
Diesel	Real diesel for industry price	Real MVA	Structural factor	1992–2018
Electricity	Real industrial electricity price	Real MVA	Structural factor	1992–2018
Other				
Total	Real weighted average price	Real MVA	Structural factor	1986–2018
Non-energy use:				
Methane	Real methane price	SABIC fertilizer production		1990–2018
Ethane	Real ethane price	Real chemical & plastic exports		1992–2018
LPG and naphtha	Real weighted average price	Real chemical & plastic exports		1993–2018
Other				
Total	Real weighted average price	Real MVA		1994–2018

Abbreviations: CDD = cooling degree days; LPG = liquified petroleum gas; MVA = manufacturing value added; GDP = gross domestic product.

$$UEDT_t = \mu_t + \text{irregular interventions} + \text{level internvetions} + \text{slope interventions} \tag{4}$$

We use STAMP 8.3 (Koopman et al., 2007), a package in OxMetrics, to simultaneously estimate Eqs. (1), (2), (3), and (4) using the Kalman filter and maximum likelihood. As discussed previously, we follow the general-to-specific procedure, adding interventions when necessary and dropping insignificant variables to obtain a final parsimonious energy demand model that passes all diagnostic tests.

4.2. *Welfare analysis of energy price reform*

We use our estimated Marshallian energy demand equations to calculate both the reductions in deadweight loss and total external costs due to energy price reform, following the approaches used by Coady et al. (2015), Davis (2017), Coady et al. (2018), and Atalla et al. (2018). Contrary to much of this previous work, we do not impose a single common elasticity value in our welfare calculations, but instead use the price elasticities we have estimated for each energy product in each sector. We also analyze the welfare effects of actual reforms and potential future reforms.

We begin with Eq. (1), which implies a constant elasticity demand function. Taking the exponential of both sides, we can express energy demand as follows:

$$E_t^j = A_t^j {P_t^j}^{b^j} \tag{5}$$

The composite variable A_t^j captures the combined effect of all the other variables in Eq. (1). E_t^j and P_t^j are respectively the quantity demanded and its price, as the same lowercase letters denote the logarithms of both variables. b^j is the estimated price elasticity, either in the short or long run. We can solve for A_t^j given data on energy demand and prices along with estimates of the price elasticities. The value of A_t^j will vary depending on whether a short- or long-run price elasticity is used for calibration. Once A_t^j is calibrated, the changes in deadweight loss and total external costs resulting from energy price reform can be estimated by varying the price variable.

We calculate the reduction in deadweight loss (ΔDWL_t^j) that occurs when the price of an energy product changes as:

$$\Delta DWL_t^j = \left(P_{t,ref}^j - P_{t,b}^j\right) * E_{t,b}^j - \left(P_{t,ref}^j - P_{t,a}^j\right) * E_{t,a}^j - \int_{P_{t,b}^j}^{P_{t,a}^j} E_t^j \, dP_t^j \tag{6}$$

where $P_{t,b}^j$ is the price before reform, $P_{t,a}^j$ the price after reform, and $P_{t,ref}^j$ the reference price, which is the international market price in most cases. $E_{t,b}^j$, $E_{t,a}^j$, $E_{t,ref}^j$ are the corresponding demand quantities at those prices. Each of these demand quantities can be obtained by plugging its corresponding price into Eq. (5). With full energy price reform, the price after the reform rises up to the reference price ($P_{t,a}^j = P_{t,ref}^j$), while the energy quantity demanded falls to $E_{t,ref}^j$ ($E_{t,a}^j = E_{t,ref}^j$). Therefore, under full energy price reform, the second term on the right-hand side of Eq. (7) falls to zero, leaving behind the more familiar equation for the change in deadweight loss used by Coady et al. (2015), Davis (2017), and Coady et al. (2018).

Substituting Eq. (5) into Eq. (6) yields:

$$\Delta DWL_t^j = \left(P_{t,ref}^j - P_{t,b}^j\right) * E_{t,b}^j - \left(P_{t,ref}^j - P_{t,a}^j\right) * E_{t,a}^j - \int_{P_{t,b}^j}^{P_{t,a}^j} A_t^j {P_t^j}^{b^j} \, dP_t^j \tag{7}$$

Evaluating the integral leads to the final equation for calculating the reduction in deadweight loss:

$$\Delta DWL_t^j = \left(P_{t,ref}^j - P_{t,b}^j\right) * E_{t,b}^j - \left(P_{t,ref}^j - P_{t,a}^j\right) * E_{t,a}^j - \frac{A_t^j}{\left(1+b^j\right)} \left({P_{t,a}^j}^{\left(1+b^j\right)} - {P_{t,b}^j}^{\left(1+b^j\right)} \right) \tag{8}$$

We calculate the reduction in total external costs (ΔTEC_t^j) due to the energy price reform by using fixed per-unit external cost estimates ($PUEC_t^j$) as follows:

$$\Delta TEC_t^j = \left(E_{t,b}^j - E_{t,a}^j\right) * PUEC_t^j \tag{9}$$

The per-unit external costs vary by fuel and end-use sector and encompass multiple components (Parry et al., 2014). The combustion of

Table 4
Summary statistics for all the model variables.

Model variable	Mean	Median	Minimum	Maximum	Standard deviation
Energy demand variables (ktoe):					
Transport gasoline	13,709	11,267	6170	26,092	6469
Transport diesel	12,286	9827	6161	22,529	4961
Transport kerosene	655	633	485	948	119
Residential LPG	962	1025	363	1542	321
Residential electricity	6096	5274	1454	12,426	3519
Residential total	7360	6525	2039	14,135	3881
Commercial & governmental electricity	3907	2665	698	10,973	3076
Industrial natural gas	14,248	11,662	4908	28,371	7322
Industrial fuel oil	7115	5692	2421	21,563	4866
Industrial diesel	2562	2325	1545	4302	829
Industrial crude oil	1832	1420	252	6146	1408
Industrial electricity	1840	1263	713	3992	1120
Industrial total	24,441	20,155	4452	49,326	14,918
Feedstock methane	3462	3142	1053	9576	2053
Feedstock ethane	9247	8990	5096	15,759	3286
Feedstock LPG and naphtha	4564	4915	1227	9097	1688
Feedstock total	19,833	20,665	10,002	31,148	6918
Energy price variables (units):					
Transport gasoline (2010 SR per L)	0.69	0.68	0.40	1.24	0.26
Transport diesel (2010 SR per L)	0.30	0.26	0.13	0.46	0.12
Transport kerosene (2010 SR per L)	0.45	0.45	0.33	0.54	0.08
Residential LPG (2010 SR per L)	0.58	0.72	0.24	0.75	0.21
Residential electricity (2010 SR per kWh)	0.09	0.09	0.07	0.16	0.02
Residential total average (2010 SR per kWh)	0.09	0.09	0.06	0.15	0.02
Commercial & governmental electricity (2010 SR per kWh)	0.15	0.14	0.09	0.24	0.03
Industrial natural gas (2010 USD per mmBtu)	0.80	0.77	0.59	1.09	0.17
Industrial fuel oil (2010 USD per mmBtu)	0.85	0.54	0.30	1.56	0.48
Industrial diesel (2010 USD per mmBtu)	2.04	2.06	0.93	3.01	0.76
Industrial crude oil (2010 USD per mmBtu)	0.86	0.92	0.65	0.97	0.11
Industrial electricity (2010 USD per mmBtu)	9.49	9.77	4.59	12.24	2.41
Industrial total average (2010 USD per mmBtu)	1.49	1.51	1.04	1.97	0.26
Feedstock methane (2010 USD per mmBtu)	0.79	0.75	0.59	1.09	0.16
Feedstock ethane (2010 USD per mmBtu)	0.84	0.77	0.59	1.52	0.27
Feedstock LPG and naphtha (2010 USD per mmBtu)	7.02	6.28	2.54	13.38	3.62
Feedstock total average (2010 USD per mmBtu)	2.44	2.58	0.87	3.82	0.91
Activity / Income variables (units):					
Gross domestic product (billion 2010 SR)	1,613	1,405	778	2,631	549
Manufacturing value added (million 2010 SR)	94,395	64,539	27,677	224,153	67,952
Real chemical exports (million 2010 SR)	52,867	38,270	9805	127,299	40,029
Fertilizer production (thousand tonnes)	5229	5297	908	8411	1920
Other (units):					
Cooling degree days (degree days)	2832	2845	2460	3195	171
Specialization factor (%)	33	32	11	49	9

Abbreviations: ktoe = Kilotonnes of Oil Equivalent; kWh = Kilowatt-Hour; LPG = Liquified Petroleum Gas; mmBtu = Million British Thermal Units; SR = Saudi Riyal; USD = United States Dollar.

all fossil fuels produces CO_2 emissions and air pollution, two critical components of the per-unit external costs. Some fuels also lead to other externalities. For example, the use of gasoline and diesel in vehicles leads to congestion and accidents on top of the CO_2 emissions and air pollution that is produced. In contrast, the petrochemical subsector's non-combusted (i.e., feedstock) use of fossil fuels like natural gas produces relatively smaller externalities.

Finally, we calculate the change in welfare (ΔW_t^j) due to energy price reform by summing the reductions in deadweight loss and total external costs:

$$\Delta W_t^j = \Delta DWL_t^j + \Delta TEC_t^j \tag{10}$$

4.3. Data

The annual time series data needed for the econometric modeling were obtained from a multitude of sources. Most time series were obtained for the 1986–2018 period, although data limitations restricted a few time series to the 1990–2018, 1992–2018, or 1994–2018 periods. We obtained the energy demand data from the IEA (2021), real GDP and manufacturing value added data from SAMA (2020), and consumer price index (CPI) data from SAMA (2020), which was used to deflate nominal values. The energy price data were constructed by combining a wide range of sources: Aleqt (2015), Alriyadh (2015), Akhbaar24 (2015), ECRA (2008-2018), ECRA (2013b), ECRA (2019), Gasim and Matar (2023), Matar et al. (2015), SPA (2017), and WTO (2005). CDDs were constructed using data from the Climate Change Knowledge Portal (2020), following the approach used by Aldubyan and Gasim (2021). The structural factor was constructed using data from CEIC (2021), following the approach in Alarenan et al. (2020). For certain feedstock sector models, SABIC fertilizer production and real chemical and plastic exports, obtained from CEIC (2021), were used as the activity variables. Table 4 provides the summary statistics for all the model variables.

Table 5

A summary of the estimated coefficients and the types of estimated trends for each final model. ^{N} No data available for estimation ^{F} Final models failed diagnostic tests or did not yield statistically significant coefficients.

End-use sector: energy product	*Price*		*Income*		*Trend*	
	Short run	*Long run*	*Short run*	*Long run*	*Level*	*Slope*
Transport:						
Gasoline	−0.12	−0.16	0.17	0.49	S	D
Diesel	−0.27	−0.29	0.50	0.35	S	D
Kerosene	−0.19	−0.19	0.38	0.38	S	D
Residential:						
LPG	–	–	0.37	0.78	S	S
Electricity	−0.15	−0.15	0.14	0.26	S	S
Other ^{N}	–	–	–	–	–	–
Total	−0.16	−0.16	0.37	0.37	S	S
Commercial & governmental:						
Electricity	–	−0.08	0.38	0.43	D	S
Industrial:						
Natural gas	−0.77	−0.60	1.31	1.03	D	D
Fuel oil ^{F}	–	–	–	–	–	–
Crude oil ^{F}	–	–	–	–	–	–
Diesel	−0.14	−0.14	–	0.14	S	D
Electricity	−0.15	−0.15	–	1.27	S	S
Other ^{N}	–	–	–	–	–	–
Total	−0.14	−0.30	0.33	0.33	S	S
Non-energy use:						
Methane	–	−0.05	–	0.26	S	D
Ethane	–	−0.15	0.17	0.20	D	S
LPG + Naphtha	−0.31	−0.31	–	0.65	S	D
Other ^{N}	–	–	–	–	–	–
Total	−0.13	−0.10	0.33	0.24	D	D

Abbreviations: S = stochastic, D = deterministic, LPG = liquified petroleum gas.

For the welfare analysis, the external costs per unit of fuel consumption in Saudi Arabia were obtained from the IMF (2020), with the introduction of some assumptions to extend the external costs to all energy products. In the case of heavy fuel oil, it is assumed that its CO_2 and air pollution externalities are equal to those of diesel on a per liter basis. We chose diesel because it and fuel oil have a similar hydrocarbon makeup, as both are relatively heavier products from the crude oil distillation process (Laffon, 2014). For crude oil, it is assumed that the externalities are equal to the average of those for natural gas and coal on a per unit of energy basis. This assumption is based on the fact that the CO_2 emission factors for oil products are between those of natural gas and coal on a per unit of energy basis (EIA, 2014). In the case of LPG, which is a mixture of propane and butane, it is assumed that the externality is equal to that of natural gas. LPG is considered one of the cleanest fuels, and its CO_2 emissions per unit of energy are closest to natural gas (EIA, 2014). For electricity, we calculated its externality using the natural gas externality and the average thermal efficiency of power plants in Saudi Arabia (SEC, 2019). Natural gas accounts for a large share of the fuel used for power generation in Saudi Arabia, a share that has grown substantially in recent years and is expected to continue growing, with liquids exiting the power generation mix (CCE, 2022). Since fuels used as feedstock do not undergo combustion but can release CO_2 emissions through chemical transformation processes, we follow Metcalf (2017) by assuming that only one-third of the potential carbon emissions get released with feedstocks. We therefore set the externality associated with natural gas feedstock to be equal to one-third of the CO_2 externality associated with its combustion. For all other feedstocks, most of which are propane and butane, which are chemically similar to natural gas, we set their externality equal to that of natural gas feedstock. Finally, we assume that the per-unit externality in 2018 is equal to that of 2017.

The welfare analysis also required conversion factors, emission factors, and reference prices for the traded and non-traded energy products. Conversion factors needed to convert energy quantities between different units were obtained from the IEA (2005). CO_2 emission factors needed to quantify the emission reductions from energy price reform were obtained from the EIA (2014). US spot prices were used as the reference prices for traded oil products, including gasoline, diesel, kerosene, LPG (propane to be specific), and fuel oil, all of which were obtained from the EIA (2021a, 2021b), while Arab light prices, obtained from SAMA (2020), were used as reference prices for crude oil. For electricity, which is largely untraded, the deregulated electricity production cost from Matar and Anwer (2017) was used as the reference price. For natural gas, which is also not traded in Saudi Arabia, the marginal cost of producing non-associated gas in Saudi Arabia was used as the reference price for methane (Alyousef and Stevens, 2011), which is 4 USD per million British thermal units (mmBtu), while for ethane, an additional 0.5 USD per mmBtu was added to its reference price to account for its processing costs, in line with Gasim and Matar (2023).

5. Results and discussion

5.1. Econometric results

Final demand models that passed all diagnostic tests were obtained using the general-to-specific approach. For sectors such as transport, in which final models were obtained for all energy products consumed within them, no total/aggregate sectoral demand model was estimated. However, for sectors with missing models for at least one energy product, a total/aggregate sectoral demand model was estimated. Missing final models were either due to the absence of necessary data or because the models had no statistically significant price and income coefficients and/or failed the residual diagnostic tests.

Table 5 summarizes the estimated elasticities and trends from all the obtained final demand models. (Detailed regression results with complete diagnostic tests, and an in-depth discussion on the interventions, can be found in Appendix A, along with stationarity and cointegration tests.) We find that the demand for almost all energy products in Saudi Arabia is price and income inelastic, with only industrial natural gas and electricity having income elasticities larger than one. Table 5 also highlights the extensive variation in elasticities across sectors and energy products. For example, the long-run price elasticities vary between −0.05 and −0.60, while the long-run income elasticities vary between 0.14 and 1.27.[8] This heterogeneity underscores the importance of using sector- and product-specific elasticity values, and not assuming that elasticities are similar across energy products in the same country. Table 5 also reveals the nature of the trends estimated for each energy product, demonstrating that the trends are stochastic in most cases, supporting the Hunt et al. (2003) recommendation to use STSMs to obtain unbiased elasticity estimates. Industrial natural gas and total feedstock are the only two models for which we found deterministic linear trends, although there are a few cases where the trend exhibits weak stochasticity, as illustrated in the subsequent subsections, so the use of a deterministic trend in their modeling may be an adequate approximation.

Comparing our econometric results to previously published studies, we find that our elasticities are somewhat consistent with previous estimates. For example, in the residential electricity sector, we estimate a long-run price elasticity of −0.15, which lies between the estimates of −0.16 by Atalla and Hunt (2016) and −0.09 by Aldubyan and Gasim (2021). However, our estimate is significantly smaller than the estimate of −0.50 by Al-Sahlawi (1999). For gasoline, our estimated long-run price elasticity of −0.16 is slightly larger than the estimates of −0.15 by Atalla et al. (2018) and −0.13 by Aldubyan and Gasim (2021), and it

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[8] Since Labandeira et al. (2017) estimated the average energy price elasticity globally in the empirical literature to be around −0.59 in the long run using meta-analysis, our results suggest that energy demand in Saudi Arabia is generally more price inelastic than the global average.

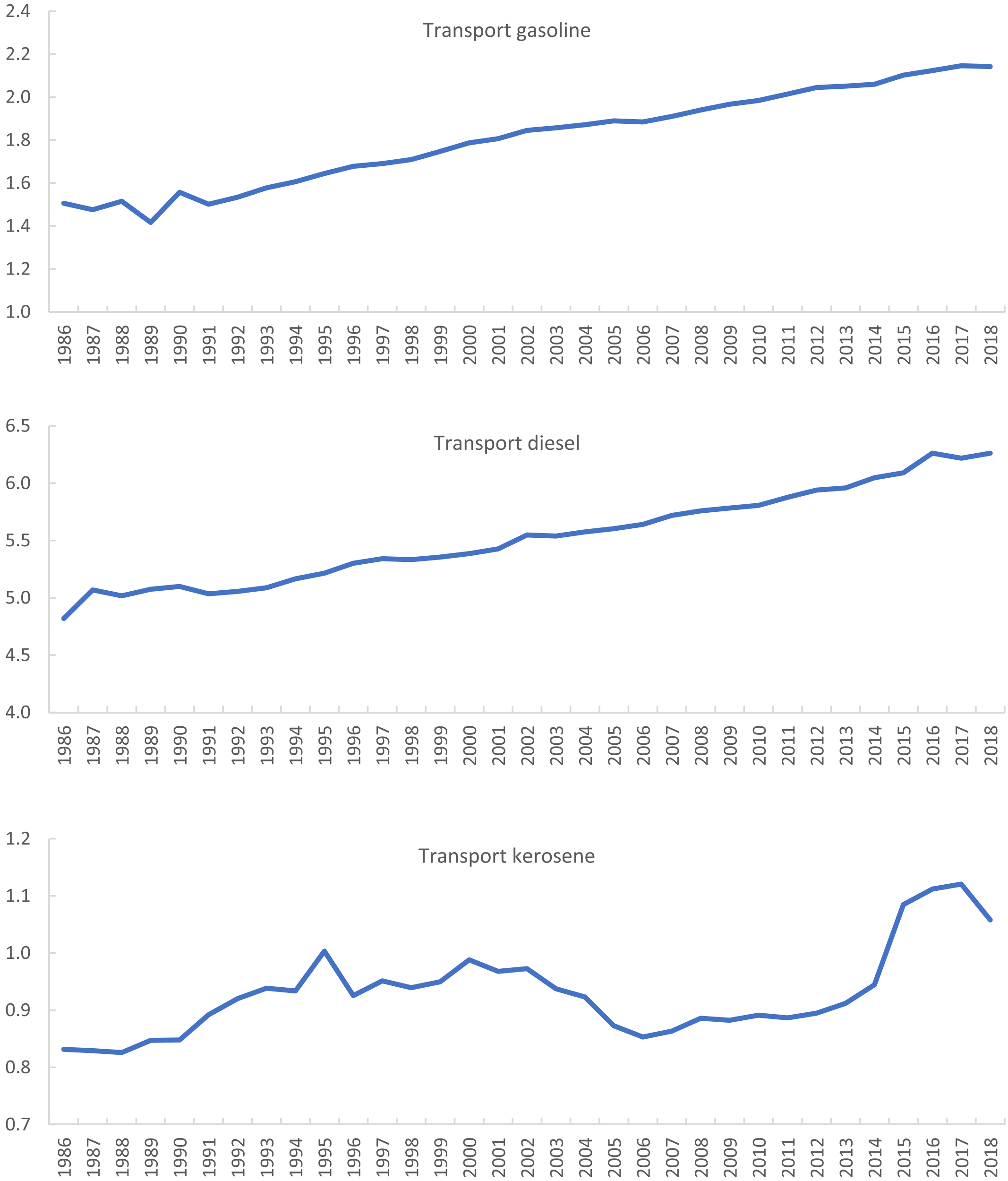

Fig. 3. UEDTs of the final demand models estimated for the transport sector.

lies in the middle of the range (−0.05 to −0.31) estimated by Mikayilov et al. (2019) using a time-varying coefficient approach, but is significantly smaller than the estimates of −0.67 and −0.80 by Al-Sahlawi (1988, 1997). For total/aggregate industrial energy demand, our estimated long-run price elasticity of −0.30 is slightly smaller than the estimate of −0.34 by Alarenan et al. (2020). For other energy products and sectors, it is difficult to make meaningful comparisons because of the absence of recent estimates or the aggregation of a single fuel across multiple sectors in previous studies. Finally, it is important to note that it is likely that the difference between our estimates and past estimates is smaller in the case of past studies that included either stochastic trends or deterministic trends that adequately captured the shape of the true non-linear trend, since both estimators are unbiased in this case.

5.1.1. *Transport*

We find gasoline demand to be both price and income inelastic, with estimated short-run elasticities of −0.12 and 0.17, respectively. The corresponding long-run price and income elasticities are estimated to be −0.16 and 0.49, respectively. We also find diesel demand to be price inelastic, with a short-run price elasticity of −0.27 and a long-run price elasticity of −0.29. Our results suggest that diesel-consuming firms are more responsive to price changes than gasoline-consuming households. The short-run income elasticity for diesel is also relatively larger, at 0.50, while the long-run income elasticity is only 0.35.[9] Unlike the final models for gasoline and diesel, our final model for kerosene is entirely static, with the price elasticity equal to −0.19 and the income elasticity equal to 0.38.

The estimated UEDTs for the transport sector, shown in Fig. 3, are all found to be stochastic and generally upward sloping over the 1986–2018 period, suggesting that exogenous factors, additional to

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[9] The relatively smaller long-run income elasticity in the diesel demand model stems from both statistically insignificant coefficients on the lagged income variables and statistically significant negative coefficients on the lagged dependent variables.

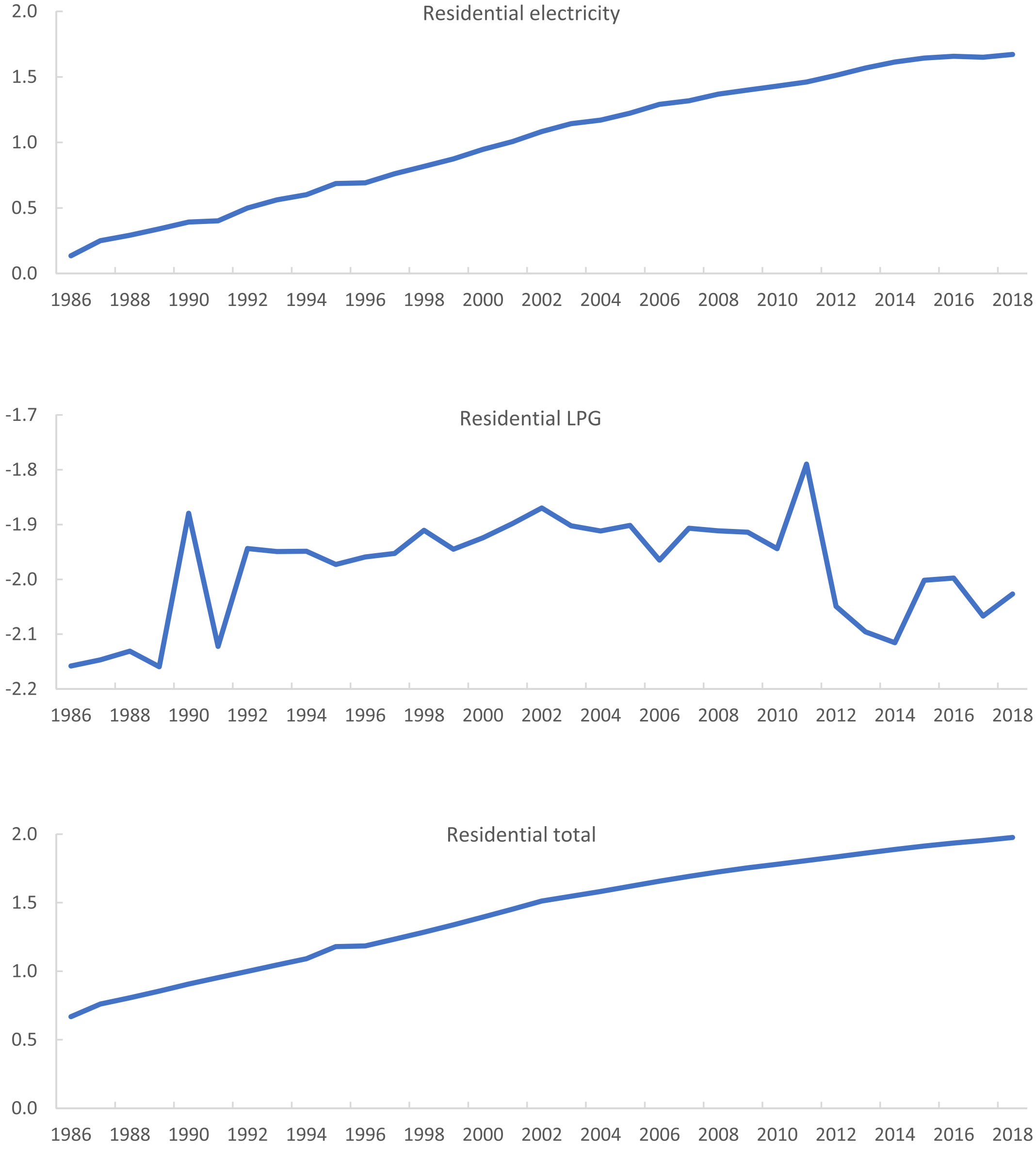

Fig. 4. UEDTs of the final demand models estimated for the residential sector.

prices and income, increased the demand for gasoline, diesel, and kerosene during this period. In the case of gasoline, it is possible that the shift towards owning larger cars, along with road network expansion and urban sprawl, led to the upward-sloping UEDT. These same reasons may also explain the upward-sloping UEDT for diesel and its similarity to gasoline. In contrast, the UEDT for kerosene appears erratic, possibly capturing fluctuating preferences regarding air travel and changes in domestic flight ticket pricing policies.

5.1.2. Residential

We find residential electricity demand to be inelastic to both price and income changes. Our estimated residential electricity model has a static price response, with a price elasticity of −0.15. We see more dynamics around the income response, with short-run and long-run

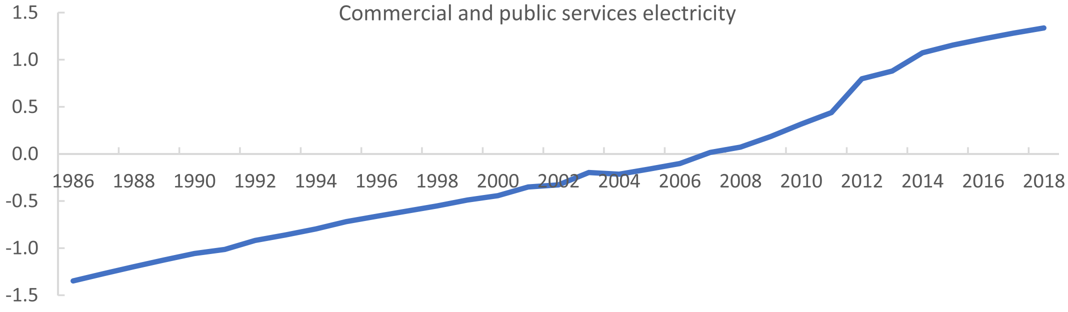

Fig. 5. UEDT of the final demand model estimated for the commercial and public services sector.

income elasticities of 0.14 and 0.26, respectively. We also find the elasticity of residential electricity demand with respect to the CDDs to be 0.45. For the residential LPG model, we do not find a statistically significant price elasticity, a result likely originating from the minimal LPG price variability during the estimation period. In fact, residential LPG was the only fuel unaffected by the comprehensive price reform implemented in 2016. Nevertheless, we estimate the income elasticity for residential LPG to be 0.37 and 0.78 in the short and long run,

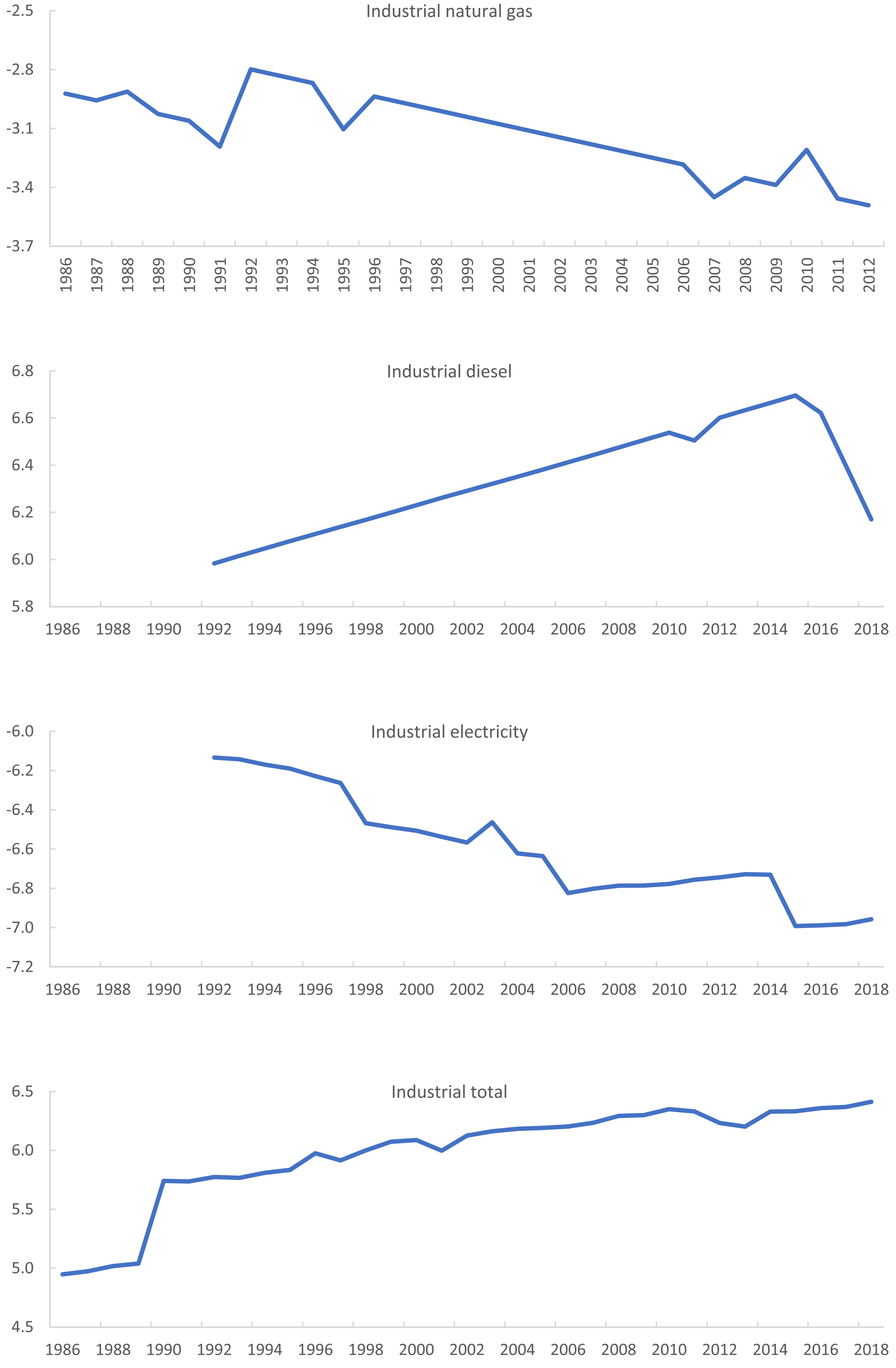

Fig. 6. UEDTs of the final demand models estimated for the industrial sector.

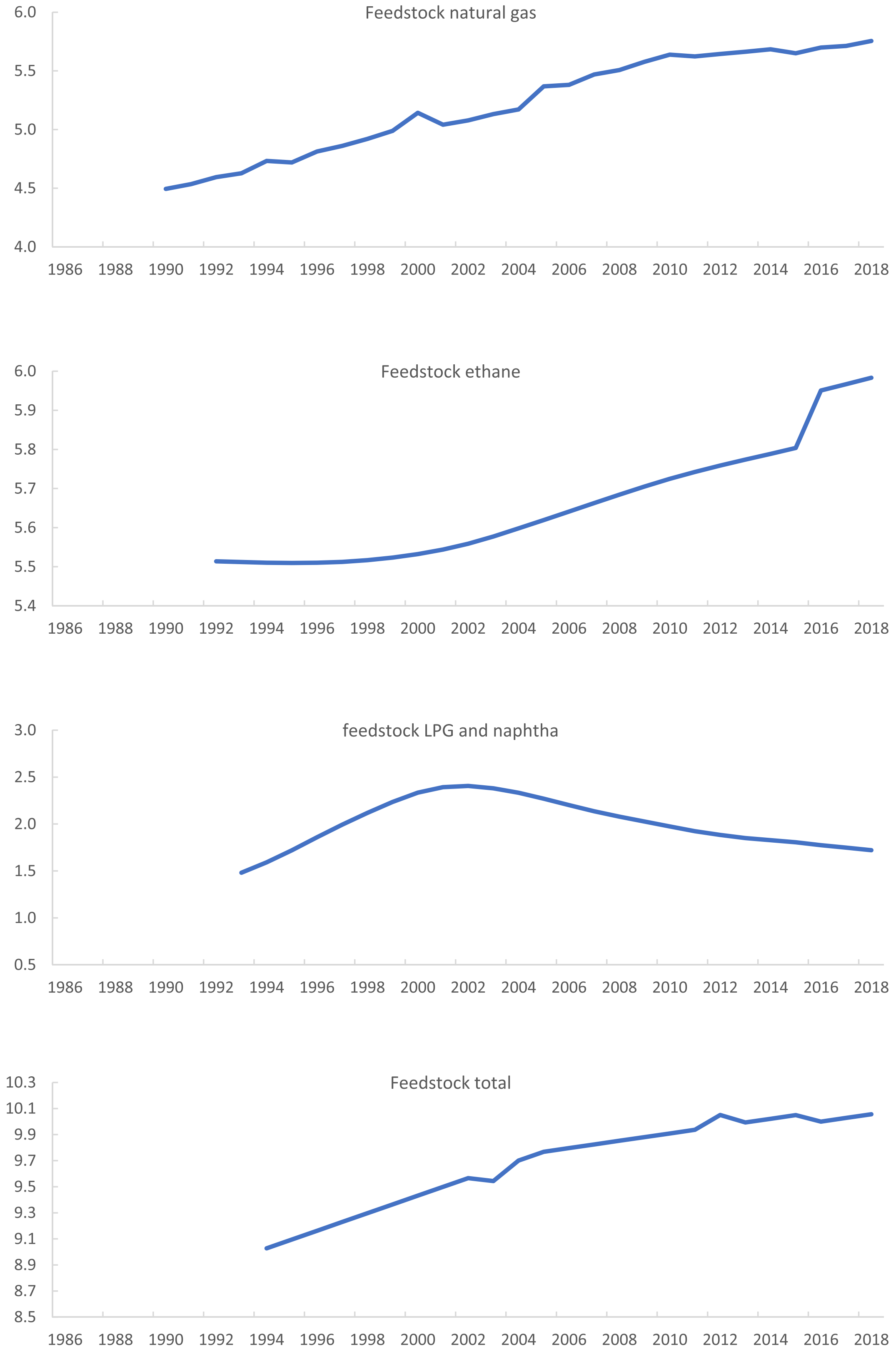

Fig. 7. UEDTs of the final demand models estimated for the non-energy use (feedstock) sector.

respectively. As for our total residential energy demand model, the estimated coefficients are very similar to the residential electricity demand model, which is not surprising given that residential electricity accounts for by far the largest share of total residential energy demand.

The UEDTs for the residential sector models, shown in Fig. 4, were all found to be stochastic. Both the residential electricity and residential total UEDTs were upward-sloping, likely reflecting an increase in the typical size of a house in Saudi Arabia, along with an increase in the number of installed electrical appliances such as air conditioners. Nevertheless, towards the end of the period (2014–2018), the slopes of both UEDTs flattened out, likely because of the implementation of energy efficiency regulations in the 2010s by the Saudi Energy Efficiency Center (Aldubyan and Gasim, 2021), which was first established in 2010. In contrast, the UEDT for LPG initially increased but decreased from 2000 onwards, a trend possibly reflecting improvements in the efficiency of LPG-based cooking stoves or a shift towards electricity for cooking purposes.

5.1.3. *Commercial and governmental*

We find commercial and governmental electricity demand to be strongly price inelastic and somewhat income inelastic in the long run. Our final model lacks a short-run price response, but we find the long-run price elasticity to be −0.08. We find more dynamics around the income response, with an income elasticity of 0.38 in the short run and 0.43 in the long run. The CDD elasticity is estimated to be 0.33 in the short run.

The UEDT for the final model, shown in Fig. 5, is found to be stochastic and upward-sloping. The upward-sloping UEDT may be capturing the use of more lighting or air-conditioning per square meter of floorspace in commercial and governmental buildings. The rate of growth accelerates between 2006 and 2012, before slowing down towards the end of the period. This slowdown is also likely the result of energy efficiency policies implemented by the Saudi Energy Efficiency Center to improve the energy efficiency of the buildings sector (SEEC, 2021b).

5.1.4. *Industrial*

We find relatively more elastic price and income responses for industrial natural gas demand. The price elasticity is estimated to be −0.77 in the short run and −0.60 in the long run due to the negative coefficients on the lagged dependent variables. One possible explanation relates to the closed natural gas market in Saudi Arabia, which, combined with the gas pricing policy, has caused demand to outstrip supply, forcing the government to ration natural gas consumption. It is likely that in the short run, a higher natural gas price causes some firms to reduce their consumption, but in the long run, when the higher price unlocks greater supply, the rationing would not be as stringent and some firms would increase their consumption, leading to the weaker long-run price response. A similar result is observed in the income response, with short- and long-run income elasticities of 1.31 and 1.03, respectively. We find strongly inelastic price and income responses in the industrial diesel model, with an estimated price elasticity of −0.14 and income elasticity of 0.14. For the industrial electricity model, we estimate a price elasticity of −0.15 and a large long-run income elasticity of 1.27, with the short-run income elasticity being statistically insignificant. For the total industrial energy demand model, we find demand to be price and income inelastic. The estimated price elasticity is −0.14 in the short run and −0.30 in the long run, while the static income elasticity is estimated to be 0.33.

The UEDTs for the final industrial sector models are shown in Fig. 6. Excluding natural gas, all UEDTs were found to be stochastic. The UEDTs for total industrial energy demand and diesel demand were generally upward-sloping. The UEDT for total demand appears to flatten towards the end of the estimation period, possibly capturing improvements in energy efficiency in the industrial sector (SEEC, 2021a). For diesel, the UEDT becomes sharply downward-sloping from 2015 onwards, a sharp trajectory change that likely reflects government policy to displace diesel use in the industrial sector. In contrast, the UEDTs for natural gas and electricity were generally downward-sloping, potentially capturing exogenous improvements in energy efficiency. Nevertheless, it is worth noting that the demand for both natural gas and electricity was found to be income elastic, so there may be a relationship between their large income elasticities and downward-sloping trends.

5.1.5. *Non-energy use (feedstock)*

We find natural gas (i.e., methane) feedstock demand to be strongly price inelastic, with long-run price and income elasticities of −0.05 and 0.26, respectively. The low price elasticity likely stems from the lack of feedstock substitutes for methane, which produces a unique set of end-products (mainly fertilizers). For ethane, we also find demand to be strongly price and income inelastic. The price elasticity is estimated at −0.15 in the long run, while the income elasticity is estimated at 0.17 in the short run and 0.20 in the long run. For LPG and naphtha, we obtain a final model with a price elasticity of −0.31 and a long-run income elasticity of 0.65. This price elasticity is considerably larger than for methane and ethane, a result that may stem from the pricing policy for LPG and naphtha. Unlike other fuels and feedstocks, whose prices are regulated and change infrequently, the prices of LPG and naphtha feedstock have been set as a percentage of the monthly international spot price. Therefore, their prices were not only much higher than other fuels when measured on a per-unit of energy basis, but also experienced a lot more volatility. Petrochemical firms that consume LPG and naphtha are thus more responsive to energy price changes. As for total feedstock, we find demand to be price- and income-inelastic, in line with the estimates for methane and ethane, which account for the largest share of total feedstock use. The estimated short-run price and income elasticities are −0.13 and 0.33, respectively. Unexpectedly, the long-run price and income elasticities are smaller in magnitude, measuring −0.10 and 0.24, respectively. The rationing of natural gas and ethane feedstocks may explain the weaker long-run response, in line with the results observed for the rationed use of natural gas as a fuel by the industrial sector.

The UEDTs for the feedstock sector models are shown in Fig. 7. Excluding total feedstock, the estimated UEDTs for all models were stochastic. The UEDTs for total, natural gas, and ethane were found to be upward-sloping. In contrast, the UEDT for the LPG and naphtha model was upward-sloping up to 2002, at which point it became downward-sloping. As noted previously, LPG and naphtha prices have been substantially higher than methane and ethane prices on a per-unit of energy basis, and they have been much more volatile. The downward-sloping trend for this model may therefore be capturing a shift away from the use of LPG and naphtha as a feedstock in the Saudi petrochemical subsector.[10]

5.2. *Impacts of energy price reform*

5.2.1. *Impacts on deadweight loss, external costs, and welfare*

Using our estimated price elasticities, we quantify the actual and potential impacts of energy price reform in Saudi Arabia. (This analysis can be done using the short- or long-run price elasticities. The long-run results are presented here, while the short-run results are presented in Appendix A.) To measure the actual impacts of the implemented reforms, we compare the deadweight loss and external costs of the baseline scenario, in which energy prices were partially reformed by the Saudi government in 2016 and then 2018, to a counterfactual scenario

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[10] We also compared the energy demand data obtained from the IEA (2021) with data obtained from Jodi (2021) and SAMA (2020). We find the values to be consistent for almost all energy products, except for LPG and naphtha consumed by the petrochemical subsector, suggesting the existence of a potential data issue related to the consumption figures for both fuels.

Table 6
The actual and potential impacts (in billion 2010 USD) of energy price reforms on deadweight loss, external costs, and welfare.

End-use sector: *Energy product*	Actual impacts of implemented energy price reforms (moving from pre-reform prices to baseline reformed prices)									Potential impacts of further energy price reform (moving from baseline reformed prices to fully reformed prices)								
	Reduction in deadweight loss			Reduction in external costs			Total welfare gain			Reduction in deadweight loss			Reduction in external costs			Total welfare gain		
	2016	2017	2018	2016	2017	2018	2016	2017	2018	2016	2017	2018	2016	2017	2018	2016	2017	2018
Transport																		
Gasoline	0.4	0.6	1.4	1.7	1.7	3.8	2.1	2.3	5.2	0.2	0.4	0.1	1.9	2.5	1.0	2.1	2.9	1.1
Diesel	1.1	1.3	1.7	3.6	3.4	3.2	4.7	4.7	4.9	0.8	1.2	2.0	5.2	5.6	6.1	6.0	6.9	8.1
Kerosene	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2
Residential																		
LPG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electricity	0.1	0.1	0.7	0.1	0.0	0.4	0.2	0.1	1.1	0.7	0.7	0.1	0.5	0.5	0.2	1.2	1.2	0.3
Commercial & governmental																		
Electricity	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Industrial																		
Natural gas	0.8	0.7	0.8	0.7	0.7	0.7	1.6	1.4	1.5	0.7	0.6	0.6	1.0	0.9	1.0	1.7	1.5	1.6
Crude oil	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.3	0.1	0.2
Diesel	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.4	0.4	0.3	0.5	0.5	0.4
Heavy fuel oil	0.5	1.0	1.3	1.8	2.3	2.2	2.2	3.3	3.5	0.8	2.0	2.9	4.5	6.7	6.8	5.3	8.7	9.7
Electricity	0.1	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Non-energy use																		
Natural gas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ethane	0.2	0.2	0.2	0.1	0.1	0.1	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
LPG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Naphtha	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Totals	**3.3**	**4.1**	**6.3**	**8.2**	**8.5**	**10.7**	**11.6**	**12.6**	**17.0**	**3.6**	**5.3**	**6.3**	**13.9**	**17.1**	**15.8**	**17.5**	**22.4**	**22.1**

in which domestic energy prices were never reformed, continuing at their regulated 2015 levels. To measure the potential impacts of further reform, we compare the deadweight loss and external costs of the baseline scenario to a counterfactual scenario in which domestic energy prices are fully reformed and set equal to their reference prices. We conduct this welfare analysis for each energy product in each end-use sector for each year between 2016 and 2018. For energy products with no estimated final models, we use the elasticities from the estimated total/aggregate sectoral models to ensure complete coverage.[11]

We find significant economic and environmental benefits from the two waves of energy price reform implemented by the Saudi government in 2016 and 2018 (see Table 6). Our analysis reveals that the 2016 reform delivered a total reduction in deadweight loss of around 3.3 billion 2010 USD in that year. Moreover, it delivered an 8.2 billion 2010 USD reduction in external costs. Summing both reductions yields the total welfare gain, at 11.6 billion 2010 USD,[12] with diesel for transport accounting for the largest share, followed by industrial fuel oil, gasoline, and industrial natural gas. The total welfare gain increased slightly in 2017, to 12.6 billion 2010 USD, even though domestic energy prices did not change between 2016 and 2017.[13] In 2018, as the second wave of energy price reform took place, the total welfare gain jumped to 17.0 billion 2010 USD, as the welfare analysis picks up the combined impacts of both the 2016 and 2018 reforms. This total welfare gain, which represents around 2.4% of real GDP in 2018, was made up of a 6.3 billion 2010 USD reduction in deadweight loss and a 10.7 billion 2010 USD reduction in external costs. We find that gasoline accounted for the largest share of the total welfare gain in 2018, having been targeted during both reform waves.

The welfare gains for each energy product in each sector depend on several factors, such as the quantity of energy consumed. The greater the consumption of an energy product, the larger the welfare gain from energy price reform, which explains why the welfare gains are larger for gasoline and diesel in the transport sector and natural gas and fuel oil in the industrial sector. The size of the price increase is another crucial factor, as larger price increases result in larger welfare gains. In 2018, the price increases were largest on residential electricity and gasoline, explaining the larger increases in welfare associated with both energy products in 2018. Finally, the size of the price elasticity also plays an essential role: the more elastic demand is for a product, the bigger the welfare gain from energy price reform. Unlike the previous two factors, the price elasticity is estimated, and these estimates have uncertainty. The results in Table 6 are sensitive to the size of the elasticities, underscoring the importance of using estimated elasticities instead of making assumptions regarding their size. In Appendix A, we present the short-run welfare results and illustrate their sensitivity to the size of the estimated price elasticities using the 95% confidence intervals for our estimated short-run price elasticities.

Our welfare results are in line with a few previously published results. For example, Atalla et al. (2018) measured the welfare gain from the 2016 gasoline price reform to be 1.7 billion 2010 USD, only a bit smaller than our estimated value of 2.1 billion 2010 USD. The difference is likely due to our larger price elasticity and our updated per-unit external cost estimates. In contrast, Aldubyan and Gasim (2021)

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[11] For certain energy products in certain sectors, we were unable to find a final model that passed all diagnostic tests and had statistically significant price coefficients, either due to the absence of necessary data for modeling or the absence of enough price variation to obtain a statistically significant price coefficient. For these energy products, the price elasticities from the total/aggregate sectoral models were used to conduct the welfare analyses.

[12] Numbers may not sum up due to rounding.

[13] While domestic energy prices in 2017 were the same as in 2016, the quantity of energy consumed, the energy products' reference prices, and the size of the associated externalities vary year to year, affecting the annual welfare calculations.

estimated the welfare gain due to the 2018 wave of gasoline price reform to be 2.3 billion USD, while we estimated a welfare gain of 5.2 billion 2010 USD. However, our welfare calculation for 2018 captures the combined welfare gain due to both the 2016 and 2018 gasoline price increases. If we isolated the impact of the 2018 gasoline price increase, our estimated welfare gain for 2018 would have been 2.9 billion 2010 USD, in line with Aldubyan and Gasim (2021), but larger due to our larger estimated gasoline price elasticity.

We also demonstrate that greater welfare gains could have been realized if further energy price reforms were implemented in the past, until domestic prices were 100% equal to reference prices in each year (see Table 6). We find that in 2016, further energy price reform could have resulted in an additional 3.6 billion 2010 USD reduction in deadweight loss and a 13.9 billion 2010 USD reduction in external costs. In 2018, despite the implementation of a second wave of partial reform, further energy price reform could have resulted in a relatively larger 6.3 billion 2010 USD reduction in deadweight loss and a 15.8 billion 2010 USD reduction in external costs. Despite domestic energy prices in 2018 being higher than in 2016, the potential welfare gains from further reforms were larger in 2018 as international oil prices were also relatively higher, increasing the reference prices in the welfare calculations. In summary, our analysis shows that although significant welfare gains have already been achieved through past energy price reforms, there remain even larger welfare gains to be unlocked through further reforms. However, further increases in energy prices will likely be challenging to implement.

The energy price increases, and their associated welfare impacts, varied across energy products between the 2016 and 2018 waves of energy price reform, raising an interesting question about the optimal rate of reform. From a welfare optimality perspective, fully deregulating energy prices in 2016 would have been the optimal decision. However, this does not consider other important factors, such as political feasibility and the pain consumers and businesses would face in the short-term as they adjust to such a shock. This explains why the Saudi government adopted a phased approach to energy price reform. The Saudi government likely had to strike a balance between energy price reform's fiscal, economic, and welfare gains, the negative impacts on households, and the negative impacts on industrial competitiveness. These factors likely influenced when each wave of energy price reform was implemented, which energy products were targeted, and how large the energy price increases were. Furthermore, to maximize the welfare gains from its phased approach, the Saudi government will likely have also considered the relative importance of each energy product in terms of the total quantity consumed. The first wave of energy price reform in 2016 targeted all energy products, including those in the transport, industrial, and residential sectors, without compensation or mitigation mechanisms. Although the energy price increases in 2016 were large in percentage terms, they were implemented on relatively low energy price levels. This likely reduced the need for compensation mechanisms, which also take time to design. Furthermore, the large budget deficit recorded in 2015 (SAMA, 2020), following the collapse in international oil prices in late 2014, probably necessitated quick fiscal action in 2016 to raise government revenue. The second wave of energy price reform in 2018 appeared to target energy products used by households and was implemented only after the launch of the Citizen's Account program to compensate eligible households (Arab News, 2017; Fiscal Balance Program, 2018). The Saudi government appears to have had more time to prepare for the 2018 wave of energy price reform, allowing it to design a comprehensive compensation scheme. The scheme allowed the Saudi government to again implement large energy price increases in percentage terms, especially on household energy products like gasoline and residential electricity (see Table 1). Furthermore, unlike in 2016, the energy price increases in 2018 were implemented on relatively higher energy price levels, likely making them appear more significant from the perspective of households. On the other hand, the energy price increases in 2018 on industrial fuels were limited, presumably because there was no mechanism yet to mitigate the negative impacts on industrial competitiveness. In 2022, the Saudi government announced plans suggesting a third wave of energy price reform at the end of 2023, focusing on industrial fuels and feedstocks (Arab News, 2022). Following the implementation of energy efficiency initiatives for the industrial sector by the Saudi Energy Efficiency Center (SEEC, 2021a), the industrial sector will likely be in a stronger position at the end of 2023 to absorb the negative impacts of a future potential third wave of energy price reform.

Table 7
The annual avoided CO_2 emissions (in million tonnes) from actual and potential energy price reforms.

End-use sector: *Energy product*	Actual CO_2 emissions avoided due to implemented price reforms *(moving from pre-reform prices to baseline reformed prices)*			Potential CO_2 emissions avoided by further price reforms *(moving from baseline reformed prices to fully reformed prices)*		
	2016	2017	2018	2016	2017	2018
Transport:						
Gasoline	5.7	5.8	13.0	6.5	8.5	3.5
Diesel	12.9	11.9	11.5	18.4	19.8	22.1
Kerosene	0.2	0.2	0.2	0.4	0.5	0.5
Residential:						
LPG	0.0	0.0	0.0	0.0	0.0	0.1
Electricity	1.3	0.9	8.5	11.1	11.3	4.0
Commercial & governmental:						
Electricity	1.0	1.0	1.2	0.5	0.5	0.3
Industrial:						
Natural gas	17.0	14.1	15.5	23.7	19.6	21.7
Crude oil	0.7	0.3	0.3	2.3	1.0	1.1
Diesel	0.6	0.5	0.5	1.9	1.8	1.5
Heavy fuel oil	8.9	11.6	11.3	22.5	33.3	34.5
Electricity	1.0	1.0	1.1	1.3	1.4	1.5
Non-energy use:						
Natural gas	0.1	0.1	0.1	0.2	0.2	0.2
Ethane	1.3	1.4	1.4	1.3	1.3	1.4
LPG	0.0	0.1	0.0	0.0	0.1	0.1
Naphtha	0.1	0.1	0.1	−0.1	0.0	0.0
Totals	**50.6**	**48.9**	**64.6**	**90.0**	**99.3**	**92.4**

5.2.2. *Impacts on CO_2 emissions*

Our analysis demonstrates that the energy price reforms implemented by the Saudi government in 2016 and 2018 delivered significant reductions in CO_2 emissions, as shown in Table 7, through reductions in energy consumption (see Appendix A for the reduction in energy consumption due to price reform). Our long-run analysis reveals that the 2016 wave delivered 50.6 million tonnes of avoided emissions annually. This value fell slightly to 48.9 million tonnes in 2017, before rising to 64.6 million tonnes in 2018 as the second reform wave ensued. The avoided emissions in 2018, due to both waves of price reform, represented around 11% of actual energy-related CO_2 emissions in Saudi Arabia in that year (BP, 2020). They also represent almost one half of the original target Saudi Arabia had submitted in 2015 in its first nationally determined contribution (NDC), when it had announced its aim "to achieve mitigation co-benefits ambitions of up to 130 million tons of CO2eq avoided by 2030 annually" (NDC, 2015). Additional programs for reducing CO_2 emissions, through the circular carbon economy framework, have been announced since then (Arab News, 2020), and in 2021 Saudi Arabia updated its NDC, increasing its target from 130 to 278 million tonnes of avoided and removed emissions annually by 2030 (NDC, 2021).

Our analysis also reveals that implementing further reforms in the past (until all domestic energy prices were 100% equal to reference prices) could have unlocked an additional 90.0 million tonnes of avoided CO_2 emissions in 2016. This value would have grown to 99.3 million tonnes in 2017, before falling to 92.4 million tonnes in 2018, as the implementation of the second wave of partial reform in 2018 absorbs some of the avoided emissions from further potential reform. Our results thus demonstrate that fully reforming domestic energy prices could have been enough to meet Saudi Arabia's first NDC (2015) target, but that full energy price reform in 2018 would only have delivered one-third of the updated NDC (2021) target. Although the avoided emissions due to full energy price reform could grow as domestic consumption increases, our analysis suggests that policymakers will need to explore other policies beyond energy price reform to achieve their climate targets.[14]

6. Conclusion

We estimate 15 energy demand equations for Saudi Arabia, covering all end-use sectors and as many energy products within each sector as possible, thereby estimating price and income elasticities for which there were no previous estimates. We show that energy demand is price inelastic for all energy products and income inelastic in all cases except for industrial natural gas and electricity. We demonstrate the existence of extensive heterogeneity in price and income elasticities across sectors and energy products, with the long-run price elasticity varying between −0.05 and −0.60, and the long-run income elasticity varying between 0.14 and 1.27. Our estimated elasticities provide policymakers with crucial information, revealing how future changes in energy prices and economic growth could affect the trajectory of domestic energy demand and CO_2 emissions.

Our econometric analysis underscores the importance of incorporating non-linear stochastic trends to obtain unbiased elasticity estimates (Hunt et al., 2003). We find that for 13 of the 15 energy demand models, the trends are stochastic, with industrial natural gas and total non-energy use being the only two exceptions with deterministic trends. There are also a few energy products whose trends exhibited weak stochasticity, so the use of deterministic trends in their modeling may be an adequate approximation. Nevertheless, for most of the models, the non-linearity of the trends is clear. Our analysis also reveals that most trends are upward sloping, reflecting the role of exogenous factors (such as larger houses, more electrical appliances, longer road networks, and urban sprawl) in driving the growth of domestic energy demand and emissions in Saudi Arabia.

Using our estimated elasticities, we quantify and highlight the large economic and environmental benefits delivered by energy price reform. We find that the 2016 reform produced an annual welfare gain of 11.6 billion 2010 USD, which grew to 17.0 billion 2010 USD as the 2018 reform was implemented. Our analysis also shows that economic efficiency gains (measured through deadweight loss reductions) accounted for roughly one-third of these welfare gains, while environmental benefits such as reduced emissions and air pollution (measured through the reduction in external costs) made up the remainder.[15]

The inelasticity of energy demand in Saudi Arabia may suggest that energy price increases do not affect demand significantly, thereby yielding only small benefits, but we find the opposite to be true, mainly due to the extent of the domestic price increases that occurred. For example, the 95-octane gasoline price increased by around 240% between 2015 and 2018. Even with a small price elasticity of −0.1, such a price change delivers a 24% reduction in gasoline consumption, all else equal, thereby yielding considerable economic and environmental benefits.

The climate change mitigation co-benefits of energy price reform in Saudi Arabia are important. Our analysis reveals that the 2016 wave delivered 50.6 million tonnes of avoided emissions annually, a value that rose to 64.6 million tonnes by 2018 as the second wave ensued. The annual avoided emissions in 2018 represent around 11% of actual energy-related CO_2 emissions in Saudi Arabia in that year (BP, 2020). Between 2016 and 2018, the total cumulative avoided emissions due to the implemented reforms summed up to 164 million tonnes. Although fiscal and resource concerns were the primary drivers of energy price reform, the Saudi government achieved extensive climate change mitigation co-benefits through the implemented reforms.

There remains scope to increase domestic energy prices further, fully linking them to reference prices, and we show that the potential economic and environmental benefits of such further reforms are substantial. We find that further energy price reform in 2016 could have produced an additional welfare gain of 17.5 billion 2010 USD. Despite implementing the 2018 wave, further energy price reform in 2018 could have delivered an even larger welfare gain of 22.1 billion 2010 USD, as international oil prices recovered in 2018 following their fall in late 2014. In terms of emissions, further energy price reform in 2018 could have delivered more than 92 million tonnes of avoided emissions annually. These avoided emissions represent one-third of Saudi Arabia's updated NDC target for avoided and removed annual emissions by 2030 (NDC, 2021), suggesting that policymakers may need to explore other policy tools to achieve this target.

Although further energy price reform could deliver a considerable portion of Saudi Arabia's updated NDC target, any further energy price increases will be challenging to implement. Large increases in energy prices are more feasible when prices are relatively low, which was the case with the 2016 and 2018 reforms in Saudi Arabia. However, energy prices are currently significantly higher than they were just a few years ago. Further price reforms will likely need to be gradual (Ekins and Barker, 2001). Additionally, it will be vital to strengthen programs such as the Citizen's Account, which compensates lower- to middle-income households for the energy price increases through monthly cash transfers. Moreover, given the potential for price reform in industrial fuels and feedstocks, programs will be needed to mitigate the negative impacts on industrial competitiveness, especially given the high levels of energy-intensive manufacturing in Saudi Arabia. Future research will therefore be needed on how to implement price reforms while mitigating the accompanying challenges and negative impacts, thereby ensuring successful outcomes.

Considering the challenges in implementing further energy price reforms, the inelastic price responses, and the upward-sloping trends, policymakers in Saudi Arabia will need to explore tools beyond energy price reform for managing the long-term growth in energy consumption and emissions. In the Saudi transport sector, which is characterized by a lack of alternatives, policymakers may need to consider policies for renewing the vehicle stock, raising fuel economy standards, introducing urban public transportation options, and developing efficient multimodal freight networks. For buildings, energy efficiency standards and regulations will be needed to manage the increasing use of electricity-intensive appliances such as air conditioners. We already observe the effect of energy efficiency regulations on the UEDT for residential electricity, which was growing rapidly but flattened in the 2010s following the implementation of mandatory thermal insulation and minimum energy performance standards. In the industrial sector, providing financial assistance for energy efficiency upgrades is one option for managing its consumption and improving its competitiveness. Many of these policies and programs are either being implemented or are under discussion. Moreover, the Saudi government has recently announced its plan to decarbonize the power sector, with the aim of producing 50% of its electricity using renewable energy (Arab News, 2021b). To conclude, a comprehensive portfolio of policies and programs that target different sectors, in addition to energy price reform, will be essential for delivering Saudi Arabia's goals of resource, fiscal, and environmental sustainability.

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[14] While the main driver of energy price reform in Saudi Arabia has largely been fiscal, the climate change mitigation co-benefits are large and significant.

[15] There exists uncertainty in quantifying these environmental benefits, as they depend on inputs such as the social cost of carbon that come with uncertainty (Anthoff and Tol, 2023).

CRediT authorship contribution statement

Anwar A. Gasim: Conceptualization, Methodology, Software, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Paolo Agnolucci:** Supervision, Writing - review & editing. **Paul Ekins:** Supervision, Writing - review & editing. **Vincenzo De Lipsis:** Writing – review & editing.

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Appendix A. Supplementary data

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