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Discussion Paper

Net Zero Emissions in Saudi Arabia by 2060

Least-Cost Pathways, Influence of International Oil Price, and Economic Consequences

Olivier Durand-Lasserve

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Summary

This paper presents possible net zero emissions (NZE) trajectories for Saudi Arabia at horizon 2060 and analyzes their possible economic consequences. We use an in-house hybrid forward-looking general equilibrium model of the Saudi economy. We construct a baseline scenario where the Saudi energy sector continues its current trends and where the domestic energy prices, which are administered by the government, remain at their 2019 level. Then, we simulate a price reform scenario where energy prices are deregulated and adjust to match supply and demand. This price reform scenario helps us understand how much domestic price deregulation can contribute to saving energy and reducing CO_2 emissions. Finally, we simulate NZE scenarios where we impose annual caps on CO_2 emissions that ramp down to zero by 2060. We let the model find the least-cost mix of technologies, as well as the implicit price of carbon that is needed to incentivize investments compatible with net zero. Saudi Arabia's journey to NZEs is paved with uncertainties, not least regarding the future of the global oil market. To assess how oil market transformations may influence Saudi Arabia's pathway to decarbonization, we simulate each scenario (baseline, price deregulation, and NZE) under three different international oil price assumptions.

In the baseline scenario, CO_2 emissions are almost doubled between 2019 and 2060, driven by growing transportation and industrial process emissions. If the international oil prices are between USD 60 and 95 per barrel, deregulating domestic energy prices and allowing them to adjust to international levels may bring emissions 25% below the baseline by 2060. Emissions mitigation comes from energy conservation, greater renewable deployment, phasing out of liquids in power generation, and partial electrification of light-duty transportation. However, if we assume that international oil prices are very low, price deregulation has a significantly lesser impact on emissions.

We find that reaching NZE in 2060 implies a profound transformation of the energy sector. Power generation becomes carbon-neutral by 2045. Renewables pick up first because they are mature technologies with a low cost. Following this, gas with carbon capture and storage and nuclear energy are deployed. In the transportation sectors, electricity and clean hydrogen substitute gasoline and diesel and represent two-thirds of energy consumption by 2060. Meanwhile, CCS is deployed in the hard-to-abate industrial sectors. However, even with all these transformations, there remain substantial unabated emissions. Direct air capture ramps up after 2040. By 2060, around 250 million tons of CO_2 are captured with DAC. This volume represents half of the CO_2 emissions of 2019. DAC is an energy-intensive technology. By 2060, it consumes the equivalent of 25% of the primary gas demand and 10% of the final electricity consumption.

The technologies required in the NZE scenario, in particular DAC, are very costly. The implicit carbon price needed to incentivize net zero increases from USD 50–65 per ton in the first years of the model to USD 270–330 per ton by 2050. The CO_2 prices are sensitive to the assumption made regarding the international oil price in our scenarios. We find that a lower oil price reduces the opportunity cost of using oil domestically and increases the implicit price of carbon needed to incentivize emissions reductions.

In the NZE scenarios, the energy system cost as a share of gross domestic product increases from around 7% to around 10-12%, whereas this share slightly decreases in the baseline scenario. If the NZE needs to be implemented in a low international oil price environment, the high bill of the domestic decarbonization has to be met with less oil export revenue. The energy system cost may eventually exceed the oil export revenue. Moreover, we find that clean hydrogen does not become a significant source of export revenue unless we assume a very high free on board (FOB) price of USD 2.5 per kg of H_2, which is above the existing projections. In this case, hydrogen export revenue in 2050 would be equivalent to around 20% of the oil revenue of 2019.

The NZE policies harm the trade competitiveness of the non-energy sector, and the massive investments in energy transition technologies crowd out non-energy investments. The model's results show the possible macroeconomic impacts of the scenarios of net zero. We find that real GDP is around 3% below the baseline by 2060. The gap reaches 8% if we assume that the net zero policy occurs in the context of very low international oil prices. Moreover, we find significantly greater negative effects on household consumption.

Keywords: Saudi Arabia net zero emissions, price controls, general equilibrium model

JEL Classifications : C61, C68, H23, Q41, Q48

I. Introduction

Saudi Arabia aims to reach net zero greenhouse gas (GHG) emissions by 2060 (SMEGI 2022). This objective is particularly challenging, given that energy is a prominent part of the country's economy. Fulfilling the net zero objective will require costly investments in restructuring the energy sectors toward carbon neutrality. Therefore, it is crucial to assess potential optimal transition pathways for Saudi Arabia, what policies could help to achieve them, and at what cost for the economy. It is also important to carefully consider external factors that will influence the domestic energy transition. In the case of Saudi Arabia, the international oil market outlook plays a key role given the importance of oil export revenue (59% of fiscal revenue in 2021), and, therefore, needs to be factored in for an analysis of domestic net zero policy.

This paper investigates the economic consequences of implementing net zero emissions (NZE) policies in Saudi Arabia. We use a new hybrid forward-looking general equilibrium model of the Saudi economy, which explicitly represents the main energy-intensive technologies and domestic energy prices. Based on various scenarios' simulations, we address two types of issues. First, we are interested in the shape of the least-cost energy transition for given assumptions about technologies. What could be the NZE energy mix? What can be the role of direct air capture (DAC) technologies? What implicit (shadow) carbon price would be needed? What could be the cost for the energy sector? What would be the effects on the rest of the economy? Second, we seek to understand the influence of international oil prices on the transformation of the energy sector and the entire economy. More precisely, we consider how the oil price can influence the least-cost energy mixes and the policies needed to achieve a net zero target. We also seek to differentiate the effect of the domestic mitigation bill—the additional costs to decarbonize the energy system—from the effect of changes in international oil prices.

Studies have stressed, from a macroeconomic perspective, the challenges fossil-fuel exporters or Gulf Cooperation Council (GCC) countries will face in achieving energy transition (Mirzoev et al. 2020; Peszko et al. 2020). Recent macroeconomic assessments of net zero scenarios have shown higher economic costs for oil exporters than for other economies (Chateau et al. 2022; Jaumotte et al. 2021), but provide little insight into the underlying transformation of the energy sectors. Some studies have presented consistent assessments of energy and macroeconomic pathways toward net zero emissions for advanced energy-exporting economies (e.g., Adams [2021] for Australia). But thus far, to the best of our knowledge, there has been no assessment of the economy-wide implications of net zero for an energy-exporting emerging economy like Saudi Arabia.

This paper contributes to the modelling literature about the energy transition in oil-exporting emerging countries in four ways. First, it fills an important gap by providing for Saudi Arabia—the world's first oil exporter—a model-based long-term baseline of CO_2 emissions rooted in a structured energy economy storyline. Second, it is the first paper that provides a general equilibrium assessment of a net zero scenario for an energy-exporting emerging economy. Third, this paper explicitly investigates the influence of the international oil price outlook on the outcome of energy policies in Saudi Arabia. Last, this work introduces a new dynamic forward-looking model of Saudi Arabia. Unlike the myopic computable general equilibrium (CGE) models where agents' foresight is limited to the current period of time, forward-looking models represent agents who consider the consequences of their current decisions on present and future outcomes. This forward-looking framework helps identify a welfare-maximizing pathway to net zero and sets milestones for policy action.

We find least-cost net zero trajectories with increasing electrification of energy demand, a large penetration of renewable electricity, and then of gas with carbon capture and storage (CCS), and nuclear technology. In fact, altogether, the carbon capture technologies (including CCS in power, industry, blue hydrogen as well as DAC) play a very significant role. The CO_2 captured by 2060 is equivalent to the total emissions of 2019. The CO_2 price consistent with this net zero starts from USD 50–65 per ton in 2020 and increases to USD 270–330 per ton by 2050. Because lower international prices reduce the opportunity cost of using liquid fuels, they lead to higher domestic carbon prices. We find that if the international oil price is high enough (above USD 70 per barrel), important emission reductions can be achieved without carbon prices, only by deregulating domestic energy prices and letting them adjust to international levels. Our results also show that reaching net zero requires increasing the share of total energy sector expenditure in gross domestic product from around 7% to 10–12% between 2021 and 2060. This rise comes from the need to invest in capital-intensive technologies such as nuclear, CCS, and finally, DAC. Net zero policies tend to increase the volume of oil exported because of reduced consumption, much like what would happen with a price reform. But if the oil price is lower, for instance because the rest of the world also implements stringent decarbonization policies, the energy revenue decreases. In the case of very low international oil prices, the cost that the energy sector has to pay for its decarbonization may exceed the oil revenue before 2040. Our results also show that the net zero policies lead to a reduction of GDP by around 3% below the baseline if international oil price remains high, and by 8% if the international oil price becomes very low. However, we find significantly greater negative effects on household consumption.

The paper is structured as follows. In the second section, we present elements of context about Saudi Arabia's net zero policies and review the related modeling literature. In the third section, we introduce the modeling framework. The fourth section describes the baseline and introduces scenarios that combine energy policies in Saudi Arabia and alternative international oil prices. The fifth section presents the main simulation results, describing the effect of the policies on the energy sector and on economic activities. It also highlights how international oil prices influences the net zero pathway of the energy sector and the overall economic performance. The last section presents the conclusion.

2. Net Zero Scenarios:

Costs of Domestic Mitigation and Costs Due to Transforming International Energy Markets

In the context of its pledge to achieve carbon neutrality by 2060, Saudi Arabia reaffirmed its commitment to the Paris Agreement. In the 2021 update of its nationally determined contribution (NDC), the country states it aims at "reducing, avoiding, and removing GHG emissions by 278 Mt of CO_2 equivalent annually by 2030."[1] Saudi Arabia has put in place a series of initiatives aimed at reaching the NDC objective and preparing for the transition to net zero. The main initiatives in the energy sector cover renewables, liquid replacement in utilities, energy efficiency, clean hydrogen, and carbon capture.

Policies in the power sector aim to increase the share of renewable energy to 50% of the electricity mix while phasing out the use of liquid fuels. Measures are also in place to improve energy efficiency in the building and transportation sectors (Belaïd and Massié 2023; Ministry of Energy 2022), and to foster carbon removal by planting 650 million trees in the Kingdom by 2030 as part of the Saudi and Middle East Green Initiative (SMEGI 2022). However, an aspect of net zero strategies specific to Saudi Arabia and the GCC region is the key role given to clean (green and blue) hydrogen and carbon capture technologies. The country plans to ramp up its carbon capture storage and utilization system to capture 44 Mt of CO_2 by 2035 (SMEGI 2022). There are multiple reasons why carbon capture is so important for Saudi Arabia's energy transition. First, in the power sector, gas with CCS can be a suitable complement to non-dispatchable renewable technologies. Moreover, CCUS is the main abatement option in the hard-to-abate industrial sectors (for instance cement or chemicals), which are particularly developed in the Saudi economy. In addition, CCUS is necessary for developing blue hydrogen, which would give value to domestic gas reserves. Last, in a net zero world where some emissions would remain impossible to abate, DAC may be an option that needs to be envisaged and Saudi Arabia may have a competitive advantage due to the presence of depleted oil reservoirs where considerable quantities of CO_2 can be stored.

The deployment of carbon capture technologies requires costly investments and further efforts will be needed to reach net zero. Households and businesses will face an increase in energy expenditure. Exporting firms will have to preserve their price competitiveness while complying with stringent environmental regulations. Moreover, the transformations in Saudi Arabia's energy sector will play out within a context where other countries implement net zero policies, with possible consequences on the global oil market. Widespread adoption of net zero policies may exert downward pressure on oil prices and influence the economies of Saudi Arabia and other oil exporters. The Kingdom may have to adjust to a context of lower oil revenue while having, at the same time, to pay a high cost for restructuring its energy system. However, the new energy landscape may also create new opportunities. Hydrogen and CCUS may also help build new competitive advantages for Saudi Arabia in global energy markets.

Assessing the costs and opportunities of net zero requires a quantification combining various technology options with a representation of possible future socioeconomic developments in the Kingdom. There have been several modeling assessments of the consequences of energy conservation policies in Saudi Arabia. Matar et al. (2015) develop and use a detailed partial equilibrium model of the energy-intensive sector to investigate administered price reforms and their consequences on oil export revenue. Soummane et al. (2022) simulate price reforms combined with structural policies using a CGE model and stress how they can offset the negative effects of lower international oil prices. Blazquez et al. (2020) use a dynamic stochastic general equilibrium model to represent the macroeconomic effect of energy price reforms. Durand-Lasserve et al. (2023) extend Matar et al.'s (2015) model to represent the impacts of price reforms both on the energy sector and on the rest of the economy.

However, despite the vast literature focused on price reform, thus far, there have been only very partial assessments of the consequence of decarbonization policies for Saudi Arabia or even for GCC countries. Using a linear programming (LP) model adjusted to Saudi Arabia, Alshammari and Sarathy (2017) study pathways to reduce CO_2 emissions by 80% in the power sector. They combine exogenous energy efficiency improvements that reduce fuel demand, caps on liquid fuel utilization, and carbon prices. They find that CCUS plays a key role in mitigation before renewable technologies are deployed at full scale. Their result is at odds with the literature on least-cost mitigation policies, which generally finds that relatively cheap renewable technology is deployed before CCS, which is relatively expensive. However, Alshammari and Sarathy (2017) stress that beyond a certain threshold of international oil prices, the oil sector would be willing to pay for CO_2 to enhance oil recovery at a price above the average capture cost. Their approach, however, has important limitations. In particular, given that the oil supply in Saudi Arabia is primarily driven by policies within OPEC, there is no reason why higher oil prices should stimulate a massive boost of oil production through enhanced oil recovery. Using an ad-hoc approach, Al-Sinan et al. (2023) explore long-term CO_2 emission pathways based on expert judgments and a series of separated calculations, assessing the impact on emissions of various policy initiatives that are to be fulfilled by 2030. The authors find that if continued beyond 2030, the initiatives will lead to almost net zero GHG emissions by 2060. However, due to the lack of an integrated modeling framework, their results are more of a narrative than a proper quantification.

The only modeling assessment thus far of a net zero trajectory for a GCC country is that performed by Babonneau et al. (2022), who use a bottom-up LP model of energy sectors to simulate net zero emission pathways in Qatar. They highlight the possible role of renewable and direct air capture technologies. Once net zero is achieved, they envisage that Qatar will further remove carbon from the atmosphere via DAC and receive offset payments from the rest of the world. More precisely, with a levelized DAC cost of USD 300 per ton of CO_2 and an international CO_2 offset price of USD 1,200 per ton at 2100, the authors find that the revenue of exporting emissions permits compensates for around 50% of the losses in gas revenue due to global climate change policies. They conduct sensitivity analysis and find tipping points in the DAC cost and in the offset price where the export of offsets speeds up. The paper is particularly interesting because it covers emissions from the entire energy system, while it also shows the influence of DAC on gas and electricity demand. However, the assumptions about the adjustment in the oil and gas revenue are ad-hoc because the scenarios assume changes in export volumes, not export prices. Therefore, the adjustment of domestic energy technologies does not reflect changes in international energy prices. Moreover, their model does not represent administered prices and the impact of price deregulation. In addition, there is little discussion on whether the carbon offset price scenarios that are used are plausible. Finally, the model does not assess possible macroeconomic feedback effects of the net zero policies. These effects are relevant for all GCC countries, given the size of the energy sector in their economy and the role of energy exports.

To assess the consequences of net zero policies on the energy sectors and on the rest of the economy, we use a new forward-looking hybrid general equilibrium model that represents least-cost policies and covers all the sources of CO_2 emissions.

3. Model Description

This section presents the model used for simulating the net zero pathways for Saudi Arabia. First, we summarize the rationale of the model. Then, we give a high-level algebraic presentation, which can be skipped if the reader is not interested in the mathematical formulation. Details about the various technologies are provided in the tables of appendices A and B.

3.1 General Overview

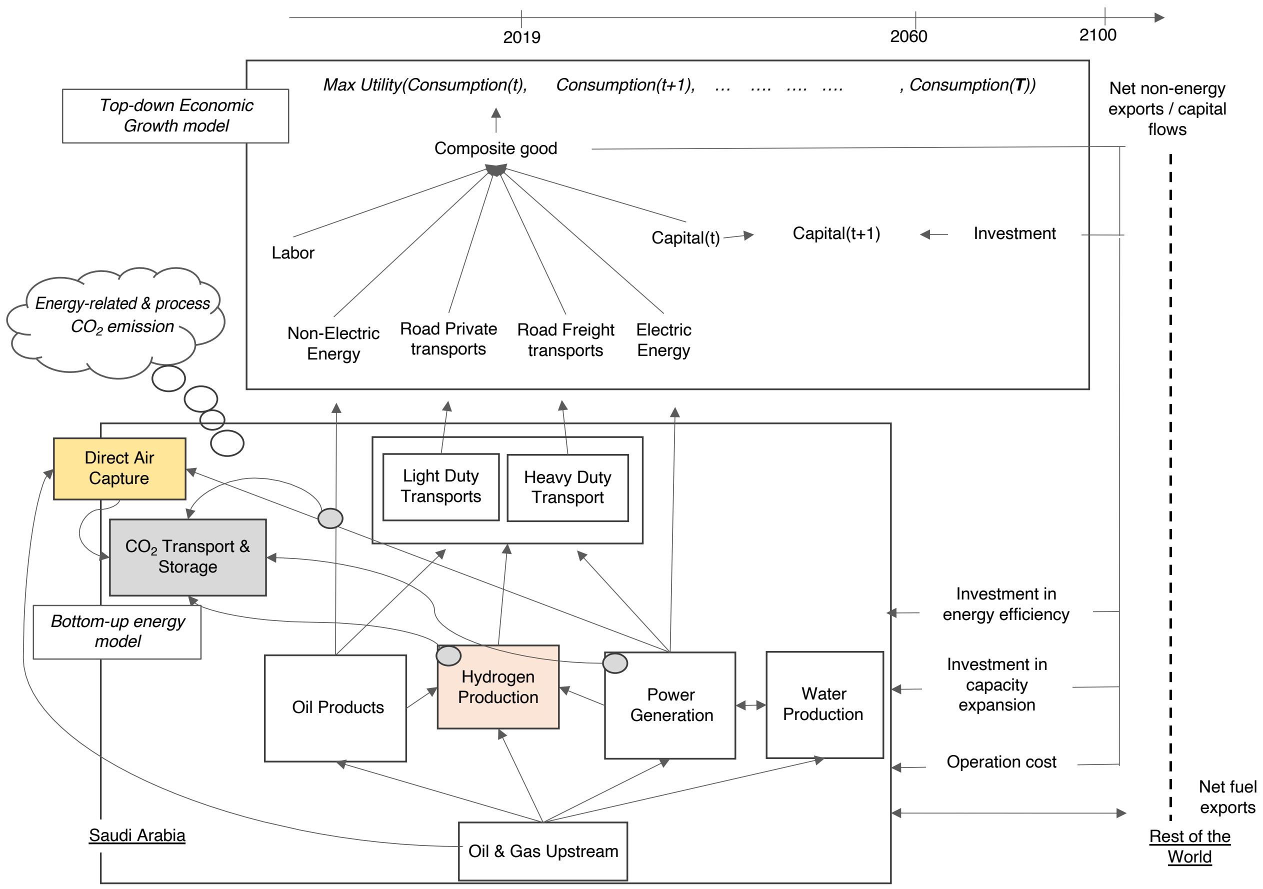
The general equilibrium model of Saudi Arabia's economy focuses on energy and GHG emissions[2] and serves to produce long-term least-cost scenarios under alternative macroeconomic, energy technology, and environmental policy assumptions. It belongs to the family of forward-looking models such as MERGE (Manne et al. 1995), WITCH (Bosetti et al. 2006), or REMIND (Leimbach et al. 2010). The model represents Saudi Arabia as an open economy and includes the most prominent features of the Kingdom's energy system, in particular price controls.

The model is based on maximizing the intertemporal welfare of a representative household (at the top of Figure 1) under technology and energy balance constraints. This maximization problem serves to mimic the functioning of energy and non-energy markets in perfect competition. Dual variables represent market clearing prices. To represent price controls, we write the first-order condition of the maximization problem and introduce endogenous price wedges to fix prices for energy consumers at the level that is set by the government. In the end, we formulate the mode as a mixed complementarity problem (MCP). The welfare is represented by an intertemporal utility function that depends on the consumption of a composite good over each period of time (one year). The composite good is produced using labor, capital, electricity, non-electric energy, water, and transportation services. Part of the composite goods produced is utilized for investment. The intertemporal utility maximization is a tradeoff between, on the one hand, the instantaneous benefits of immediate consumption and, on the other hand, the net present value of the gains from having a larger capital stock that increases future production and consumption. The tradeoff depends on (i) how easily households can reallocate consumption through time without incurring utility losses, and (ii) what additional production is made available in the future thanks to investments.

The energy submodel (at the bottom of Figure 1) represents the supply and the transformation of energy. Crude oil and gas are produced by the upstream sector. Some of the crude is transformed into oil products. Oil products, crude, and gas are utilized for power and water production, heavy and light-duty transportation, and other final energy consumptions (in buildings, industry, agriculture). Crude and oil products are also exported, and gas can be used to produce blue hydrogen. Electricity can be produced from fossil fuels and renewable sources. It serves the final consumption (buildings, industry, electric vehicles) and also powers the production of green hydrogen and the capture, transportation, and storage of CO_2. The non-fuel cost of producing and transforming energy and providing energy services is a claim on the output of the composite good. Therefore, the non-fuel cost decreases household consumption and utility. At equilibrium, if there are no price controls, the welfare-maximizing technology portfolio minimizes the intertemporal cost of supplying energy. Moreover, the social planner will adjust the demand of the various energy-intensive inputs to ensure that their marginal productivity is equal to their marginal cost.

Climate policies such as GHG emissions constraints or GHG prices can be represented in the model. These policies influence the least-cost energy mix and lead to the adoption of technologies that would not be welfare-maximizing otherwise. The model also allows CCS technologies to be deployed in power generation, for capturing process emissions, and for DAC. These CCS options will only be deployed in the case of ambitious climate policies.

Figure 1. Schematic View of the Model.



Source: Author.

The linkage with the rest of the world is represented succinctly through the trade of energy, non-energy products, and capital flows. The surplus (deficit) of the current account balance represents an outflow (inflow) of capital. At each period, the closure rule of the model imposes a fixed current account balance. Because of the fixed current account balance, exporting (importing) more energy commodities requires importing more (less) consumption goods. The adjustment of the real exchange rate—which determines the trade competitiveness of the non-oil sector—ensures that the current account remains fixed. Specifically, if oil export revenues increase, the real exchange appreciates and the non-oil export revenue decreases. Therefore, the model represents the Dutch disease effect.

3.2 High-Level Mathematical Formulation

Here, we represent the model as an optimization problem that maximizes the intertemporal welfare W of a representative household.

$$W = \sum_t \beta_t \frac{C_t^{\,1-\theta}}{1-\theta},$$

where C_t is consumption of the composite good at time t, β_t is the social discount factor, and θ is the elasticity of domestic saving to the interest rate. Note that the intertemporal elasticity of substitution is equal to $\frac{1}{\theta}$. In the simulations, we consider the case where $\theta = 1$, which corresponds to a Cobb–Douglas intertemporal (or logarithmic) utility function.

The domestic demand corresponds to consumption, C, investment I in the non-energy sectors, and net non-fuel energy system costs, denoted by ECOST:

$$XA_t = I_t + C_t + ECOST_t. \qquad (1)$$

The composite good XA is an Armington aggregate of goods XD produced domestically and goods XM that are imported. Domestic and imported goods are combined using a constant elasticity of substitution function denoted by F_t^{arm}:

$$F_t^{arm}(XD_t, XM_t) \geq XA_t. \qquad (2)$$

The domestic economy produces an aggregate output Y that is allocated to the domestic market (XD) or exports (XX). To represent how production is assigned to domestic and foreign markets, we use a constant elasticity of transformation function, denoted as F_t^{cet}:

$$Y_t = F_t^{cet}(XD_t, XX_t). \qquad (3)$$

The composite output Y_t is produced by a representative firm as a combination of exogenous effective labor (AL), capital (K), electricity (E), non-electric energy (N), heavy-duty and light-duty transportation services (HDV and LDV respectively). All these inputs are combined in a putty-clay nested CES production function noted F_t that has the structure described in Appendix A. We denote the inputs or output from the latest vintages with the letter "Δ". The production function can be written as:

$$\Delta Y_t = F_t(\Delta\overline{AL}_t, \mathrm{I}_{t-1}, \Delta E_t, \Delta N_t, \Delta HDT_T, \Delta LDT_t)$$

with:

$$Y_{t+1} = (1-\delta_y)Y_t + \Delta Y_{t+1},\ K_{t+1} = (1-\delta_y)K_t + \mathrm{I}_t,$$
$$E_{t+1} = (1-\delta_y)E_t + \Delta E_{t+1}, N_{t+1} = (1-\delta_y)N_t + \Delta N_{t+1},$$
$$HDV_{t+1} = (1-\delta_y)HDV_t + \Delta HDV_{t+1}, \qquad (4)$$
$$LDV_{t+1} = (1-\delta_y)LDV_t + \Delta LDV_{t+1}$$

At each period, the firm chooses an input mix for the new vintage of equipment. However, the proportion of inputs is fixed for the equipment of older vintages, which decay at an annual rate, δ_y. The representative firm is forward-looking. It minimizes the cost of supplying output for given input prices over the entire time horizon. Because of the vintage structure, demand for the various energy services depends on their current and anticipated prices, and the price elasticities of input demands are greater in the long run than in the short run. The elasticities of substitution in the production function are calibrated such that the long-term own price elasticity of demand for electric, non-electric energy, and transportation services are close to −0.2. as in Durand-Lasserve et al. (2023). The rate of decay, δ_y, is extrapolated from social accounting data and is equal to 1.8%.

Products MM can be imported to be incorporated into the Armington good (Equation 2), and their price is denoted by PM. Products XX produced domestically can be exported (See Equation 3) and their export price is denoted as PX. The import and export prices are exogenous and serve as numeraire in the model. The current account balance, CAB, is exports minus imports of composite goods, plus exports minus imports of energy commodities, determined in the bottom-up model and denoted by EXP^{bu} and IMP^{bu}, respectively:

$$CAB_t = PX_t.XX_t - PM_t.XM_t +$$
$$PX_t^{bu}.EXP_t^{bu} - PM_t^{bu}.IMP_t^{bu}. \qquad (5)$$

Here we give a high-level algebraic representation of the bottom-up model. First, the bottom-up model supplies energy services (denoted by the superscript bu) that meet the input demand from the representative firm of the top-down model:

$$E^{bu} \geq E,\ N^{bu} \geq N,\ HDV^{bu} \geq\ HDV,\ LDV^{bu} \geq\ LDV. \quad (6)$$

The bottom-up model also determines the quantities of energy commodities that are imported and exported. Finally, an outcome of the bottom-up model is a trajectory of energy services and energy commodity imports and exports. Now, we can define the feasible set of activities in the bottom-up model that allows the fulfillment of a given outcome. The feasible set is the set of X that satisfies:

$$H.(E^{bu}, N^{bu}, HDV^{bu}, LDV^{bu}, EXP^{bu}, IMP^{bu}, X) \leq b, \quad (7)$$

where the supplies of energy services are represented as trajectories (i.e., vectors of dimensions T) and where and EXP^{bu} and IMP^{bu} are matrices that contain the trajectories of exports and imports of the various commodities. The feasible production set in Equation (7) includes all the energy balances, the various energy efficiency coefficients, and all the expenditures needed to produce and transform energy. For instance, in Equation (7), H contains the production of electricity by type of power generation plant, at a given period, while H also includes the formula that aggregates production from different plants into the total supply of electricity, and it also represents how much fuel needs to be consumed per unit of electricity produced by this technology and how it will influence total gas demand. The feasibility set H also represents the OPEX and the CAPEX needed for the power generation technology. Last, H includes intertemporal constraints, for instance, capacity expansion dynamics or the maximum penetration rate of technologies. At each time point, the total cost for the energy system $ECOST_t$ corresponds to:

$$ECOST_t = coste_t . X_t,$$

where $coste_t$ represents the sum of all CAPEX and the non-energy OPEX associated with each action. The total cost for the energy system is a claim on the demand for domestic goods, as shown in Equation (1). Welfare maximization implies that, for a given demand for energy services in the top-down model—exports and imports—the energy system cost is minimized. Increasing imports or reducing exports—in short, reducing net exports—can be a way to reduce energy costs and could increase welfare. However, reducing net exports will exert downward pressure on the current account balance in Equation (5). However, given that the closure rule of the model imposes that the current account is fixed, the real exchange rate will depreciate. The net exports of non-energy goods ($PX.XX\text{-}PM.XM$) need to increase, which reduces domestic demand XA in Equation (1). Therefore, changing net energy exports will also tend to reduce welfare.

At the welfare optimum, the marginal benefit of consuming an energy commodity domestically must be equal to the marginal benefit of the revenue generated by exporting this commodity. In other words, if a commodity is exported, its price for domestic consumers needs to align with its export price. The export price is here the opportunity cost of the commodity.[3] Note that, in the baseline scenario, the domestic prices are administered and that they cannot adjust to the opportunity cost. Therefore, in the baseline scenarios, the welfare is not maximized. In our model, welfare maximization requires that commodity prices are deregulated.

4. The Baseline and the Policy Scenarios

Here, we present the baseline and policy scenarios that combine domestic policies with different international oil prices. We also discuss the implications of the closure rule on the type of macroeconomic response.

4.1 The Baseline Scenario

The *baseline* scenario represents what would be the Saudi economy at the horizon of 2060 without stringent global and domestic climate policies. In this scenario, we consider that, because of the absence of widespread emissions regulation, world oil demand and price remain high in the long run. In our *baseline* scenario, the oil price converges to USD 95 per barrel in the long run, as projected in the Stated Policies Scenarios (STEPS), which is the scenario of IEA (2022) with the least ambitious climate objective.

The macroeconomic and energy baseline aims to reflect some elements of structural change in the Saudi economy that would occur if the oil prices were high and in the absence of climate policy or domestic energy price reform. In terms of the modeling process, a preliminary baseline is elaborated with a spreadsheet accounting model that translates into an organized dataset of key assumptions about the driving forces that will shape the Saudi economy. Then, the dataset is used to calibrate the macroeconomic part of the general equilibrium model. Finally, we run the model to obtain the baseline scenario that fully respects the circular accounting relationships that cannot be represented in the simple spreadsheet model while reflecting with relative accuracy the projections of the individual series and the characteristics of the various energy technologies contained in the bottom-up part of the model.

Here, we briefly describe our main assumptions and how they influence the shape of the baseline. We begin the baseline construction by building a long-term growth trajectory. We project employment, capital, and labor productivity. For employment projections, we construct population, then activity and unemployment rate trajectories. We make distinctions between nationals and foreigners, men and women, public and private sector. This distinction represents how changes in the relative weights of these segments of the labor markets will impact potential growth. The population of nationals is assumed to grow in line with the population projections (without migrations) of the UN (2022). We assume that the share of foreign workers will increase from 40% in 2018 to 60% in 2060. We assume that the participation rates of Saudi men and women (63% and 22%, respectively, in 2018) increase to reach the OECD averages by 2050 (53% and 69% respectively). At the same time, we assume that the unemployment rates of Saudi men and women (7% and 30% in 2018) ramp down to 5% and 12%, respectively, by 2030, in line with the Vision 2030 objective. We also assume that employment in the public sector, which concerns mostly nationals, slows down compared with the pre-2018 growth rate and that policies reduce the gender gap. The number of women in the government sector is assumed to increase by 1.5% annually, and the number of men by 0.5%, leading to a public employment growth below 0.7% per year. The private sector is assumed to be the main job creator for nationals, with an annual increase of private employment of nationals of around 5.6% annually between 2019 and 2030, before slowing down afterward. In the long run, the share of Saudis in employment will be stable until 2050, despite the share of foreigners in the total population increases. We assume annual labor productivity growth of 1% for all categories of workers. However, because of changes in the employment structure, the aggregate productivity growth is slightly negative before increasing by around 0.3% annually by 2040. We finalize the projection of non-oil GDP by assuming that the investment rate will be scaled up, in line with the National Investment Strategy (NIS 2021).

Once we have determined the potential output, capital stock, and labor trajectories, we define the consumption of electric, non-electric energy, water, heavy-duty, and light-duty transportation. For energy trajectory, we assume that the sectoral structure of the economy evolves towards slightly more services, in line with Vision 2030, and then remains stable afterward. Then, we consider that, in each sector, energy efficiency gains until 2040 will reflect those of the last decade. Moreover, we assume that the use of private-duty vehicles increases at the same rate as the population and that heavy-duty vehicle utilization increases at the same rate as non-oil GDP. Likewise, we assume that water consumption increases at the same rate as the population. We use the input demands, as well as the potential output, to calibrate the production function of Equation (4). Using the projection of input demand, we establish a summary of domestic energy consumption. We also make summary projections of oil production, in line with the objective of increasing capacity to 13 million barrels per day, and assuming that spare capacity will be reduced to around 700,000 barrels per day. From the supply and domestic consumption of oil and oil products, and given the international oil prices, we evaluate the net oil export revenue.

Table 1. Main Characteristics of the Baseline Scenario.

	2019	2030	2040	2050	2060	CAAG (2019-2030)	CAAG (2030-2060)
Population (th.)	35.4	46.3	55.6	64.5	71.9	2.5%	1.5%
Labor Force (th.)	15.9	23.5	31.1	38.3	43.3	3.6%	2.1%
Employment (th.)	15.3	22.9	30.1	37.1	42.0	3.7%	2.0%
Nationals	5.7	8.9	11.6	13.5	13.4	4.2%	1.4%
Public	1.8	2.0	2.1	2.3	2.5	0.7%	0.8%
Private	3.8	6.9	9.5	11.2	10.9	5.6%	1.5%
Foreigners	9.6	13.9	18.5	23.5	28.6	3.4%	2.4%
Unemployment rate	12.7%	7.4%	7.9%	8.3%	8.5%	−4.8%	0.5%
GDP (billion 2019 SAR)	2,910	4,176	5,339	6,590	7,765	3.3%	2.1%
Oil	813	1,083	1,102	1,119	1,132	2.6%	0.1%
Non-oil	2,097	3,093	4,237	5,471	6,634	3.6%	2.6%
Non-oil GDP/capita (th. SAR)	59,301	66,850	76,225	84,803	92,259	1.1%	1.1%
Current account[a] (billion SAR)	141	154	110	48	−73	-	-
Energy goods	749	883	866	864	783	-	-
Non-energy goods & services	−485	−508	−438	−376	−275	-	-
Current Account Balance as % of GDP	4.8%	3.3%	1.9%	0.7%	−0.9%	-	-
World oil price (USD/Barrel)	65	82	88	95	95	2.1%	0.5%
GHG emissions (Mt CO_2eq)	681	853	1,043	1,238	1,444	2.1%	1.8%
CO_2	567	693	827	957	1,088	1.8%	1.5%
Combustion & processes	576	702	836	965	1,096	1.8%	1.5%
Land use	−9	−9	−9	−9	−9	0.0%	0.0%
CH_4	60	84	114	153	202	3.1%	3.0%
N_2O	11	12	13	14	16	0.9%	0.9%
F-GAS	44	65	89	114	139	3.6%	2.6%
Primary energy demand (Mtoe)	266	316	368	417	482	1.6%	1.4%
Energy Intensity[b] (Mtoe/Million SAR)	127	102	87	76	73	−1.9%	−1.1%
CO_2 Intensity[c] (tCO_2/toe)	2.17	2.22	2.27	2.31	2.27	0.2%	0.1%

Sources: Author's calculations. Notes: [a] Including remittances. [b] Primary energy intensity of the non-oil sector. [c] CO_2 intensity of primary energy consumption.

Finally, for the baseline projections, we determine what the current account position of Saudi Arabia will be. To this end, we project the oil and non-oil imports and exports. We assume that the non-oil exports increase at a 2% annual growth rate, while imports increase by less than 1% per year only; hence, we represent an improvement of the non-energy trade balance, and then we add the oil export balance to complete the current account balance. We calibrate the CGE models to replicate the various baseline assumptions and obtain the baseline scenario projections described in Table 1.

4.2 Scenarios of Domestic Policies Under Alternative International Oil Price Contexts

To illustrate the influence of the international oil price on Saudi Arabia's energy transition, we define scenarios around alternatives to the baseline along two dimensions: (i) the domestic energy or emission reduction policy, and (ii) the international oil price trajectory. The first line of Table 2 corresponds to the scenarios with no-mitigation action and no-price reform in Saudi Arabia.[5] We find on this line the baseline scenario[6] explained above, where the oil price is USD 95 per barrel in the long run and where there is no domestic mitigation action. The other scenarios—*Baseline-MidOil* and *Baseline-LowOil*—feature lower international prices of USD 60 and USD 24 per barrel in 2050 based on IEA's (2022) Announced Pledges and NZE scenarios respectively. Note that the *Baseline-LowOil* scenario represents what would happen if Saudi Arabia were flying solo, having no climate policies while the other countries do.

In the second line of Table 2, we represent scenarios of price reforms where the Saudi government lets domestic energy prices adjust to market conditions. Energy producers who can export their commodities will consider the opportunity cost of not selling at the international price, and they will ultimately adjust their prices to the international level. We consider price reforms under the three different oil prices to assess whether higher or lower oil prices increase or decrease the emissions impacts and the economic benefits of the price reforms.

Table 2. Overview of the Scenarios.

		International price of oil and oil products in 2050[a]		
		High ($95/bl)	**Medium ($60/bl)**	**Low ($23/bl)**
Mitigation Policy in Saudi Arabia	Business as usual policy: • No domestic climate policies. • Domestic energy prices are set by the governments	**Baseline** *(=Baseline-HighOil)*	*Baseline-MidOil*	*Baseline-LowOil*
	Domestic energy prices are deregulated	*Reform-HighOil*	*Reform-MidOil*	*Reform-LowOil*
	Emissions reduction Domestic energy prices are deregulated,[a] uniform carbon prices cover all the emissions	*NZE-HighOil*	*NZE-MidOil*	*NZE-LowOil*

Notes: [a]The prices are taken from IEA (2022), STEPS = Stated Policies, APS = Announced Pledges Scenario, NZE = Net Zero Scenario.

Policies other than price deregulation will be needed to decarbonize the economy and to reach NZE. Therefore, we introduce scenarios with a domestic net zero policy (line 3 of Table 2) where the price deregulation is accompanied by a cap and trade system that covers CO_2 emissions from energy combustion and industrial processes. The cap corresponds to an exogenous quantity of emissions allowances that are distributed every year and that are gradually decreased, until reaching net zero by 2060. To allow for some flexibility and to represent policies that minimize the intertemporal mitigation cost, we allow for the banking of emission permits. If, at some periods, the emissions do not reach the cap, allowances in excess can be saved and used to exceed the cap in subsequent periods. As previously, we examine the results of the net zero policy under the three different oil prices mentioned above. The scenario *NZE-LowOil*—with decarbonization and low oil price—corresponds to a global net zero policy where Saudi Arabia and all the other countries of the world would implement net zero policies. Note that the scenario with decarbonization and high international oil price (*NZE-HighOil*) seems rather inconsistent because it depicts a situation where Saudi Arabia would be a single climate leader, implementing net zero on its own, while other countries would merely implement their NDCs. However, this scenario is useful because it serves to isolate the "pure effects" of the net zero policy (i.e., the effects due to the domestic net zero policy only, and not to changes in international energy markets).

5. Simulation Results

First, we present the emissions trajectories and the energy mix in the baseline, the price reform, and the net zero scenarios. Then, we show the effect of the various scenarios on energy system costs and energy export revenues, and we discuss the contribution of clean hydrogen exports. Finally, we explain possible macroeconomic impacts, seeking to differentiate the effect of the domestic mitigation bill from the effect of changes in international oil prices..

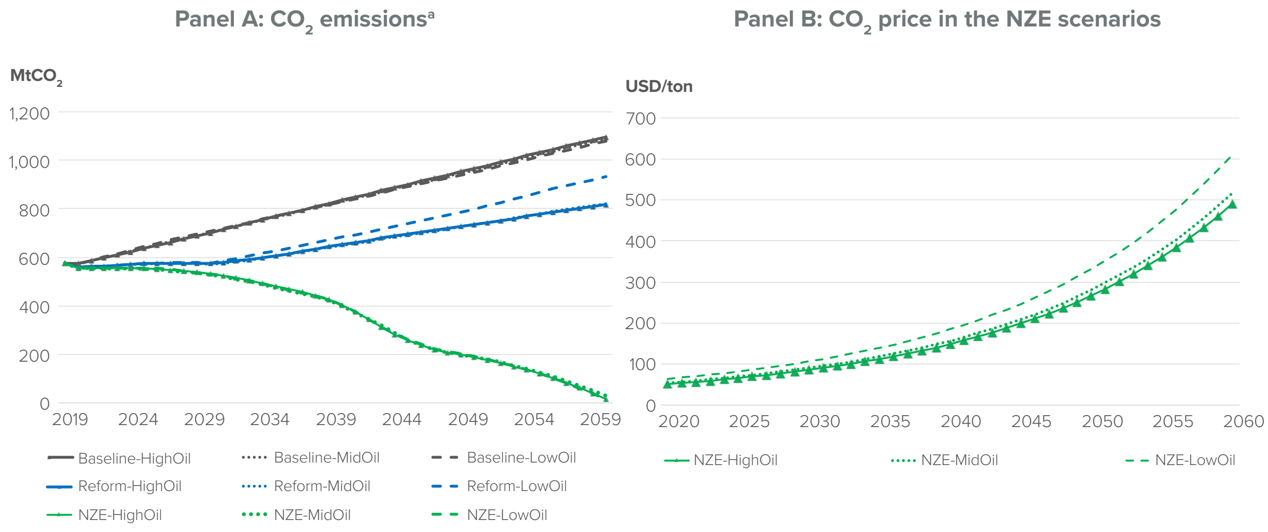
5.1 Emissions and Energy Mix

In the three baseline scenarios (i.e., in the *Baseline*, *Baseline-MidOil*, and *Baseline-HighOil* scenarios, represented by black lines in Figure 2), CO_2 emissions will almost double over the next 40 years and reach 1.1 giga tons by 2060. The international oil price has little influence on the emission trajectory. In these three scenarios, domestic energy prices are administered and set at the same level, yielding similar carbon intensities. The slight difference in emissions comes from a macroeconomic activity effect (see infra, Figure 10). Lower oil revenues deteriorate the real exchange rate, and stimulate non-oil output growth and energy consumption at the beginning of the model's horizon. Then, non-energy output is negatively affected by a reduction in investment and emissions are slightly lower. However, the activity effects are extremely limited, and emissions are very close among the baseline scenarios.

Price reform scenarios (blue lines in Figure 2) give substantially less CO_2 emissions than the baseline scenarios. Price reforms reduce CO_2 emissions compared with the three baseline scenarios by 18% in 2030 and 15% to 25% by 2060. The reduction is realized because domestic energy prices have been adjusted upward to match international prices. Moreover, oil prices influence the emissions trajectory. As the figure shows, when the prices are deregulated, low international prices lead to higher emissions (see *Reform-lowOil* scenario). This is the result of the predominance of price effects: lower international prices involve less upward adjustment of domestic price, less energy conservation, and more CO_2 emissions. There is slightly less non-oil sector activity if the oil price is low (see infra in Figure 10), but this activity effect is limited compared with the price effect.

In the net zero scenarios (green lines in Figure 2) the decarbonization objective is so constraining that emissions follow a similar path, close to the maximum abatement potential. Here, CO_2 emissions ramp down to zero in a very similar way, whatever the oil price is. By 2030, CO_2 emissions will be around 170 Mt below the baseline. However, is this 170 Mt CO_2 emissions reduction compatible with the objective of reducing total GHG emissions by 278 Mt CO_2-eq below a baseline in 2030 as stated in the NDC? Achieving this NDC target would require reducing net GHG emissions by 108 (278–170) Mt CO_2-eq due to (i) non-CO_2 GHG emissions mitigation and (ii) carbon removal with nature-based solutions. A few side calculations show that it would be extremely difficult to realize. First, abating 110 Mt CO_2-eq of non-CO_2 GHGs by 2030 would require a two-third reduction of non-CO2 GHG emissions compared with the baseline level (160 Mt of non-CO_2 GHG emissions in 2030, as Table 1 shows). Second, a nature-based solution can only play a limited role by 2030. For instance, back of the envelop calculations suggest that the fulfillment of the Saudi Green initiative with the plantation of 650 million trees by 2030 would not lead to an emissions reduction of more than 15 Mt of the CO_2,[7] which is only a very small portion of the 108 Mt net CO_2 emission reduction needed to meet the NDC. We conclude that, paradoxically, the GHG emissions reduction objective for 2030 announced in the current NDC may be more ambitious than what is needed to meet net zero by 2060.

Figure 2. Saudi Arabia CO_2 Emissions and CO_2 Shadow Prices.



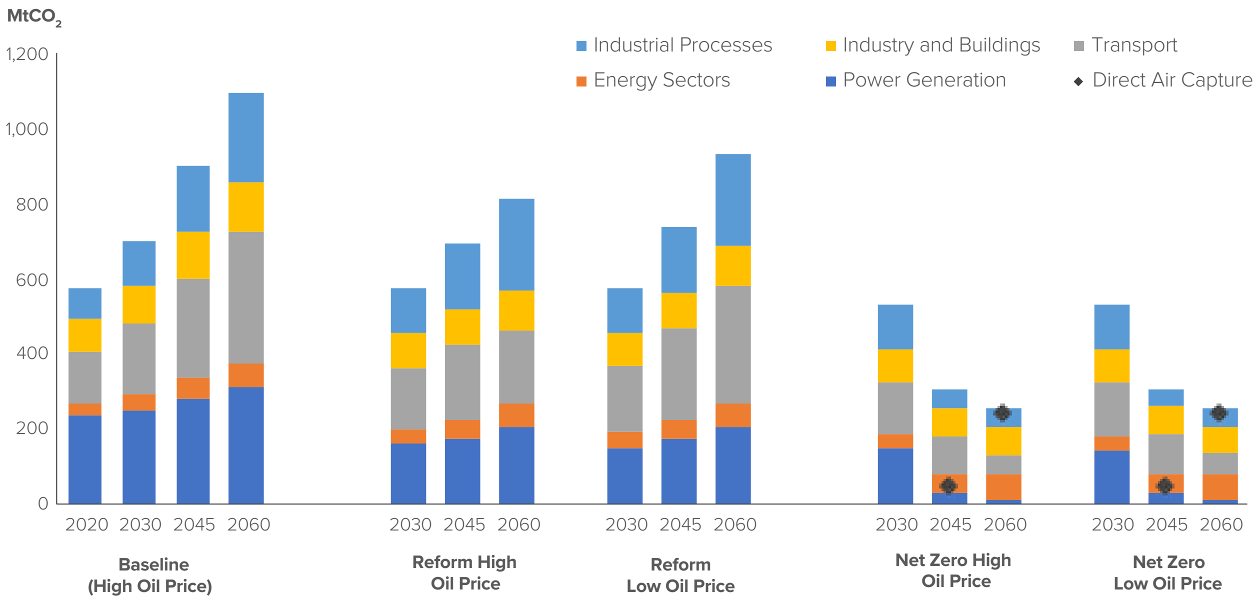
Source: Author's calculations.

Notes: A) CO_2 emissions from combustion and processes.

Our results show that even if different oil prices yield the same net zero emissions trajectory, there are different CO_2 shadow prices (Figure 2, panel B). In contexts of high and medium international oil prices (*NZE-HighOil* and *NZE-MidOil* scenarios), the CO_2 price starts at around USD 50 per ton and reaches around 270 USD per ton by 2050. A low international oil price (*NZE-LowOil* scenario) leads to a carbon price that increases from USD 65 in 2020 to USD 330 per ton in 2050. The opportunity cost of oil, which directly relates to the international oil price, is an important incentive for reducing liquid fuel consumption and emissions during the first years of the model. If the international oil price is lower, the opportunity cost is lower, and a higher carbon price is needed to discourage the use of oil products. This is why the carbon price is higher in the *NZE-LowOil* scenario, despite lower economic activity (see activity on Figure 10, panel D). The carbon prices needed to reach net zero, as shown in Figure 3, are high and can weigh on the competitiveness of the energy-intensive industries in Saudi Arabia if the rest of the world does not take stringent mitigation action as well (as in *NZE-HighOil* scenarios).

In the net zero scenarios, the carbon price grows at the same rate as the interest rate of the economy, which is around 5%. Least-cost emission abatement implies that the marginal abatement cost is constant in discounted value. From an emission market perspective, it means that in early periods, emissions were lower than the quotas, and that emissions permits were therefore banked. Emissions permits are an asset that is withheld as long as its annual rate of return is not less than the interest rate of the economy. Consequently, the prices of emission permits increase at the interest rate of the economy.

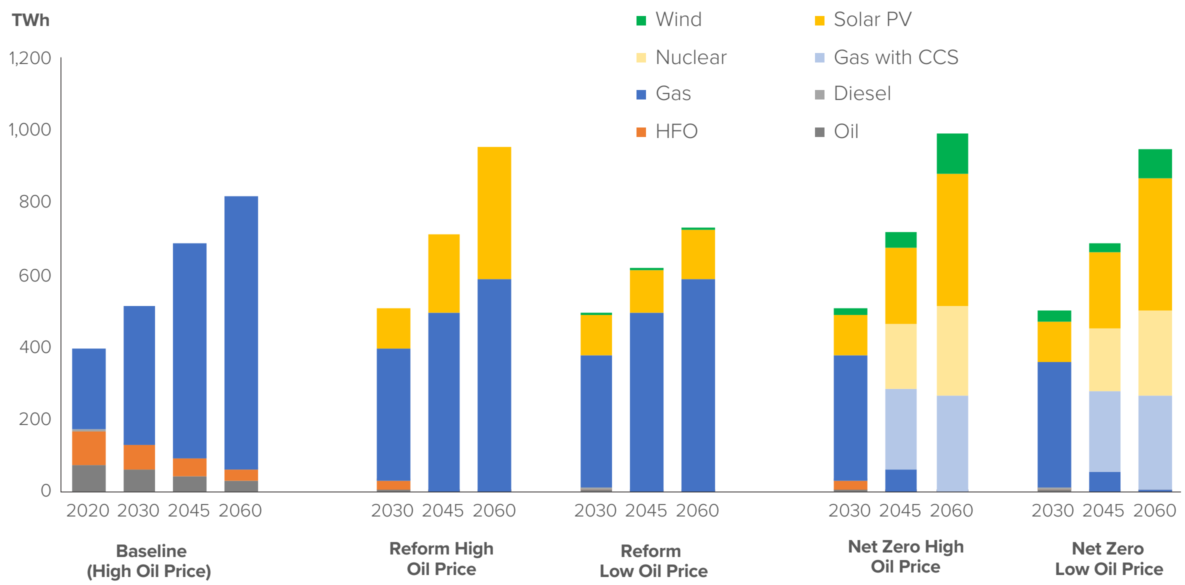
Figure 3. Sectoral Emission Pathways in Selected Scenarios.



Sources: Author's calculations.

When considering the sectoral breakdown of the CO_2 emissions (Figure 3), it is clear that in the price reform scenarios, emissions keep increasing in all sectors. We also see that a price reform leads to the same emissions in the power sector, whether the oil price is high or low. However, the price reform mitigates more transportation emissions if the oil prices are high. In the case of low international oil prices, the adjustment of relative transportation fuel prices after the price reform is not sufficient to simulate energy saving and fuel switching. In the case of the net zero emissions scenarios, the decarbonization pathways are the same whatever the oil price is. The electricity sector is totally decarbonized, and emissions decrease for all the sources represented, except emissions from the energy sector (own use of energy by the energy sector). Process emissions are reduced compared with the reference scenario, due to carbon capture and the substitution of blue for grey hydrogen. By 2060, there will be around 250 Mt of CO_2 emitted in the net zero scenarios. The abatement of these remaining emissions is extremely costly because it requires DAC, which starts being massively deployed by the mid-2040s. DAC runs using electricity that is already carbon neutral, and natural gas that is made available as more power generation comes from nuclear and renewable and less from gas. The levelized cost of abatement with DAC is reflected in the CO_2 price that we obtain by the end of the time horizon, which is around USD 500 per ton.

Figure 4. Electricity Mix in Selected Scenarios.

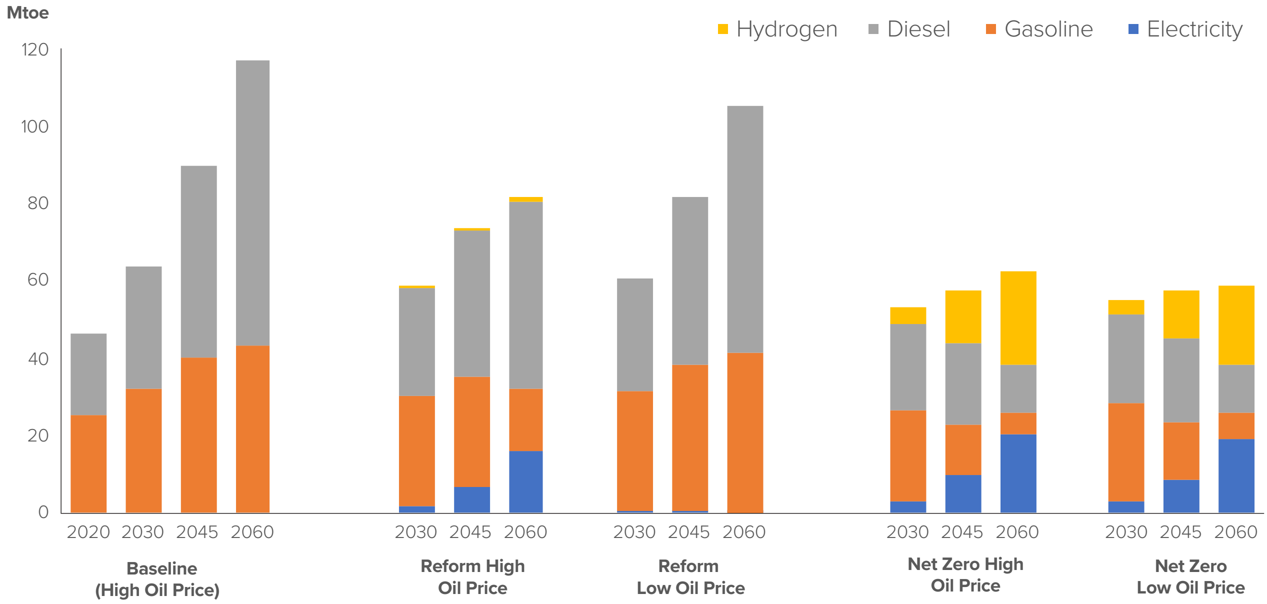


Sources: Author's calculations.

The price reforms and, to a greater extent, the net zero policy, lead to a considerable transformation of the electricity mix (Figure 4). In the baseline scenarios, the electricity mix is dominated by gas, which has a price administered and set below marginal production cost. Liquid-fired generation persists because, due to low administered liquid fuel prices, existing liquid-powered capacities are operated until the end of their lifetime. Price reforms lead to important transformations of the electricity mix. The first consequence is an accelerated phase-out of liquid generation in the power sector because of the opportunity cost of liquid fuels. Interestingly, even if the international oil price is low, the price reforms are sufficient to render liquids no longer competitive in power generation. Therefore, our results show that policies to phase out the liquid in power generation are cost-effective whether the oil price is high or low. In addition, because gas prices are higher in the deregulation scenarios, solar and wind generation ramps up quickly. In the long run, in the deregulation scenarios, electricity is supplied entirely by solar, wind and natural gas. Importantly, in the case of higher oil prices, there is greater electricity demand. If the oil price is high, the electricity is cheaper relative to other energy carriers, and there is more electrification of demand. Moreover, there is a higher demand from the transportation sectors, where part of the demand switches to electricity (Figure 5).

Figure 4 shows that total power generation is greater in the net zero scenarios than in the baseline scenarios. Moreover, in the net zero scenario, the electricity mix is not affected by the oil price. The least-cost pathways for net zero are based on electrifying of demand and decarbonizing power generation. In addition, the need to fuel DAC facilities and reach net zero increases the total electricity demand. In 2060, the electricity demand from DAC is equivalent to around 10% of the electricity consumption of 2019. Electricity generation is carbon neutral before 2050. Unabated gas generation is phased out very early, with no investment in new units and a large deployment of solar technologies. By the 2030s, nuclear, then gas with CCS capacities expand. Finally, in 2060, power generation comes entirely from solar technologies (PV and CSP), and nuclear and CCS technologies.

Figure 5. Energy Consumption in Transportation.

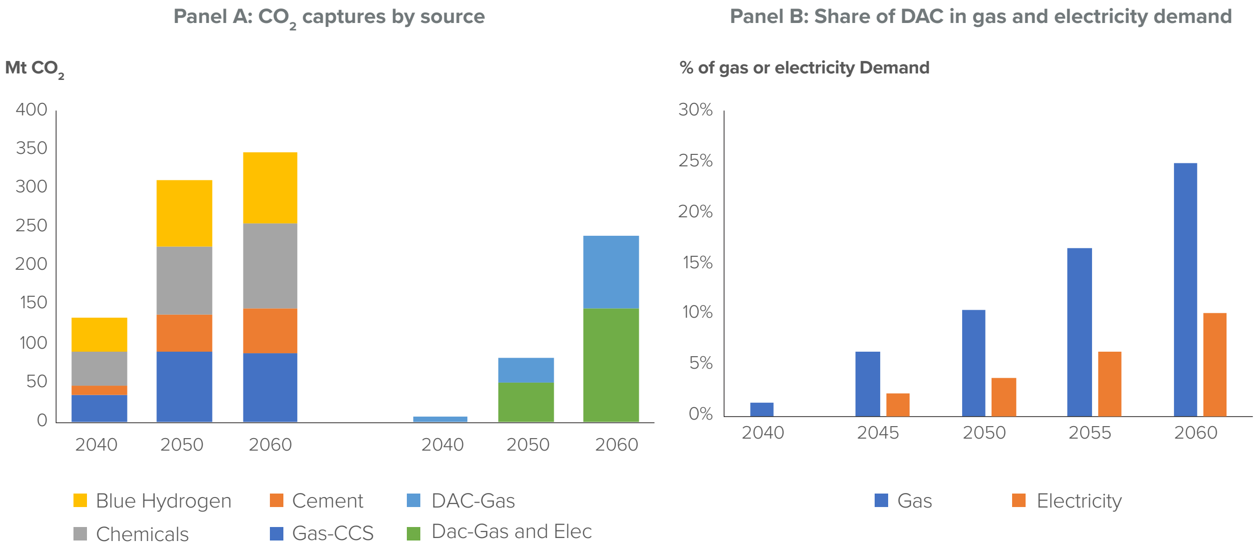


Sources: Author.

In the baseline, transportation fuel demand (Figure 5) grows quickly, driven by non-oil GDP and population. Light-duty vehicles entirely rely on gasoline, the administered price of which is close to the international level. Heavy-duty vehicles entirely rely on diesel, the administered price of which is very low. Price deregulation has a significant impact on energy consumption in transportation. The upward price adjustment reduces demand for diesel, even in a situation where the international price is low. Moreover, with a high oil price, the opportunity cost of liquid is high, and it encourages the penetration of electric vehicles. In the low oil price scenarios with reforms, the opportunity cost of liquids is too low to encourage fuel switching. In the net zero scenarios, we see a much slower growth of transportation fuel demand, as well as a change in the fuel mix that increases the energy density of fuel (with more electricity and hydrogen). In 2060, the demand for liquid fuel is around 60% lower than in 2020, and hydrogen and electricity represent more than 70% of the mix. The fuel switching, which is needed early on to achieve net zero, cannot be achieved with price deregulation if the international oil price is low. Therefore, a higher CO_2 price is needed to reach net zero with low international oil prices, as shown in Figure 2.

The net zero scenarios require considerable carbon capture and storage by 2060 (Figure 6, panel A). As early as 2040, 130 Mt of CO_2 are captured, coming in the same proportion from gas CCS, capture in industry, and blue hydrogen production. Capture from these sources accelerates by the 2050s and then slows down as gas CCS stalls and most of the carbon from processes has been captured. Then, DAC starts being deployed on a large scale. Total carbon capture finally reaches around 600 Mt CO_2 by 2060. This large number implies the construction of a considerable transportation and storage infrastructure in the net zero scenario. Moreover, to capture 250 Mt of CO_2 by 2060 the DAC sector consumes considerable quantities of energy: 25% of the primary gas demand and 10% of the final electricity consumption (Figure 6, panel A). Hence, the net zero stimulates gas demand.

Figure 6. Carbon Capture Technologies in the NZE-High Oil Scenarios.



Source: Author. Notes: share of gas used for powering DAC as a share of primary gas demand, and share of electricity used to power DAC as a share of final electricity demand.

5.2 Mitigation Costs, Oil and Hydrogen Export Revenue

The net-zero scenarios require very costly investments to mitigate domestic emissions and to expand carbon capture technologies, including DAC. At the same time, the energy export revenue will be impacted by the variations in international oil prices. Therefore, Saudi Arabia may be in a situation where it needs to fund considerable investments to achieve its net zero while simultaneously facing a substantial decrease in hydrocarbon revenue and even a slowdown of non-energy sector activities. Figure 7 summarizes the expenditure needed in the energy sectors and compares the total with the energy export revenue for various scenarios. On the expenditure side, we include all the non-energy CAPEX and OPEX to reflect the purchase of equipment for energy production, transformation, and consumption. Moreover, we have included the expenditure of the upstream, power, water, and hydrogen sectors. We have also added equipment that relates to carbon capture and storage—for DAC, capture in industry, and carbon transportation and storage infrastructures. We represent the energy export revenue on the same graphs with a line. The energy exports correspond to crude oil and oil products, as no hydrogen is exported in the scenarios presented in Figure 7 (there are exports of hydrogen in the sensitivity analysis scenarios shown later in the present subsection).

In the baseline scenario (Figure 7, panel A), the energy export revenue stagnates and then decreases in the long run. The reason for this is that we have taken a conservative assumption concerning oil production capacity in Saudi Arabia, considering that it will remain at 13 million barrels per day over the entire model horizon. At the same time, because of the low administered fuel prices, domestic consumption of liquids continues to increase and erodes oil export revenue. However, these revenues remain way above energy system costs (the stacked areas), showing that the energy sector is still a considerable net source of revenue by 2060. In the case of price reform with high international prices (Figure 7, panel B), the net revenue of the energy sector is even greater than in the baseline. Thanks to energy conservation induced by the upward adjustment of domestic prices, more liquids are available for export. We see that the energy export revenue is around 30% higher than in the baseline scenario and keeps increasing until 2050. However, a very low international oil price environment would lead to an accelerated decrease of the net energy sector revenue, which would ultimately become negative by 2045, despite the price reform (Figure 7, panel C).

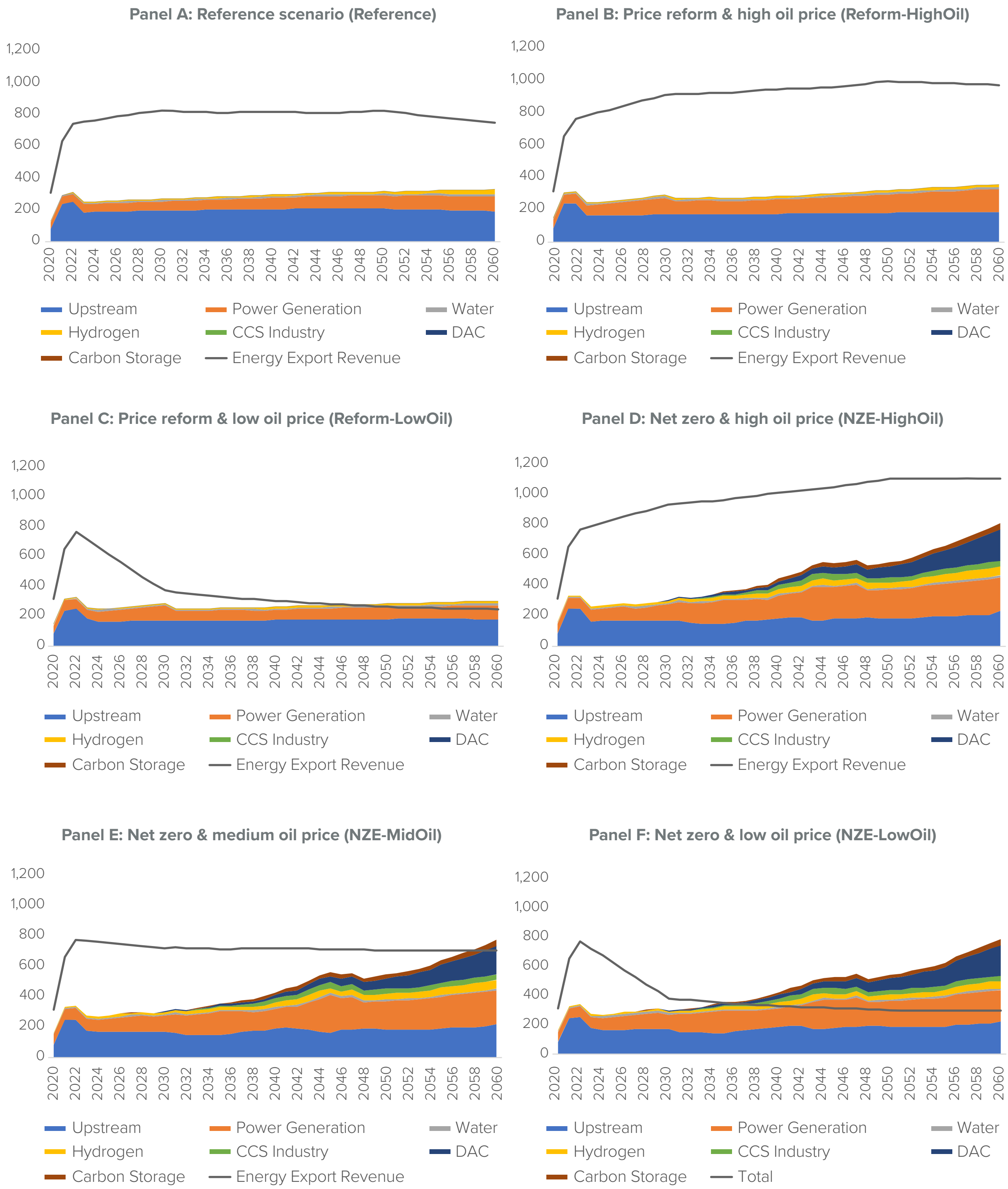
The scenarios with decarbonization (Figure 6, panels D, E and F) imply very high energy system costs. Expenditure in the power sector starts increasing from the first years of the time horizon. Decarbonizing the energy sector requires the early decommissioning of some gas unabated generation capacities and the deployment of solar CCS, and nuclear technologies that are capital intensive. Moreover, these new investments need to match a power demand that is greater because of the electrification of energy consumption, particularly in transportation. Last, carbon capture, and in particular DAC equipment, represents a considerable cost, especially after 2050.

Finally, in the net zero scenarios, the total energy system cost is multiplied by 2.4 between 2020 and 2060, whereas it increases by only 2.7% in the baseline scenarios, and a little less in the price deregulation scenarios. The share of energy system costs in the economy increases considerably in the decarbonization scenario: from 7% of GDP by 2020 to 12% of GDP in 2060. In contrast, in the baseline and price reforms scenarios, this ratio declines from 7% to 6% over the same period.

In the scenarios with net zero and high international oil prices, the net revenue of the energy sector remains largely positive, even in 2060, albeit that it has seriously thinned down (the line and the stacked area in Figure 7, panel D are becoming close). In this scenario, energy system cost represents around 75% of oil revenue in 2060, against 50% in 2021. In the scenarios with lower energy prices, net revenue becomes negative. Panels D and E of Figure 7 show that this occurs in around 2055 in the decarbonization with medium oil prices scenario, and as soon as 2035 in the decarbonization with low oil price scenarios.

We can expect that with the global energy transition, an international hydrogen market will emerge (IRENA 2022). Saudi Arabia has a large potential for clean hydrogen (blue and green) production. Clean hydrogen exports may offset part of the losses in oil revenue due to lower oil prices. In all the scenarios explored thus far, we have assumed that there is no international market for hydrogen. We could conduct a sensitivity analysis by considering that in scenarios of decarbonization where the price of oil is low (NZE-LowOil), Saudi Arabia can export blue or green hydrogen to international markets. We assume three alternative world prices for hydrogen. First, we consider that in a world of net zero, the free on board price of hydrogen would be USD 1.5 per ton of hydrogen. This price is roughly in line with BloombergNEF (Hostert 2022) and DNV (2022), who find a delivery hydrogen price of around USD 2.5U for importing regions, and with IRENA (2022) who consider a hydrogen transportation cost of around 1 USD/ton in 2050. Second, we consider a higher FOB price of hydrogen of USD 2.5, this price is very high compared with existing projections, and it will provide a highly optimistic assessment of hydrogen exports. Last, we take a hydrogen price of USD 0.5 per kg, which will give an extremely pessimistic assessment.

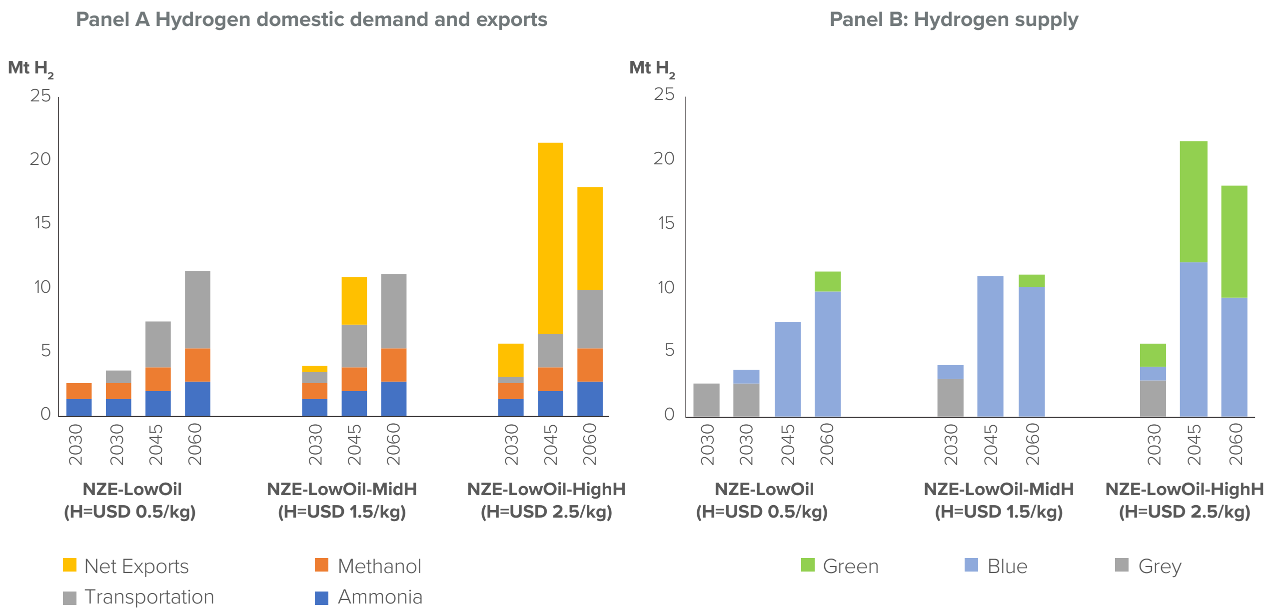
Figure 7. Energy System Cost Energy Export Revenues (2019 SAR per year).



Source: Author's calculations.

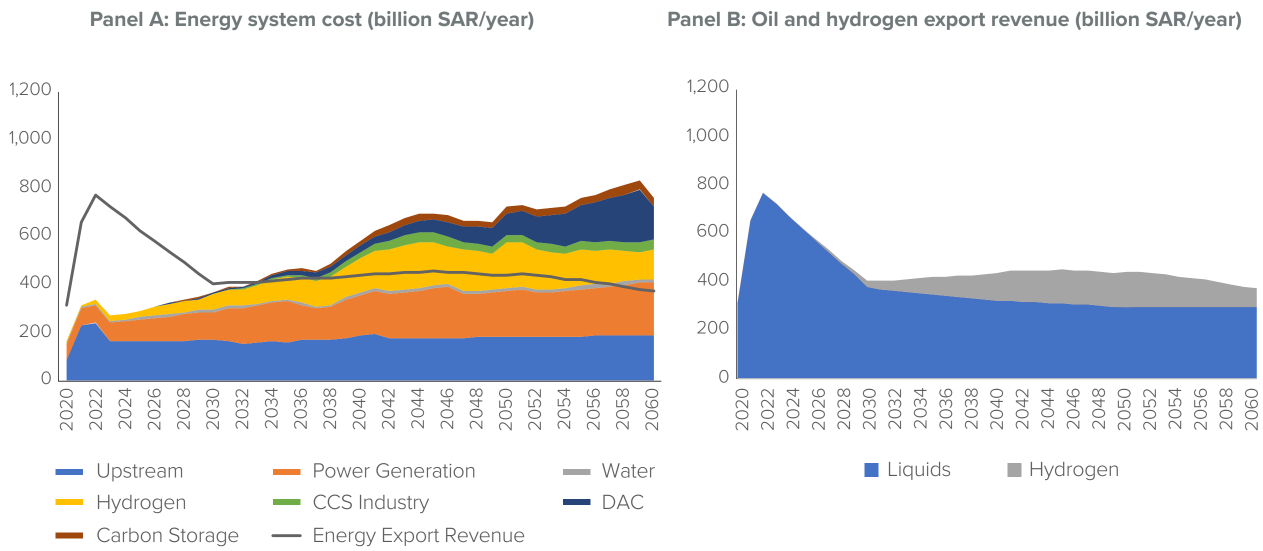
For prices of USD 1.5 per kg and above, Saudi Arabia starts exporting hydrogen by 2030 (Figure 8). However, then its exports peak as the domestic demand for clean hydrogen is too high, stimulated by the decarbonization of transportation and substitution to grey hydrogen in industries. If the price of hydrogen is not greater than USD 1.5 per ton, there is no export by 2060. Blue hydrogen is the privileged technology for clean hydrogen in the 2030s and 2040s, thanks to large volumes of gas that are available following the fuel switch to renewable energy in power generation. Then, the domestic price of gas increases due to demand from gas CCS power generation and DAC. Consequently, green hydrogen becomes more competitive.

Figure 8. Analysis of Sensitivity to Hydrogen Price in the *NZE-LowOil* Scenario.



Sources: Author. Notes: the graphs do not represent the demand for hydrogen in refineries and in the steel sector. Hydrogen production for refineries and steel was in 2020, hydrogen consumption in these two sectors represented around 50% of Saudi Arabia's hydrogen consumption.

Figure 9. Energy System Costs and Export Revenue in *NZE-Low Oil* scenario with hydrogen at USD 2.5/kg.



Source: Author. Note: hydrogen price = USD 2.5 per kg.

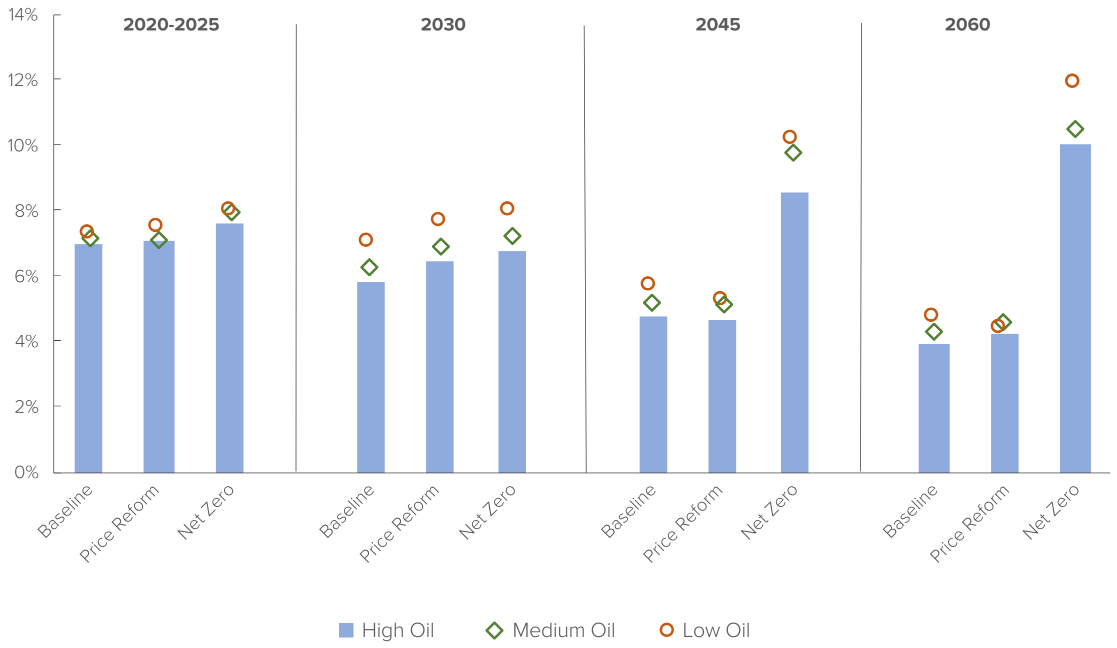
The export of hydrogen brings additional energy revenue to Saudi Arabia (Figure 9, panel B). However, even if taking the highly optimistic assumption of a hydrogen price of USD 2.5 per kg, hydrogen exports do not represent in value more than 20% of the energy export revenue that Saudi Arabia had in 2019. Moreover, the development of hydrogen exports requires considerable spending to increase production capacity.

5.3 Macroeconomic Effects of Mitigation Cost and Variations in International Oil Prices

In the baseline and price reform scenarios, the share of energy in GDP decreases in the long run: from around 7% in the early 2020s to around 4% by 2060. This decrease comes from the technological improvements and from the gains in energy efficiency that were assumed in the baseline. Another reason is that without an implicit price of carbon, the energy mix in the baseline and in the price reform scenarios can rely on low-cost carbon-intensive technology options. In contrast, in the net zero policy scenarios, the share of energy expenditure in GDP increases to reach 10–12% by 2060 (Figure 10). The implicit price of carbon leads to the adoption of technologies that are way more expensive than those adopted in the baseline (Figure 8).

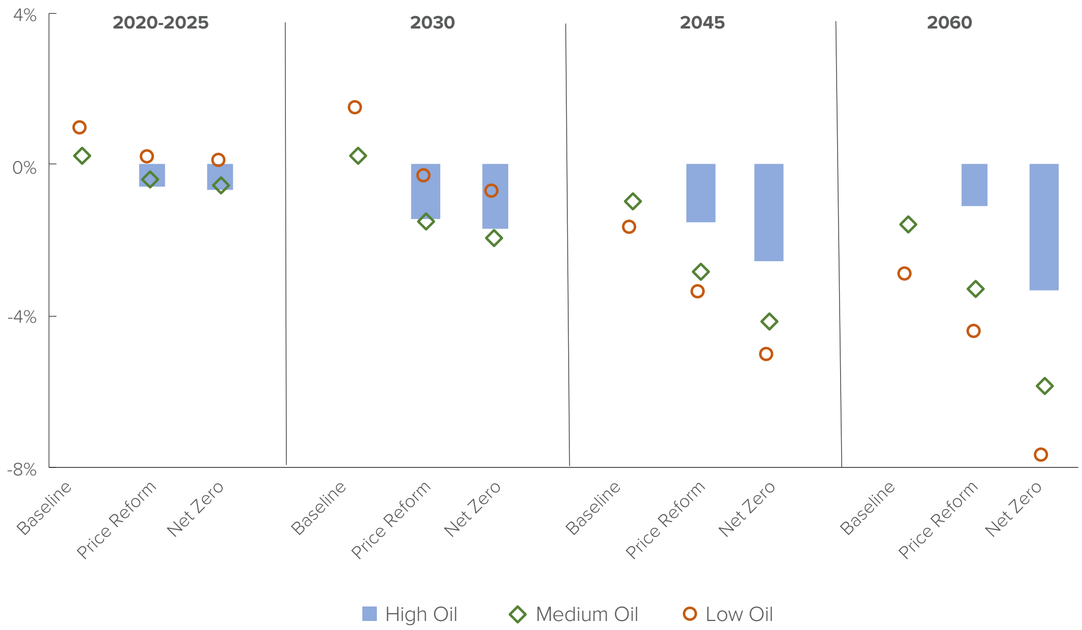
The net-zero policy has a significant impact on real GDP. Figure 11 shows that by 2060, the net zero policy can reduce real GDP by around 3% compared with the baseline if the international oil prices remain high, and up to 8% if the oil prices are low. Net zero policies have three distinct effects that are all detrimental to GDP. First, the greater energy system expenditure that is needed for decarbonization crowds out domestic demand and non-energy investments, leading to a lower non-energy output. Second, the net zero policies raise energy costs, which leads to an inflationary effect. The real exchange rate increases and reduces the trade competitiveness of the non-oil sector which, as a result, produces less. Third, the net-zero policies exaggerate the Dutch disease effect. Domestic mitigation policies reduce the domestic consumption of oil products and increase their exports. Oil revenue inflows increase. As a result, the real exchange rate appreciates, which harms the competitiveness of the non-oil sector. Note that the price deregulation scenarios also increase the export of fossil fuels and lead to the same type of Dutch disease effect as net zero scenarios, with a negative impact on GDP. Lower international prices of oil tend to mitigate the effect of the Dutch disease. They limit the oil revenue inflows and keep the real exchange rate at a low level. As Figure 11 shows, paradoxically, in the medium run (until 2030), lower oil prices are associated with a greater GDP. However, in the longer run (after 2030), lower oil prices depress domestic consumption and investment in the non-energy sector and lead to worse real GDP outcomes.

Figure 10. Energy System Costs as Percentage of GDP in the Various Scenarios.



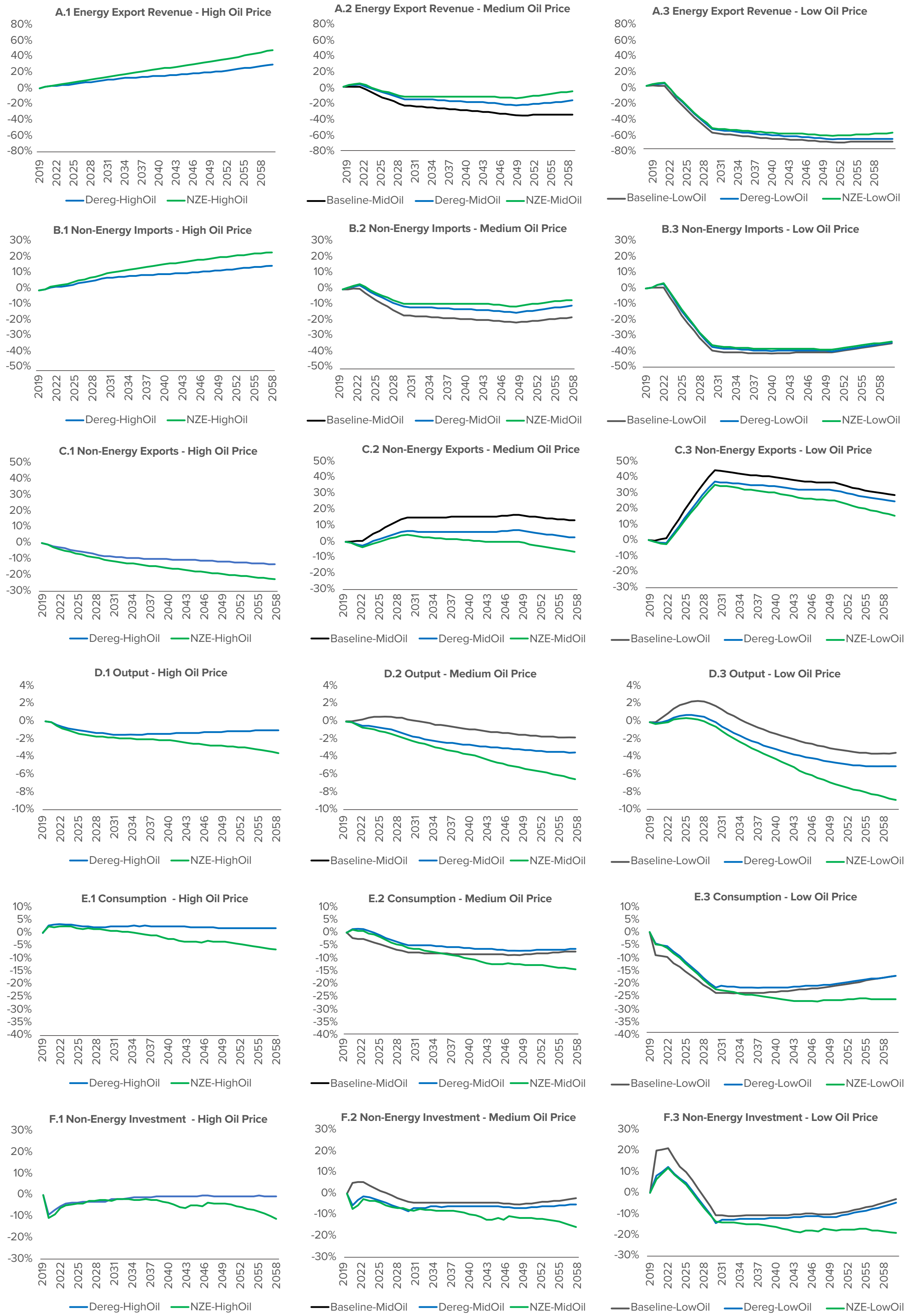
Source: Author.

Figure 11. Real GDP in The Various Scenarios as Percentage Deviation from the Baseline.



Source: Author.

Figure 12. Key Macroeconomic Indicators as Percentage Deviation from the Baseline.



Source: Author.

We plot the key macroeconomic variables in Figure 12. All the results are represented as deviations from the baseline scenario. The left side quadrants represent the responses of variables to domestic policies (price reforms and net zero) in a high oil price context. The quadrants in the middle and the right represent the responses in a medium and low oil price context.

First, let us examine the left quadrants of Figure 12 to understand the effect of price reforms and net zero policies if the international price of oil remains high. Both policies increase energy saving and, therefore, energy export revenue (panel A.1). This positive revenue shock gives way to an appreciation of the real exchange rate that deteriorates the non-oil trade balance. Non-energy imports increase (panel B.1) and non-energy exports decrease (panel C.1). Finally, the non-energy output decreases (panel D.1). The decrease is more pronounced in the case of the net zero policy. In this case, the real exchange rate appreciates more than in price reform scenarios because the high domestic decarbonization bill crowds out non-energy investment (panel F.1). In the price reform scenarios, the reduction of price distortion leads to an increase in consumptions (blue line on panel E.1). Overall, in both the price reform and the net zero scenarios, the higher real exchange rate has a positive influence on consumption. However, in the net zero scenarios, the increase in energy system cost crowds out consumption, which, after an initial rise, slides below the baseline (panel E.1). Higher energy prices, as well as exchange rate appreciation, reduce investment over the first periods of the time horizon (panel F.1). Moreover, we see that, in the net zero scenario, the crowding out effect on non-energy investment worsens gradually, following the increase in the domestic decarbonization bill.

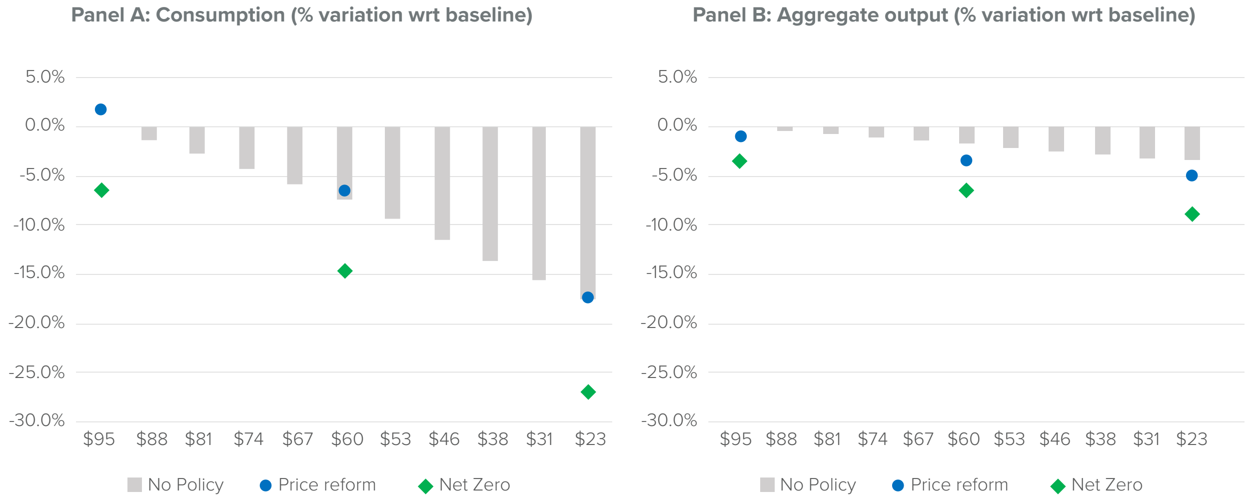
The middle and right-side quadrants show the adjustment mechanisms in cases of lower international oil prices. As seen previously, net zero policies, and, to a lesser extent price reforms, increase non-energy exports (panels C.2 and C.3). This, in turn, affects non-oil output. In the medium run, lower oil prices stimulate non-energy output (before 2030, the black line on D.3 is above the black line of D.2, and both are above the baseline). However, in the longer run, they depress non-oil output (after 2030, the black line of D.2 is above the black line of D.3 and both slide down below the baseline). In the long run, total output is negatively affected by lower international oil prices (Figure 12, panel E). However, in the short run, as lower energy export revenue improves the non-energy trade balance, there is a positive effect on output. In the case of price deregulation with low international oil prices, over the first periods, output is higher than in the baseline scenario. Nevertheless, with time, output decreases, because of the reduction in domestic demand and non-energy investment. The response of investments is particularly interesting. On the one hand, negative terms of trade shock that stimulate domestic output will stimulate investment. Therefore, over the first time periods of the scenarios with the low oil price, investment tends to be higher than in the reference scenario. However, in the longer run, investment is negatively affected by lower domestic demand, and crowded out by the considerable increase in energy system costs (panels F.2 and F.3).

We see that the domestic decarbonization bill and the change in oil prices impact consumption and output in different proportions. Figure 13 shows the results of a sensitivity analysis on the oil price and plots the results in terms of consumption and output. This shows that the oil price environment has a greater influence on consumption than the domestic decarbonization bill. This is due to the importance of the terms of trade effects. If the oil price is high, consumption decreases to 6% below the baseline; if the oil price is very low and without net zero, the decrease reaches 17%. The net-zero policy affects consumption similar to a USD 25–30 decrease in oil price. Panel A of Figure 13 shows that the consumption loss in net zero scenarios with a USD 95 (USD 60) oil price is roughly equal to the consumption loss in a baseline scenario with a USD 67 (or USD 31) oil price. Overall, we find that in the long run, the non-energy output (Figure 13, panel B) is more resilient than consumption to the oil price. Moreover, the output is more impacted by the cost of decarbonization than by the oil price because the energy system spending crowds out investment.

Last, the results show that price reforms always increase consumption above the baseline (the blue lines are on the top in Figure 12, panel E) whatever the oil price is. Moreover, we see that the effects of the price reforms are more pronounced at the beginning of the time horizon. Therefore, price reforms appear to be a winning strategy with an early payoff. However, the gains from price reforms are less important in lower oil price contexts because of the lower initial price distortions.

However, to conclude this section on macroeconomic impacts, it is important to note that the closure rule we have chosen tends to exaggerate the adjustment that is realized through consumption. The assumption that the current account is fixed is highly restrictive. In general, when oil revenues fluctuate, to the current extent, price reforms significantly offset the decrease in revenue and domestic demand does not fully absorb the revenue shocks. For instance, a decrease in revenue generally leads to a worsening of the current account balance. Hence, the negative shock would probably be absorbed more smoothly by domestic demand than shown by our simulations. However, a large degradation of the current account balance cannot persist indefinitely. Therefore, there should be a mechanism that reduces imbalances. The fixed current account assumption is a simple way to represent this mechanism.

Figure 13. Effect of Domestic Policy and International Oil Price on Output and Consumption in 2060.



Source: author.

Note: As percentage of the baseline.

6. Conclusions

We used a forward-looking hybrid general equilibrium model to project possible net zero emission pathways for Saudi Arabia at horizon 2060 under alternative international oil price environments. Our net zero scenarios show a drastic transformation of the energy sector. Power generation becomes carbon-neutral by 2045 thanks to renewable, gas with CCS, and nuclear technology. Electricity and clean hydrogen represent two-thirds of the energy consumption of the transportation sectors by 2060. Abatement in industry occurs due to fuel switching, clean hydrogen, and a large deployment of CCS. However, substantial unabated emissions remain, and DAC ramps up after 2040. By 2060, around 250 Mt of CO_2 are captured with DAC, which is half the CO_2 emissions of 2019; DAC emerges as a new energy-intensive technology. By 2060, it consumes the equivalent of 25% of the primary gas demand and 10% of the final electricity consumption.

The implicit carbon price that incentivizes net zero increases from USD 50–65 per ton in the first years of the model to USD 270–330 per ton by 2050. This CO_2 price varies when we change our exogenous oil prices assumptions. Here, a lower oil price reduces the opportunity cost of using oil domestically and increases the implicit price of carbon needed to incentivize emissions reductions.

In the NZE scenarios, the share of energy system costs in GDP increases, from around 7% in the first years of the model horizon to around 10–12% by 2060. In addition, we find that if the NZE has to be implemented in a low international oil price environment, the energy system cost may eventually exceed the oil export revenue. Moreover, clean hydrogen export revenues are not significant unless we assume future hydrogen prices above the current mainstream institutional projections.

The NZE policies harm the trade competitiveness of the non-energy sector, and the massive investments in energy transition technologies crowd out non-energy investments. The model's results show the possible macroeconomic impacts of the scenarios of net zero. Real GDP is around 3% below the baseline by 2060. The gap reaches 8% if we assume that the net zero policy occurs in the context of very low international oil prices. Moreover, we find significantly greater negative effects on household consumption. The results also show the importance of price reforms to improve welfare, even though the gains from the reform are less important in a low oil price context.

The results provide several policy insights that can inform Saudi Arabia's net zero strategy. They show that in the medium term, existing and announced policy initiatives are aligned with the net-zero targets. The announced 2030 target of 50% of renewable and liquid displacements in the power sector is roughly on the trajectory of our net-zero least-cost pathways, whatever international oil price we assume. The support for carbon capture projects is consistent with the need to abate emissions from the energy-intensive sector to develop CCS in power generation and DAC. Given the size of the required carbon capture infrastructure, the results highlight the importance of initiating the development to create a sizeable industry that can be scaled up and benefit from learning by doing. Price deregulation policies can play an important role in mitigating emissions, but the results show that they are not sufficient, especially if the international oil price is low. Specific carbon mitigation actions are needed and the policies will have to be coordinated with a shadow price of carbon that harmonizes the incentives in the energy sector.

This price would have to consider the international oil price. Moreover, we find that that the current NDCs of reducing GHG emissions by 278 Mt CO_2-eq by 2030 relative to a baseline may be considered highly ambitious and may lead to a pathway below even that needed to reach net zero. The NDCs may be reformulated with an updated GHG abatement target and possibly an assessment of the baseline emissions to evaluate the progress towards reducing, avoiding, and removing GHG emissions and the alignment of the current policy efforts.

The results also provide insights into how Saudi Arabia can smoothly overcome the double challenge of investing in mitigation and seeing changes in export revenue. Several policy options can be envisaged to attenuate the cost and to shelter households and firms from high energy prices and financial stress. First, Saudi Arabia can use offsets to reduce the domestic cost of mitigation. Nature-based solutions in the country and the Middle East can serve this purpose, but more options can be envisaged. These offsets could be available at costs many times below the cost of abatement with DAC and they would significantly reduce the mitigation bill paid by Saudi Arabia. However, the country also needs to continue supporting the development of all the technology options that can reduce net emissions, especially carbon capture. Moreover, diversification within and beyond the energy sector will be essential to mitigate the cost of the transition for the economy. Hydrogen may generate revenue, but only in favorable market configurations, and costly investment will need to be backed by guarantees on the security of demand. Moreover, the scale of the net zero transformation is so important that it will stimulate certain activities. Sectors such as clean construction, building retrofitting, energy efficient material, renewable and carbon capture equipment, and critical minerals mining and processing will become particularly strategically important to reap new opportunities created by net zero. Industrial policies can support these sectors with targeted policy packages. The structure of the economy will also need to continue the adjustment toward improving the competitiveness of the non-oil sectors. Finally, budget policies must play a role by smoothing the cost of the energy transition. Our projections based on Vision 2030 parameters show strong current account surpluses in the first decades of the model's horizon, which means that the ongoing transformation of the Saudi economy may help generate large buffers able to absorb some of the cost of the energy transition and shelter firms and households from negative shocks.

The results help bring a consistent representation of possible energy transition pathways rooted in given technology and macroeconomic assumptions. The policy insights mentioned in the previous paragraphs deserve further modeling and analysis. Here we simply highlight two points. First, our macroeconomic closure rules, where the current account surplus is maintained as high as in the baseline, may leave too little room for mitigating potential negative effects on consumption. Part of the shocks in cost and revenue seen in the scenarios may be absorbed by the current account, through, for instance, changes in government spending. Moreover, the large surplus on the baseline could be used in the policy scenarios to partially offset negative effects on households. This would, however, reduce the competitiveness of the non-oil sector. Second, additional scenarios could be used to investigate the sensitivity of mitigation cost to the quantity or the prices of carbon offsets from abroad.

Endnotes

[1] See https://unfccc.int/sites/default/files/resource/202203111154---KSA%20NDC%202021.pdf

[2] Note that this paper focuses on CO_2 emissions only.

[3] Here, the opportunity cost is the export price because we assume no response of international energy prices to changes in energy exports. The international oil prices used in the model are exogenous and they are defined with the scenarios in Table 2. See Karanfil and Pierru (2021) for a generalization of the notion of opportunity cost to cases where the international price responds to exports.

[4] The international oil price trajectories of IEA (2022) are shown in Figure C.1.

[5] The only policy susceptible to limiting emissions is the ban on investment in liquid fired power plants and in thermal desalination. These policies are active in all the scenarios.

[6] The baseline scenario can be called *Baseline-HighOil* scenario, in line with the scenario names used in Table 2. But for simplicity we simply call it "*Baseline*."

[7] Assuming that a mature tree captures 22 kg of CO_2 per year (EEA 2012), the 650 million trees would, at maturity, capture 14.3 million tons of CO_2.

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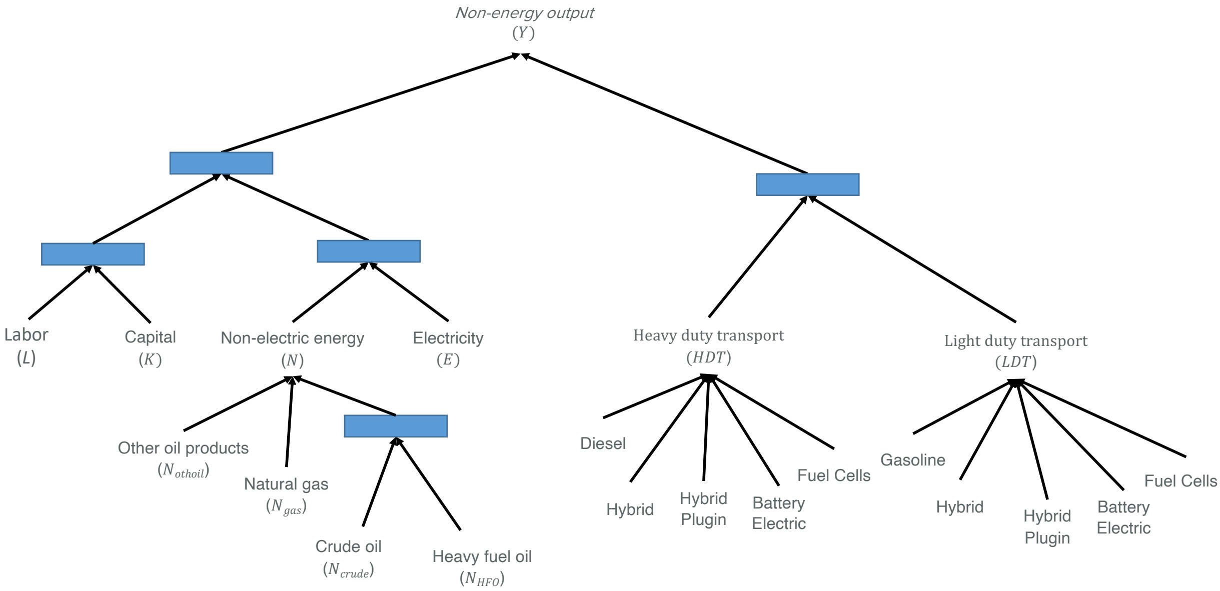
Notes

Appendix A

Figure A.1 Nest Structure of the Production Function.



Source: Author.

Appendix B

We summarize below how the various energy-related and emission abatement technologies are specified and calibrated in the bottom-up model.

Electricity can be supplied with 10 different electricity-only plants (Table B1). We allow for new investment in gas (with or without CCS), solar (photovoltaic or concentrating solar), wind, or nuclear capacity. As part of its “liquid displacement,” Saudi Arabia has already stopped investing in liquid-base power generation. Therefore, we exclude investment in power generation with heavy fuel oil, diesel, or crude oil. The heat rates of the already-installed technologies are computed based on IEA (2021a). The projected heat rates, CAPEX, and OPEX are drawn from IEA (2020) complemented by Irlam (2017) for gas with CCS and Feldman et al. (2021) for solar-PV. The load factors of the plants are set to match historical capacity and production. The split between various oil products (HFO, Diesel, and crude) is performed using ECRA (2019). To represent the need for backup technologies in the case of the large penetration of renewables, we imposed a minimum ratio of dispatchable (gas generation) to intermitted capacity (solar and wind) of 22%. This value is set based on the projections made in the sustainable development scenarios of IEA (2021d) for the Middle East and North Africa region. We also impose that nuclear does not exceed 25% of power generation. This upper bound is high compared with projections from IEA (2021d), and it can regarded as optimistic. For comparison, the shares of nuclear in the Middle East and the world projected in IEA’s (2021d) SDS do not exceed 5% and 9%, respectively.

The model includes thermal desalination plants that desalinate water and generate electricity using the excess heat (Table B.2). The model also includes desalination by reverse osmosis, which is a technology that runs on electricity only. In fact, RO is more energy efficient than cogeneration. Over the past few years, Saudi Arabia has invested in RO plants only. Therefore, the model excludes investments in cogeneration desalination plants. The heat rates of the water and electricity output of cogeneration power plants and the electricity intensity of RO plants are calibrated based on consumption and output from ECRA (2019) and MEWA (2019), and through using the water desalination technology reviews from Antonyan (2019) and Curto et al. (2021). The investment costs and the electricity efficiency of RO are based on Advisian (2018) and Curto et al. (2021).

Table B.1 Characteristics of the Electricity Technologies.

	Heat rate (GJ/Mwh)	Emission rate (tCO_2/Mwh)	Load factor	Investment cost (million $/Mw)
Oil (old)	12	0.8	30%	-
HFO (old)	6.5	0.47	30%	-
Diesel (old)	5.4	0.39	10%	-
Gas (old)	8	0.45	70%	-
Gas	6	0.33	70%	0.84–1.2
Gas-ncs	6.6	0.038	70%	1.86–2.66
Nuclear	-	-	80%	4
Solar PV	-	-	20%	0.7–0.96
Solar CSP	-	-	50%	5.00–7.46
Wind Onshore	-	-	20%	1.78–1.84

Source: Author's calculations based on IEA (2020), IRENA (2020), Feldman et al. (2021), and Irlam (2017).

Note: HFO = Heavy Fuel Oil, CCS = Carbon Capture and Storage.

Table B.2 Characteristics of the Main Desalination Technologies.

	Heat Rate of electricity GJ/Mwh	Heat rate of Water (GJ/km^3)	Electricity intensity (Mwh/km^3)	Load factor (%)	Investment cost kUSD/m^3/day)
Cogen Oil	13	223		80	
Cogen Gas	11	163		80	
Reverse Osmosis	-	-	5	90	1.5

Source: Author's calculations based on IEA (2021a), ECRA (2019), MEWA (2019), Antonyan (2019), Curto et al. (2021).

Non-fuel cost of the transportation equipment for the base year (Table B.3) is proxied using the import of vehicles and parts from the UN Comtrade (2021) database. The fuel costs are calculated using oil product consumption from transportation reported in IEA (2019) and information about proportions of diesel and gasoline consumption is drawn from SAMA (2022). Using administered transportation fuel prices, we obtained the total driving cost. The demand for transportation services is met by various power train technologies, as represented in TableB.3. The costs and fuel efficiencies of the various vehicles are based on Sheldon and Dua (2021), Burnham et al. (2021), Plötz et al. (2017), and IEA (2021b). Within the light-duty and the heavy-duty group, the power train technologies are potentially infinitely substitutable. However, to avoid a “winner takes all” solution, we impose limits on the decline and expansion rates of the different powertrain types.

Table B.3 Cost and Energy Consumption of the Transportation Technologies.

	Non-fuel cost (USD/unit of activity index)		**Energy intensity (in energy unit/unit of activity index)**	
	2020	**2050**	**2020**	**2050**
Light Duty				
Gasoline	11.80	11.80	0.86 GJ of gasoline	0.68 GJ of gasoline
Hybrid	13.12	12.57	0.64 GJ of gasoline	0.46 GJ of gasoline
Plugin Hybrid	18.33	13.56	57.2 kWh, 0.21 GJ of gasoline	44.2 kWh, 0.16 GJ of gasoline
Battery	12.03	10.56	80.6 kWh	63.5 kWh
Fuel Cells	19.19	12.23	3.02 kg of hydrogen	2.44 kg of hydrogen
Heavy duty				
Diesel	2.75	2.75	0.81 GJ of diesel	0.64 GJ of diesel
Hybrid	3.98	4.20	0.83 GJ of diesel	0.63 GJ of diesel
Plugin Hybrid	4.74	2.74	56.08 kwh, 0.61 GJ of diesel	41.38 kwh, 0.45 GJ of diesel
Battery	3.97	2.20	117.82 kWh	90.98 kWh
Fuel Cells	6.16	2.38	5.65 kg of hydrogen	4.34 kg of hydrogen

Source: Author’s calculations based on motor vehicle trade data from UN Comtrade (2021), and technology and cost data from Sheldon and Dua (2021), Burnham et al. (2021), Plötz et al. (2017) and IEA (2021b).

Hydrogen production is represented by four technologies (Table B.4). Blue and grey hydrogen are produced by methane steam reforming without CCS and with CCS, respectively. Producing 1 ton of hydrogen with MSR emits around 10 tons of CO_2, but we assume a 90% capture rate for blue hydrogen. Hydrogen is also obtained by electrolyzing either using grid electricity or green hydrogen (i.e., using off-grid renewables). The costs of hydrogen production and the utilization rates of the equipment are calibrated based on Hasan and Shabaneh (2022) and are consistent with IEA (2021d). One of the key uncertainties is the variable cost of green hydrogen because it is extremely difficult to assess the cost and the production profiles of the off-grid green electricity systems. All types of hydrogen can be consumed domestically. However, there is an international market for low-carbon hydrogen only, meaning only green and blue hydrogen can be traded.

Table B.4 Characteristics of the Hydrogen Production Technologies.

	Efficiency (%)	Emission rate (tCO_2/tH_2)	Investment cost USD/kW		Variable cost USD/tH_2	Utilization Rate (%)
			2025	2050		
Blue Hydrogen	69	1	2.01	1.625	0.3	80
Grid Hydrogen	67	-	1.48	0.63	0.3	60
Green Hydrogen	67	-	4.44	1.89	2	60

Source: Author's calculations based on Hasan and Shabaneh (2022) and IEA (2021d). A variable cost includes the cost of renewable electricity.

The model also includes specific carbon capture technologies (Table B.5). Carbon can be captured in the petrochemical and cement industries. To mimic the increased marginal abatement costs within each sector, we use different investment costs based on the range provided by IEA (2021c). We also include two DAC technologies, one running on gas only and the other on gas and electricity. The investments cost and the energy intensities of these technologies are calibrated by Keith et al. (2018). Finally, we represent the cost of the carbon transportation and storage infrastructure based on Irlam (2017).

Table B.5 Carbon Capture and Storage Technologies for Direct Air Capture and Process Emissions.

	Investment Cost ($/t$CO_2$/year)	**Electricity Intensity (Mwh/tCO_2)**	**Gas Intensity (GJ/tCO_2)**	**Assumed Available in:**
Industry				
Petrochemicals	165–500	-	-	2030
Cement	415–640	-	-	2030
Direct Air Capture				
Gas powered	1,200–1,750	-	8.1	2030
Gas + Electricity powered	1,050–1,200	0.36	5.25	2030
Transportation and Storage	95	-	-	2020

Source: Author's calculations based on Keith et al. (2018), Irlam (2017), and IEA (2021c).

Oil and gas production are represented with investment and variable production consistent with ARAMCO (2019). The oil production capacity corresponds to the announcement made in ARAMCO (2020). The base year oil and gas production is calibrated based on the IEA (2021a) data, and the split between associated and associated gas was extrapolated from reserves data. We also added shale gas production, with specific costs based on information on the Jaffura field provided in ARAMCO (2021).

Table B.6 Main Characteristics of Oil and Gas Production Technologies.

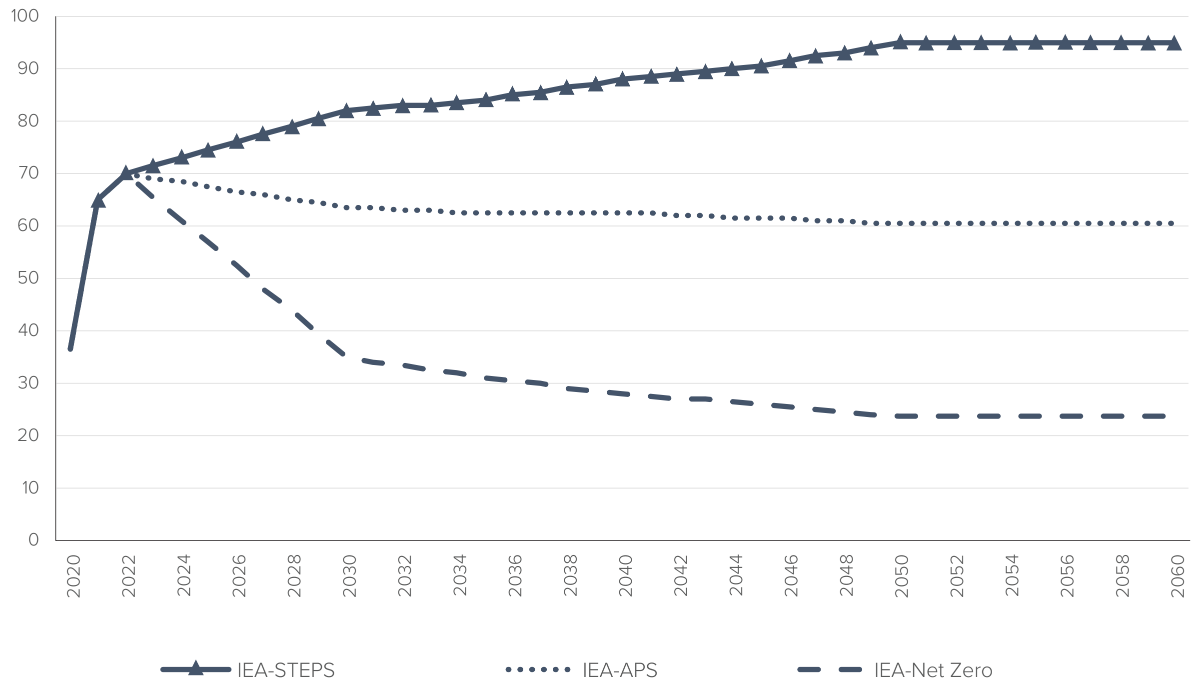
	Capital cost	Lifting cost	Maximum capacity	Production	Cap on cumulative production [b] (reserves)
			2025	2050	
Crude oil	4.7 $/barrel	2.8 $/barrel	13 mb/day	13 mb/day	-
Gas[a]	3.7 $/MMBtu	0.2 $/MMBtu	57 Bcm/year	97 Bcm/year	-
Shale gas	4.5 $/MMbtu	0.5 $/MMbtu	-	-	1,086 Bcm

Notes: a) covers non-associated gas that is not shale gas, b) the hyphens denote that there is no constraint that limits capacity or cumulative production in the model.

Source: Author's calculations based on oil and gas production costs from ARAMCO (2019); the oil production capacity corresponds to the announcement made in ARAMCO (2020). The cost and the reserves of shale gas are calculated based on the information given on the Jaffura field by ARAMCO (2021), assuming that with future discoveries, shale gas reserves could be 50% higher than the reserves of Jaffura (estimated to be 724 Bcm).

Appendix C

Figure C.1 International Oil Price Trajectories.



Note: Prices are in real 2020 USD.
Source: IEA. 2022, World Energy Outlook 2022. Paris: OECD/IEA. STEPS = Stated Policies, APS = Announced Pledges Scenario, NZE = Net Zero Scenario.

About the Author

Olivier Durand-Lasserve

Olivier is a fellow at KAPSARC. Previously, he was an economist at the OECD and at the International Energy Agency (IEA) in Paris, where his activities covered macroeconomic policy analysis and applied general equilibrium modeling. He contributed to various modeling studies on assessing the macroeconomic, environmental and distributional consequences of energy and environmental policies. He also worked on the land-water-energy nexus and the economic consequences of air pollution. Before he joined the OECD, Olivier worked at ENGIE, in Paris, where he developed an in-house modeling framework for quantifying global long-term energy-economy scenarios. While completing his Ph.D., he was a research assistant at the Center for Operations Research and Econometrics (CORE) in Louvain-la-Neuve, Belgium.

About the Project

Given the large size of the Saudi energy and energy-intensive sectors, and the structural changes that these sectors will experience over the coming years, it is essential to capture feedbacks between the energy and non-energy components of the economy with sufficient realism. The KAPSARC Energy Model – General Equilibrium (KEMGE) is a novel hybrid model that combines the KAPSARC Energy Model (KEM) with a representation of the rest of the Saudi economy. It will provide an open-source technology-rich tool to assess the impacts of energy policies on the Saudi economy and the impacts of non-energy policies on the energy sectors.

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