Cost, Emission, and Macroeconomic Implications of Diesel Displacement in the Saudi Agricultural Sector: Options and Policy Insights

Amro M. Elshurafa, Hatem Alatawi, Fakhri J. Hasanov, and Frank A. Felder

January 2022

Doi: 10.30573/KS--2022-DP03
About KAPSARC

The King Abdullah Petroleum Studies and Research Center (KAPSARC) is a non-profit global institution dedicated to independent research into energy economics, policy, technology and the environment across all types of energy. KAPSARC’s mandate is to advance the understanding of energy challenges and opportunities facing the world today and tomorrow, through unbiased, independent, and high-caliber research for the benefit of society. KAPSARC is located in Riyadh, Saudi Arabia.

This publication is also available in Arabic.

Legal Notice

© Copyright 2022 King Abdullah Petroleum Studies and Research Center (“KAPSARC”). This Document (and any information, data or materials contained therein) (the “Document”) shall not be used without the proper attribution to KAPSARC. The Document shall not be reproduced, in whole or in part, without the written permission of KAPSARC. KAPSARC makes no warranty, representation or undertaking whether expressed or implied, nor does it assume any legal liability, whether direct or indirect, or responsibility for the accuracy, completeness, or usefulness of any information that is contained in the Document. Nothing in the Document constitutes or shall be implied to constitute advice, recommendation or option. The views and opinions expressed in this publication are those of the authors and do not necessarily reflect the official views or position of KAPSARC.
Summary

The Saudi agricultural sector relies on diesel for irrigation, which is provided to farmers at a much lower price than the average global price, implying significant opportunity costs. With the aid of soft-coupled power and macroeconometric models, we assess the cost and macroeconomic implications of electrifying irrigation activities in the Saudi agricultural sector. Three electrification scenarios are considered: electrifying each individual farm with a dedicated hybrid renewable micro-grid, electrifying the entire farm cluster with central generation, and connecting the entire cluster via transmission to the national grid. Compared with the base-case, connecting the farm cluster to the national grid is found to be the most economical but the least environmentally friendly. The renewable and central generation scenarios are costlier (compared with the transmission scenario) due, respectively, to the high battery costs and gas infrastructure needed. Further, the financial viability of the renewable microgrid option depends on the opportunity cost assumption. From a macroeconomic perspective, we find that (1) the job and value-added creation effects of saved-diesel spending from export revenues is positive but quite small, implying the more diesel displaced the more benefits realized and (2) the sectoral-specific spending effect is more growth-enhancing than the general government spending effect. Thus, taking such measures can further enhance the efficiency of governmental spending, as highlighted in the Fiscal Sustainability Program (the former Fiscal Balance Program) of the Saudi Vision 2030.
Key Points

The Saudi agricultural sector relies on diesel for water pumping. Diesel is provided to farmers at a price much lower than the average global price, implying significant opportunity costs.

The costs and macroeconomic implications of electrifying water pumping activities was assessed via three scenarios: (1) a hybrid renewable micro-grid, (2) central generation supplying the entire cluster, or (3) connecting the entire cluster to the national grid.

Compared with the base-case, connecting the farm cluster to the national grid was found to be the most economic option but least environmentally friendly. Further, the financial viability of the renewable microgrid option depends on the opportunity cost assumption.

Job and value-added effects of the spending saved diesel export revenues is positive, but small implying that the more diesel displaced the more benefits realized. Moreover, targeted sectoral supply-side effect is more growth-enhancing than general government spending.
1. Introduction

The agricultural sector is crucial to all countries for several reasons. First and foremost, the sector is the backbone of any policy related to food security (Bureau and Swinnen 2018). The COVID-19 pandemic, along with the global supply chain disruptions, has further affirmed how governments view the interlinkages between the agricultural sector and food security (Deaton and Deaton 2020). Second, the agricultural sector contributes to economic diversification, especially in oil-based economies, and it can also play a role in direct and indirect job creation (Loizou et al. 2019). Third, the farming industry, with all its activities, limits migration to urban areas (Hatab et al. 2019). High levels of migration from rural communities to urban areas stress the urban infrastructure and delay rural development (Ge et al. 2020).

Given the above-mentioned factors (among others), countries around the world have paid particular attention to the agricultural sector and Saudi Arabia is no exception. For decades, Saudi Arabia has incentivized the farming industry through various mechanisms including, for example, interest-free loans, favorable credit schemes and low energy prices. This facilitating role is viewed as necessary by both the government and the population given the minimal arable land available, extreme summer temperatures and low precipitation levels (Mahmood et al. 2019). Despite these challenging environmental conditions, Saudi Arabia possessed around 500,000 hectares (ha) of cropland in 2019, according to the Food and Agriculture Organization of the United Nations (FAO).1 Among the country’s notable produce is dates, of which the Kingdom is the world’s second-largest producer, accounting for 17% of global production.

In Saudi Arabia, similar to other countries, center pivot irrigation systems (CPIS) are common. A CPIS consists of a pipe with sprinklers along its length that moves in a circular pattern around a central pivot. Water is supplied to the pipe through the pivot point. Globally, CPIS are the most popular sprinkler irrigation systems due to their many advantages, including high efficiency, ability to irrigate uneven terrains, and low operation and maintenance costs (Waller and Yitayew 2016). The typical CPIS pipe length is around 400 m, which irrigates a total farm area of approximately 50 ha.

By and large, the water supply for farms utilizing CPIS in the Kingdom comes from aquifers. After wells are dug, a vertical turbine pump, which uses impellers, lifts the water to the surface. The mechanical rotation for the pump is provided by a diesel engine. An alternator can also be attached to the diesel engine to provide electricity to the motors, which move the wheels of the CPIS. In addition to its low administered price, diesel has been historically used in CPIS because most of the Kingdom’s farmland is situated far from the national grid. However, the use of diesel results in a considerable amount of emissions and implies a significant opportunity cost. Further, there are logistical challenges and significant costs associated with maintaining a steady diesel supply to these farms.

In 2015, Saudi Arabia embarked on a national journey of energy price reform to rationalize energy consumption and enhance efficiencies across all sectors. With respect to the Saudi agricultural sector in particular, Hasanov and Shannak (2020) have empirically shown that investing in capital stock and technological progress leads to better sustainable development compared with the continuation of electricity incentives. As incentives are removed from the sector, alternatives, including renewable energy technologies for example, become more competitive. Whereas renewable technologies may not have been previously economical, technological advancements in the renewables industry coupled with potential and gradual price reforms in the agricultural sector can make them attractive.
Hasanov and Shannak (2020) also note that the government may wish to invest in and support renewable energy infrastructure in the sector as a policy option for the gradual removal of electricity incentives.

In this paper, we assess the financial, environmental and macroeconomic impacts of retiring the use of diesel in the agricultural sector in Saudi Arabia. We focus on farms located in Tubarjal in the northern region of the Kingdom. Within that region, there are thousands of circular crop fields (CCF) that all rely on diesel powered vertical pumps and CPIS. This study answers two questions. First, what are the costs of electrifying agricultural water pumping activities (i.e., retiring the use of diesel) in the northern region of Saudi Arabia? Second, what are the macroeconomic implications of such a switch? The displaced diesel could, for example, be a source of significant revenues for the Kingdom as it could be exported.

The contributions of this paper are multifold. First, we collect hourly pumping data from actual farming facilities in the region of interest over a period of three years. Further, we use the most current specifications on electric pumps from actual vendors. These two steps, representing primary data, are key pillars that aid in accurately quantifying the impacts of diesel retirement. We then soft-link power-sector models with a macroeconometric model to answer the questions mentioned above. We use hybrid micro-grid optimization modeling and capacity expansion modeling to inform our subsequent macroeconometric modeling. In retiring diesel, we consider renewable generation and connecting those remote farms to the national grid. The findings of this paper may help shape the energy policy discussion in the Kingdom. For example, our findings can inform future revisions of diesel prices and the agricultural electricity tariff as part of the wider energy price reforms taking place within the Kingdom. Moreover, insights stemming from this analysis are important to current discussions related to the transmission interconnection between Saudi Arabia and its northern neighbors, Jordan and Iraq.

The remainder of the paper is organized as follows. Section 2 provides a review of the literature on similar research efforts directed toward agriculture. In section 3, we provide the modeling details and associated assumptions. The results are presented and discussed in section 4, before finally concluding the paper in section 5.
2. Brief Literature Review and Saudi Context

For the past two decades, the use of renewables in the agricultural sector has been increasing globally (Carrêlo et al. 2020). This growing share of renewables is generally a result of increasing electricity prices (Langarita et al. 2017) and cost reductions achieved in renewable technologies. The potential of reducing emissions is also a driver for more renewable deployment in agriculture (Ridzuan et al. 2020). Although these factors generally apply globally, there are specific details that exist in each country that warrant a tailored analysis.

Typically, farms with predictable and continuous energy demand are the ones that have good potential for renewable energy and the case for renewable energy becomes stronger if the generation matches irrigation demand (Eyre 2015). Several studies have shown that a mismatch between agricultural water demand and renewable energy generation substantially affects the economic feasibility of the renewable system (Chandel, Naik, and Chandel 2015).

Jadhav, Sawant, and Panicker (2020) compare off-grid solar photovoltaic pumps, grid-connected solar photovoltaic pumps and high voltage distribution systems (HVDS), while simultaneously considering the seasonality of irrigation, sizes of water pumps and cost of electricity infrastructure in India. The authors find that grid-connected solar photovoltaic (PV) pumps are the most economic option followed by separated agricultural feeders. Similarly, in the context of Australia (Eyre 2015), solar PV is found to be costly if there are no other energy uses on the farm.

When assessing the economics of different options for powering irrigation activities, it is important to incorporate the incentives associated with each technology to arrive at the real cost of pumping. Historically, diesel pumping has been an incentivized option. Even though numerous studies have shown that solar-powered pumps are more efficient and more cost-effective over the lifetime of the project compared with diesel pumping, fuel incentives make diesel pumping more economic, irrespective of any technical advantages that solar pumping would achieve (Closas and Rap 2017). As a result, many studies have assessed the feasibility of introducing renewable-based irrigation with policy support. For example, Rubio-Aliaga et al. (2019) examine various scenarios in the context of Spain, where farmers can export excess energy, generated by PV, to the grid. The authors recommend policy interventions to displace diesel motors with renewables. This discussion about incentives is particularly important and relevant in the context of this paper because, as mentioned, diesel is incentivized in the Kingdom.

When a monetary value is associated with pollution (e.g., carbon tax), the financial attractiveness of the different options changes considerably. However, whatever climate change mitigation policy is to be enacted, food security must not be compromised (Frank et al. 2017). Reducing emissions in this sector usually requires an examination of all farming activities that result in externalities, such as plowing, tilling, manuring and irrigation (Jaiswal and Agrawal 2020). Carbon taxes or emission caps in the agricultural sector will trigger the search for alternatives to current business-as-usual activities such as, for example, converting diesel engines to use both diesel and natural gas (Grebnev et al. 2020). In some countries where the carbon tax is significantly high, such as Sweden (125 $/ton), traditionally expensive technologies not typically used in the agricultural sector, like hydrogen electrolyzers, become financially viable (Janke et al. 2020).
2. Brief Literature Review and Saudi Context

Although several water pumping alternatives exist, each application should be assessed individually to determine the most suitable option. The farms under consideration in this study are fodder farms, which are water intensive. Further, the aquifer water is found at a depth of around 200 meters. Given this depth, coupled with the high flow rate required (1,000 gallons per minute), direct current (DC) pumps cannot be used. Generally, solar-powered DC pumps are used for much lower well depths and much lower flow rates (Ibrik 2020; Korpale, Kokate, and Deshmukh 2016). Alternating current (AC) motors are also more efficient than DC motors in terms of energy. As such, for the application examined in this study, AC motors are the more suitable option (Li et al. 2017).

With respect to Saudi Arabia, previous work has attempted to assess the use of different non-diesel resources for the purposes of irrigation. For example, Benghanem et al. (2013) investigated the use of a solar-powered DC pump in the western region. The study is concerned with an 80 m head and low water requirements (22 m³/day). Other studies consider the use of wind turbines for underground water pumping (Sahin, Bolat, and Al-Ahmari 2011; Rehman and Sahin 2012), where the well is 50 m deep. Moreover, the performance of diesel- and solar-powered water pumping is assessed in five different geographical locations in the Kingdom (Rehman and Sahin 2015). This study finds that using PV reduces the costs of water pumping considerably. However, the dynamic head considered is only 50 m. Although other papers related to the topic exist (Alawaji et al. 1995; Rehman and Sahin 2016), none deal with the same depth or flow rate as the application examined in this study.

From the above literature review, three important observations can be made. First, the studies focusing on irrigation in Saudi Arabia are relatively old. Renewable technologies have progressed significantly in the past decade, which makes the previous literature less relevant for assessing the current costs and capabilities of technology. Second, earlier studies dealt with relatively short heads (<80 m) and low flow rates, whereas the irrigation applications discussed in this study require much higher energy levels. Third, the energy price reforms currently being implemented in the Kingdom are not considered in any previous study, given that most of these reforms have only been applied since 2016. As a result, the new technological and governmental developments that have occurred in the past few years warrant an updated analysis.
3. Scenarios and Modeling Description

There are thousands of CCFs in the Kingdom. This study focuses on farms in the northern region of the Kingdom near the southern Jordanian border. In this area, all farmers irrigate using diesel engines. As mentioned, diesel is the chosen source of energy because these farms are far from the national grid. Most of these farms grow fodder, which are water-intense crops. The wells providing water are around 180m deep. To irrigate these fodder fields, a water flow rate of around 1,000 gallons per minute (gpm) is required. A map of this region is shown in Figure 1.

Figure 1. A Google Map showing the geographical location of the farms: (a) map of Saudi Arabia, (b) a zoom-in of the northern part of Saudi Arabia where the farms are located and (c) further zoom on the circular crop fields.

Field data are collected from actual farms within the area of interest, including daily diesel consumption, diesel engine specifications, water flow and the energy required to move the CPIS. The information related to the diesel engine and water flow are particularly important as they guide our choice for electrifying the pumping and irrigation activities. Specifically, an hourly load profile, in kilowatt hours (kWh), for a full year is synthesized from the data collected.

For electrification, solar photovoltaic (PV) and wind are the renewable technologies considered. Battery storage is also a candidate technology to augment PV and wind given their intermittent nature. We also consider connecting these farms to the national grid. To aid in designing the optimal energy mix, we employ PLEXOS and HOMER, which are two mainstream, commercially available software packages that support the technoeconomic optimization of the supply side. In addition to the energy requirements, subsequent emissions implications are also quantified.

Investments in energy infrastructure are capital intense and are recovered over a relatively long time. Hence, in addition to the finances, knowing when the aquifers will run out of water is another critical factor that influences the attractiveness of each proposed solution. The literature estimates that the ground water supplies in the area will be depleted in around 50 years (DeNicola et al. 2015; Drewes, Patricio Roa Garduño, and Amy 2012), which works in favor of the energy options considered herein, as it is ample time to recover investments.
3. Scenarios and Modeling Description

In light of the above, we consider the following four scenarios in this study: (1) base case, (2) switching each individual farm from relying on diesel to an electric motor powered by an individual on-site renewable microgrid, (3) switching the farms from relying on diesel to an electric motor powered by a power plant that supplies energy to the entire farm cluster and (4) switching each individual farm from relying on diesel to an electric motor powered by the national transmission grid.

3.1. Scenario 1 – Base Case

This base case scenario, which we refer to as \( BC \), is the benchmark to which all other scenarios are compared. It assumes a continuation of business-as-usual activities; that is, the farms would continue to rely on diesel engines for irrigation. Table 1 shows the primary data collected from actual farmers for the total annual diesel consumption of representative farms (values rounded to the nearest 1,000).

<table>
<thead>
<tr>
<th>Year</th>
<th>Diesel Consumption (liters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>294,000</td>
</tr>
<tr>
<td>2019</td>
<td>280,000</td>
</tr>
<tr>
<td>2020</td>
<td>266,000</td>
</tr>
</tbody>
</table>

Source: KAPSARC based on interview with farmers.

During the summer months of 2020, diesel consumption averaged 1,400 liters per day (L/day). However, during the winter months, diesel consumption dropped to around 400 L/day. As mentioned earlier, this diesel consumption throughout the year is required to maintain a water flow rate of about 1,000 gpm. Diesel is sold to farms at an administered rate of 0.52 Saudi Riyals per liter (SAR/L), which is equivalent to 0.14 $/L.

3.2. Scenario 2 – Microgrid

In the microgrid scenario, the goal would be to switch each individual farm from a diesel engine to an electric motor powered by an individual on-site renewable microgrid. Electric motors are generally more efficient than diesel motors and this option would require relatively less energy to pump the water. Most of the energy would be used for water lifting and only a small amount would be used to power the motors that move the pivot. In this scenario, we do not consider renewables to partially replace diesel. Rather, the intention is to fully replace diesel. While a hybrid renewable-plus-diesel microgrid may be a suitable transitional solution, the objective of the paper is to assess the cost and benefits of full diesel retirement.

The technologies that could be used at the scale of individual farms are solar PV and storage, and wind turbines could also potentially be used. This is explained with the aid of Figure 2, which shows a conceptual schematic of a CCF. Most CCFs have a diameter of 800 m. At the center of this field, a small, circular area for services and operation (100 m in diameter) exists. It contains the diesel engine, pumping apparatus, CPIS electronic control box and other operational functions.
3. Scenarios and Modeling Description

If a microgrid were to be built, it would be situated in the services area. As the water line (as shown in Figure 2) rotates, the presence of a wind turbine in the services area would not allow the water line to complete a full revolution (the water line is approximately 3–4 meters above the ground). Although the CPIS can move in the counter direction, this is not practical. An alternative solution would be for the wind turbine to be located at the outer edge of the CCF. In the modeling, we consider a microgrid with and without a wind turbine. In Tables 2 through 4, the assumptions used for PV, wind and storage are summarized, respectively.

Figure 2. A conceptual schematic of a typical circular field irrigated with a central pivot line. The circular field (green region) has a small services area (white region) in the middle and the water line pivots around the center.

Source: Authors’ illustration.

Table 2. Assumptions used for the solar PV system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital cost</td>
<td>1,200 $/kW</td>
</tr>
<tr>
<td>Efficiency of module</td>
<td>16%</td>
</tr>
<tr>
<td>Nominal operating cell temperature</td>
<td>47 °C</td>
</tr>
<tr>
<td>Temperature dependent power loss</td>
<td>-0.4%/°C</td>
</tr>
<tr>
<td>Overall system losses</td>
<td>15%</td>
</tr>
<tr>
<td>Operation and maintenance cost</td>
<td>5 $/kW/year</td>
</tr>
</tbody>
</table>

3. Scenarios and Modeling Description

### Table 3. Assumptions used for the wind turbine.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital cost</td>
<td>1,000 $/kW</td>
</tr>
<tr>
<td>Overall losses</td>
<td>7%</td>
</tr>
<tr>
<td>Hub height</td>
<td>Various</td>
</tr>
<tr>
<td>Operation and maintenance cost</td>
<td>1,000 $/year</td>
</tr>
</tbody>
</table>


### Table 4. Assumptions used for the battery storage system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital cost (4 hours of storage)</td>
<td>1,000 $/kW</td>
</tr>
<tr>
<td>Replacement cost</td>
<td>800 $/kW</td>
</tr>
<tr>
<td>Days of autonomy</td>
<td>1 day</td>
</tr>
<tr>
<td>Degradation limit</td>
<td>80%</td>
</tr>
<tr>
<td>Round trip efficiency</td>
<td>85%</td>
</tr>
<tr>
<td>Calendar life</td>
<td>10</td>
</tr>
<tr>
<td>Minimum allowed state of charge</td>
<td>20%</td>
</tr>
</tbody>
</table>


A local vendor that sells pumps and motors was contacted to provide a quote for the application studied. A submersible pump configuration powered by a submersible AC motor was provided; the AC motor was rated at around 160 kW. As power is required to move the CPIS and maintain other farm operations (fan, lights, electronics, etc.), we assume that the farm needs 180 kW of continuous power.

According to the data obtained from several farms, the CPIS operate for 20 hours per day during the summer months (CPIS are turned off between midnight and 4:00 am). Conversely, in winter months, the CPIS run only four hours per day during midday because lower water levels are needed in the cooler months due to reduced water evaporation. From this data, the full load profile of a sample farm for an entire year has been synthesized, as shown in Figure 3, where the x-axis represents the day of year and the y-axis represents the hour of day. The color scale shown on the right axis represents the load. Note, the summer daily load occurs from March through October, while the winter daily load occurs from November through February. As can be seen, the load is either approximately 180 kW or very low.
Figure 3. The annual load profile of the farm, shown via what is referred to as a D-map. The x-axis represents the day of the year and the y-axis represents the hour of day. The color scale shown on the right depicts the load magnitude in kW.

Source: Authors’ illustration.

If microgrids were built, the farmers would presumably be the ones to maintain the equipment. The maintenance costs would be small. In addition, there would be no actual electricity bill incurred by the farmers and they would no longer be purchasing diesel. This latter situation would translate to no realized returns for the government. Hence, in this scenario we set a fixed monthly payment that the farmers would pay the government as a representative average monthly bill (based on the agricultural electricity tariff). In other words, this fixed monthly payment can also be viewed as a mechanism for the government to recover the investment that it would have to put forward to support the farmers. For comparison purposes, we will also consider a variation, where farmers do not pay for the energy generated on-site. These scenarios will be referred to as Microgrid-1 and Microgrid-2.

3.3. Scenario 3 – Powerplant

The Powerplant scenario assesses building a power plant for the whole cluster of farms. The technologies that are considered in this scenario are combined cycle (CC) gas turbines, single cycle (SC) gas turbines, PV, wind, battery storage and concentrated solar power (CSP). The analysis is performed for a duration of 20 years. There is a total of around 1,430 farms in the region of interest, which translates to a peak load of about 250 MW.

The projections for capital costs of PV, wind, battery storage and CSP technologies (for the period 2021 to 2040) are summarized in Table 4. In addition to the power plant, the costs of supplying this power plant with gas from the eastern region (e.g., a pipeline) are considered. Given the benefits of gradually retiring incentives allocated for the agricultural sector, as detailed earlier, and recalling that the Kingdom is implementing an energy price reform plan, we consider two gas prices. The first is the current gas price of 1.25 $/MMBtu and the second is a price of 3 $/MMBtu, which is the Henry Hub price as projected by the U.S. Energy Information Administration. In both cases, an additional cost of 0.5 $/MMBtu is incorporated in the model to account for gas transportation. The emission factors used for gas and diesel are 130 lb/MMBtu and 172.4 lb/MMBtu, respectively.
3. Scenarios and Modeling Description

It is well known that CC turbines are more efficient than SC turbines. However, SC turbines have higher ramping capability and lower capital costs. In the model, which we solve in PLEXOS, the efficiencies and ramp rates are both considered. Specifically, the heat rates and ramping rates used for CC and SC turbines are 6,000 and 9,000 Btu/kWh and 20 and 40 ΔMW/minute, respectively.

<table>
<thead>
<tr>
<th>Year</th>
<th>PV</th>
<th>CSP</th>
<th>Wind</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>773</td>
<td>3,669</td>
<td>1,159</td>
<td>1,100</td>
</tr>
<tr>
<td>2022</td>
<td>736</td>
<td>3,616</td>
<td>1,139</td>
<td>1,005</td>
</tr>
<tr>
<td>2023</td>
<td>703</td>
<td>3,563</td>
<td>1,120</td>
<td>918</td>
</tr>
<tr>
<td>2024</td>
<td>674</td>
<td>3,511</td>
<td>1,100</td>
<td>840</td>
</tr>
<tr>
<td>2025</td>
<td>646</td>
<td>3,460</td>
<td>1,080</td>
<td>760</td>
</tr>
<tr>
<td>2026</td>
<td>626</td>
<td>3,409</td>
<td>1,064</td>
<td>750</td>
</tr>
<tr>
<td>2027</td>
<td>607</td>
<td>3,360</td>
<td>1,046</td>
<td>708</td>
</tr>
<tr>
<td>2028</td>
<td>589</td>
<td>3,311</td>
<td>1,028</td>
<td>678</td>
</tr>
<tr>
<td>2029</td>
<td>572</td>
<td>3,263</td>
<td>1,010</td>
<td>650</td>
</tr>
<tr>
<td>2030</td>
<td>555</td>
<td>3,215</td>
<td>992</td>
<td>640</td>
</tr>
<tr>
<td>2031</td>
<td>538</td>
<td>3,168</td>
<td>974</td>
<td>620</td>
</tr>
<tr>
<td>2032</td>
<td>522</td>
<td>3,211</td>
<td>961</td>
<td>600</td>
</tr>
<tr>
<td>2033</td>
<td>508</td>
<td>3,077</td>
<td>942</td>
<td>586</td>
</tr>
<tr>
<td>2034</td>
<td>493</td>
<td>3,032</td>
<td>927</td>
<td>571</td>
</tr>
<tr>
<td>2035</td>
<td>479</td>
<td>2,988</td>
<td>912</td>
<td>560</td>
</tr>
<tr>
<td>2036</td>
<td>466</td>
<td>2,944</td>
<td>896</td>
<td>549</td>
</tr>
<tr>
<td>2037</td>
<td>454</td>
<td>2,901</td>
<td>881</td>
<td>538</td>
</tr>
<tr>
<td>2038</td>
<td>442</td>
<td>2,859</td>
<td>866</td>
<td>528</td>
</tr>
<tr>
<td>2039</td>
<td>431</td>
<td>2,817</td>
<td>850</td>
<td>520</td>
</tr>
<tr>
<td>2040</td>
<td>419</td>
<td>2,776</td>
<td>833</td>
<td>518</td>
</tr>
</tbody>
</table>

In addition to power generation, this scenario also requires a substation and a distribution network to be built to provide energy to all the farms. The costs of substations vary depending on the specifications. Given the loads, areas and distances considered, we assume a representative overnight cost of the substation to be $150x10^6 and the cost of building a distribution network to be $340x10^6. These numbers are reached by consulting several documents from the literature (Karhammar et al. 2006; NERCA...
3. Scenarios and Modeling Description

2019; Warwick et al. 2016; Wattanasophon and Eua-Arporn 2009; Yuan, Liu, and Li 2016). As will be shown later in the analysis, even if these numbers vary considerably, the overall insights still hold.

3.4. Scenario 4 – Transmission

The fourth and final scenario, which we call Transmission, would be to connect the entire farm cluster with the national transmission grid. The difference between this scenario and the Powerplant scenario (i.e., scenario 3) is that there would be no new generation capacity built. However, there would be a need for transmission lines to be built along with a substation and a distribution network. The cost of building the transmission line is assumed to be 437,000 $/km (Giani et al. 2020) and the costs of the substation and distribution network are as mentioned in section 3.3.

3.5. Summary of scenarios

The following table summarizes the four scenarios. The base-case scenario is the scenario with which all other scenarios are compared.

<table>
<thead>
<tr>
<th>Scenario number and name</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Base Case</td>
<td>This is the benchmark scenario—(BC) and describes the status quo; that is, all farms satisfy their irrigation needs using diesel. All other scenarios are compared with this scenario.</td>
</tr>
<tr>
<td>2. Microgrid</td>
<td>Each individual farm is powered with a dedicated hybrid microgrid (PV, wind and storage). Diesel engine to be retired and water pumping to occur via an electric submersible pump and submersible motor. This scenario tests for two variations: farmers paying and not paying for electricity — Microgrid-1 and Microgrid-2, respectively.</td>
</tr>
<tr>
<td>3. Powerplant</td>
<td>The complete cluster of farms is powered by a power plant (candidate technologies are single cycle gas, combined cycle gas, wind, PV, CSP and battery storage). Diesel engines to be retired and water pumping to occur via an electric submersible pump and submersible motor. This scenario tests for two variations of gas price: 1.25 and 3.00 $/MMBtu — Powerplant-1 and Powerplant-2, respectively.</td>
</tr>
<tr>
<td>4. Transmission</td>
<td>The complete cluster of farms is powered by connecting all farms to the national grid. Diesel engines to be retired and water pumping to occur via an electric submersible pump and submersible motor. We refer to this scenario as Transmission.</td>
</tr>
</tbody>
</table>
4. Results and Discussion

4.1. Base Case

For the BC, calculating the costs is straightforward. As shown from Table 1, the total consumption for diesel was 266,000 liters in 2020. At that amount, the total diesel bill for the farm under study is around 133,000 SAR annually. However, the current price of diesel in the Kingdom (0.52 SAR/L or 0.14 $/L) is among the lowest in the world — the global average diesel price is about 1 $/L. Prices can reach as high as 2 $/L, for example in Hong Kong. Regarding emissions, around 665 tonnes of CO$_2$ is emitted every year from each farm. In total, around 1 million tonnes of CO$_2$ would be emitted from the entire cluster.

4.2. Microgrid

As mentioned earlier, solar PV, wind and storage are the candidate technologies for designing the microgrid. For reliability purposes, we assume that a battery can provide energy for the farm for one full day (i.e., one day of autonomy). As a result, a battery with an energy content of 180 kW x 20 hours = 3,600 kWh (3.6 MWh) would be needed. Standard lithium-ion batteries with 1 MW/4 MWh power/energy capacity can easily satisfy this requirement in a relatively small footprint (around 6 m x 2 m container). The performance of the battery incorporates the impacts of high temperatures (please refer to Table 4).

The area requirement for solar PV, however, is much larger. As shown in Figure 2, the services area in the middle of the CCF has a radius of 50 m, or an area of 7,850 m$^2$. Assuming an area-to-power ratio of 1 m$^2$:0.11 kW for PV modules (Elshurafa and Muhsen 2019), then the maximum solar PV capacity that could be deployed is 860 kW. Clearly, the services area cannot be fully covered by modules. For the purposes of this study, we limit the area allocated for PV in the services area to be 75% of the total 7,850 m$^2$. This assumes 5,900 m$^2$ available for PV would translate to being able to deploy a maximum of around 650 kW of PV in the services area.

Using HOMER, and given the area constraints, the optimal microgrid would comprise 600 kW of solar PV plus the battery storage if no wind turbine is included. However, if a wind turbine is considered in the optimization problem, the optimal mix becomes 505 kW of PV, 50 kW of wind and the battery. Both options have very similar financial profiles in terms of net present cost, capital and levelized cost of energy: $2.68 million, $1.6 million and 0.20 $/kWh, respectively. For this option, there would be no emissions associated with energy generation.

In Figure 4, we show how the load is being met with PV and storage for a sample day in summer. As expected, storage meets demand in the early morning hours. During midday, the solar PV then meets demand. The over-generation by solar PV during midday charges the battery. Figure 5 shows the valuable role of the battery. The contribution of the battery to meeting demand during the winter months is small; it provides almost no energy to meet demand. During the summer months, however, the battery contributes significantly to meeting demand. Further, the minimum energy content that the battery reaches is 800 kWh, which is the minimum allowed state of change we have specified (i.e., 20% of 4 MWh, as indicated in Table 3).
4. Results and Discussion

**Figure 4.** The role of PV and battery in meeting the load of the farm during a summer day. The battery meets demand during the early hours of the day and after sunset. The high output of PV during midday is used to meet demand and charge the battery.

![Graph showing PV and battery output](image)

Source: Authors' modeling.

**Figure 5.** The energy content of the battery. The battery rarely discharges during the winter months. However, it reaches the minimum state of charge needed to meet demand during the summer months.

![Graph showing battery energy content](image)

Source: Authors' modeling.
4. Results and Discussion

4.3. Powerplant

The third option considered is to provide energy for the whole cluster of farms through a power plant. As described in section 3, we use PLEXOS to aid in identifying the optimal energy mix that would yield minimum cost. Recall that two gas prices are simulated given the energy price reforms taking place in the Kingdom.

At a gas price of 1.25 $/MMBtu, we see that the model builds gas turbines only: 220 MW of CC and 70 MW of SC (for a total of 290 MW of turbine capacity; numbers are rounded to the nearest 10). None of the other technologies can compete. This result is expected as the gas price is low and the efficiency of these turbines is high. At a gas price of 3 $/MMBtu, an identical gas capacity of 220 MW of CC and 70 MW of SC is built. However, around 45 MW of PV are also built in the first two years of operation. None of the other technologies are chosen by the model. Clearly, the high gas price scenario promoted PV deployment, which lowers emissions. At a price of 1.25 $/MMBtu, annual emissions totaled 0.47 million tonnes compared with 0.44 million tonnes for the 3 $/MMBtu case.

Figure 6. The optimal energy mix that would satisfy the load at the farms at minimum cost. Two scenarios are shown: one at a low gas price of 1.25 $/MMBtu, Powerplant-1 and another at a high gas price of 3 $/MMBtu, Powerplant-2. At the high gas price, considerable PV capacity comes online.
4.4. Transmission

For the transmission scenario, operational costs are minimal. Once the farming area is electrified with the transmission and distribution lines, the farmers would be paying only for their consumption. Clearly, the capital costs of erecting the transmission lines are highly dependent on the length of the lines. However, as shown in Table 7, the capital costs required for the Transmission scenario are lower than the other scenarios, even assuming an exaggerated distance given our context (e.g., 200 km). The additional load of 1 TWh, in energy terms, that would be borne by the national grid for this farming area does not pose any challenges as it represents less than 1% of the total electricity consumption of the Kingdom. Recall that the additional load that would be borne in power terms is 250 MW, which is around 0.4% of the total national peak in the Kingdom.

4.5. Compilation of Results

The costs of the three proposed solutions are all summarized in Table 7 and are benchmarked against the BC scenario. The table calculates the costs from the viewpoint of the government and the farmers. For the Microgrid scenario, there are no operation and maintenance (O&M) costs incurred by the government, as it is assumed that the farmers will maintain the equipment at their own cost. We also consider two variations, as mentioned earlier: the farmers (1) paying a fixed amount to the government for electricity (Microgrid-1) and (2) paying nothing (Microgrid-2).

For the Powerplant and Transmission scenarios, the O&M costs, including running the plants, fuel supply and transportation, and the transmission and distribution network maintenance, are assumed to be incurred by the government. Farmers would pay only for the energy they use according to the current electricity tariff applied to the agricultural sector, which is 0.20 SAR/kWh (i.e., 0.053 USD/kWh). As expected, all scenarios result in a reduction in emissions. The Microgrid scenario fully eliminates emissions, whereas the Powerplant scenario, with both of its variations, reduces emissions only in the high gas price variation, cutting emissions by around 60%. The Transmission scenario, which used the national emission rate of 0.70 kg CO₂/kWh to calculate emissions, reduces emissions the least.

With the aid of Table 7, the financial viability of each scenario can be assessed in terms of net present value (NPV). Recall that diesel is sold to farmers at 0.14 $/L, while the average global price is around 0.72 $/L. For scenarios 2, 3 and 4, there would be 380 million liters of saved diesel. To calculate the NPV, a monetary value should be assigned to this saved diesel. If the global average diesel price is to be considered a reference, each liter of diesel is currently incentivized at a rate of 0.59 $/L. With that in mind, the NPV is calculated given two cost-saving values of 0.59 $/L and 0.22 $/L. The former value is based on the average global diesel price and the latter is based on half of the average global diesel price. The value of the saved diesel can be viewed through the lens of opportunity cost. In addition to the monetary values tied to the saved liters of diesel, we also calculate the NPV using three different discount rates: 3%, 4% and 5%. Overall, 36 scenarios are simulated, as summarized in Figure 7.
### 4. Results and Discussion

Table 7. Summary of the costs and emission implications for all scenarios. The numbers below are for the complete cluster of 5,100 farms.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Summary</td>
<td>Water lifted via existing diesel engines. No capital costs required.</td>
<td>A dedicated microgrid installed at each individual circular farm.</td>
<td>A powerplant to be built to provide energy to all farms. This scenario requires building power plant(s), a substation and a distribution network.</td>
<td>Farms connected to the national grid. This scenario requires building transmission lines, a substation and a distribution network. However, no power plants are needed.</td>
</tr>
<tr>
<td>Overnight capital cost in USD(^1)</td>
<td>NA</td>
<td>2.3 × 10(^9)</td>
<td>2.3 × 10(^9)</td>
<td>1.78 × 10(^9)</td>
</tr>
<tr>
<td>Annual operational cost in USD(^2)</td>
<td>62.7 × 10(^6)</td>
<td>12.8 × 10(^6)</td>
<td>12.8 × 10(^6)</td>
<td>16.8 × 10(^6)</td>
</tr>
<tr>
<td>Annual fuel offtake(^3)</td>
<td>380 × 10(^6) L</td>
<td>0</td>
<td>0</td>
<td>7.2 TBTu</td>
</tr>
<tr>
<td>Annual CO(_2) emissions in tonnes(^4)</td>
<td>1.1 × 10(^9)</td>
<td>0</td>
<td>0</td>
<td>0.47 × 10(^9)</td>
</tr>
<tr>
<td>Annual energy bill paid by the farmers in USD(^5)</td>
<td>53.5 × 10(^6)</td>
<td>62 × 10(^6)</td>
<td>0</td>
<td>62 × 10(^6)</td>
</tr>
</tbody>
</table>

\(^1\) Capital costs are assumed to be overnight costs and include costs of submersible pumps and motors. In Powerplant, capital costs include power generation, substation, distribution network and gas pipeline connection (assumed at 1 × 10\(^6\) $/km) costs. In Transmission, capital costs include the transmission lines, substation and distribution network.

\(^2\) Annual operational costs include fixed and variable costs. For BC and Microgrid, operational costs are incurred by the farmer. For Powerplant, costs include gas transportation.

\(^3\) For Microgrid, results are obtained from the PLEXOS model. For Powerplant, results are obtained assuming a grid efficiency of 40%.

\(^4\) For BC, results are obtained from HOMER. For Microgrid, results are obtained from PLEXOS. For Powerplant, results are obtained assuming an emission factor of 0.7 kg CO\(_2\)/kWh.

\(^5\) For BC, energy bill represents costs to purchase diesel. In the rest of the scenarios, the costs represent paying for the electricity provided.
With the aid of Table 7, the financial viability of each scenario can be assessed in terms of net present value (NPV). Recall that diesel is sold to farmers at 0.14 $/L, while the average global price is around 0.72 $/L. For scenarios 2, 3, and 4, there would be 380 million liters of saved diesel. To calculate the NPV, a monetary value should be assigned to this saved diesel. If the global average diesel price is to be considered a reference, each liter of diesel is currently incentivized at a rate of 0.59 $/L. With that in mind, the NPV is calculated given two cost-saving values of 0.59 $/L and 0.22 $/L. The former value is based on the average global diesel price and the latter is based on half of the average global diesel price. The value of the saved diesel can be viewed through the lens of opportunity cost. In addition to the monetary values tied to the saved liters of diesel, we also calculate the NPV using three different discount rates: 3%, 4%, and 5%. Overall, 36 scenarios are simulated, as summarized in Figure 7.

**Figure 7.** The net present value (NPV) in billion dollars of all scenarios considered. Note that the combinations include two opportunity costs, three discount rates and six main scenarios, resulting in a total of 36 scenarios simulated.

Several insights can be extracted from Figure 7. First, as expected, we see that BC results in a negative NPV because the returns that are collected by the government at the current diesel prices are low. Further, we see that the Transmission Scenario is financially viable, regardless of the discount rate and opportunity cost assumptions. However, the Transmission scenario results in significantly more value compared with the Powerplant scenario. This is mainly due to the large capital costs associated with the Transmission scenario, which are a result of the gas pipeline infrastructure required.
4. Results and Discussion

The **Microgrid** and **Powerplant** scenarios, however, are sensitive to the assumed discount rates and/or opportunity costs. As can be seen on the left of Figure 7, at an opportunity cost of 0.22 $/L, the **Microgrid** scenarios are not financially viable. In contrast, at an opportunity cost of 0.59 $/L, electrifying the farms via renewables becomes justifiable. This is an important observation as the capital costs required for this scenario, as shown in Tables 2 and 7, are considerably high. The latter is somewhat balanced by the fact that minimal operational costs are needed to run the renewable sources. Based upon our analysis, the **Transmission** scenario is the most attractive option. Even if the **Powerplant** scenario, for example, yielded a comparable NPV to the **Transmission** scenario, the **Transmission** scenario would still be preferable as it requires lower capital. The **Powerplant** scenario possesses a lower NPV compared with the **Transmission** scenario because the **Powerplant** scenario requires high capital costs to build the gas pipeline infrastructure.

All the scenarios considered possess positive NPV at the high opportunity cost assumption, even at the current agricultural tariff of 0.20 SAR/kWh. In other words, if Saudi agricultural water pumping activities are electrified, there would be economic benefits, even if the electricity tariff remains at its current low level. This is an important finding based on the numerical analysis conducted in this study.

Table 7 tells us also that the farmers would be paying more if their farms were to be electrified at the current electricity tariff assigned for the agricultural sector. Currently, at a diesel price of 0.52 SAR/L, the diesel bill of a farmer for a single CCF would be around 140,000 SAR. Conversely, if the farm were to be electrified at a rate of 0.20 SAR/kWh, the farmer would pay around 160,000 SAR. For both options to be equivalent, diesel prices would have to rise to around 0.60 SAR/L or electricity prices would need to decrease to around 0.17 SAR/kWh. If either of these two options are implemented (i.e., raise diesel price or reduce electricity tariff), then the farmers would be indifferent as to whether they use diesel or electricity for their water pumping needs. At a tariff of 0.17 SAR/kWh, there would be approximately $30 million of forgone revenues.

In addition to **Transmission** being the most attractive scenario financially, it can offer other benefits in terms of connecting Saudi Arabia with its northern neighbors, Iraq and Jordan. In other words, planning for a single line or two lines would be considered early on to reduce overall transmission line erection and cross-border interconnection costs. Specifically, costs related to permits, obtaining right of way clearances and conducting civil works, for example, could all be done at one time. Indeed, Saudi Arabia signed a memorandum of understanding with Jordan in 2020 to start an interconnection transmission project. If the same line served the agricultural region and is simultaneously used for export, then Saudi Arabia would be hitting two birds with one stone.

4.6. Carbon Emissions

As shown in Figure 7, when the diesel opportunity cost is valued at 0.59 $/L, all options are financially viable, with the **Microgrid** alternative being the least attractive. From an emissions perspective, however, the **Microgrid** scenario yields no emissions, while the **Transmission** scenario is the most emitting alternative. Compared with the **BC**, all considered options are less polluting. Note also that the **Microgrid-2** scenario results in lower emissions than **Microgrid-1** given the large solar PV share associated with **Microgrid-2**. However, given that Saudi Arabia emits around 620 million tonnes of carbon, the share of the agricultural sector is
negligible and efforts in reducing emissions should be directed toward other sectors.

4.7. Macroeconomic and Sectoral Implications

After assessing the different electrification options available for the agricultural sector, this subsection evaluates the macroeconomic impact of displacing the diesel used (i.e., 380 million liters in 2021). The aggregate and sectoral indicators of interest that are impacted are non-oil investment, non-oil employment, non-oil value-added and inflation. Further, we assess the impacts on value-added and employment in the agriculture and utility sectors. We assume that the saved diesel is exported at an average world price of $0.72/L, which generates $273.6 million additional export revenue for the government. Saudi Arabia exports both crude oil and refined oil products (including diesel). For the purposes of this paper, we assume that the exports are diesel in refined form because it is more profitable to do so.

Two scenarios are considered, in addition to the business-as-usual scenario, for how these additional export revenues could be used. In the first scenario, we assume that the Saudi government spends the SAR 820.8 million net diesel export revenues in addition to its planned spending in 2021. We will refer to this scenario as General spending. In the second scenario, we assume that the government allocates the net revenues from the saved diesel exports equally between the capital stock in the agriculture and utilities sectors, which translates into SAR 371.16 million in real terms (after adjusting for the price effect) for each sector. We refer to this second scenario as Agri-utility. Last, we have the business-as-usual (referred to as BaU) scenario, in which the economy moves forward without any diesel displacement. Thus, no additional revenue is generated to spend or allocate to either sector. This is the reference case, against which the other two scenarios are compared. It is important for the reader to distinguish between the two sets of scenarios in this study: the scenarios available for electrifying the agricultural sector, which are detailed in section 3, and the scenarios considered in this subsection, which are concerned with the macroeconomic implications of diesel displacement.

The rationale for the first scenario (i.e., General spending) is that the energy resources are owned by the government and therefore the government could decide to spend the saved diesel revenues over and above the planned government spending in 2021. The second scenario (i.e., Agri-utility) is justified by the fact that diesel is displaced in agriculture. Therefore it is reasonable to assume that the government will use the additional revenue from the saved diesel exports to develop this sector. The same reasoning applies to the utility sector, where additional capital is needed to meet any additional electricity demand from agriculture resulting from the fuel displacement (see required capital cost for the Microgrid, Powerplant and Transmission scenarios in Table 7). As discussed above, we evaluate the effects of the saved diesel on key indicators, such as employment, output and prices. Any potential direct or indirect cost effects of this displacement are not evaluated in the scenario analyses.

We run the scenarios in the KGEMM (KAPSARC Global Energy Macroeconometric Model). The KGEMM is a policy tool for assessing the impacts of internal decisions by Saudi decision-makers and changes in the global economy (including energy markets) on Saudi Arabia’s energy macroeconomic environment. It is a general equilibrium model extended to include the energy sector. KGEMM is constructed as a hybrid macroeconometric model.
that combines theory-driven and data-driven approaches. This is because hybrid models have been shown to be superior to pure theory-driven models (such as dynamic stochastic general equilibrium models [DSGE] or computable general equilibrium [CGE] models) and pure statistical models, such as unrestricted vector autoregression (VAR) models (Ballantyne et al. 2020; Cusbert and Kendall 2018; Giacomini 2015; Hendry 2018; Hendry and Muellbauer 2018; Jelić and Ravnik 2021). KGEMM contains eight interacting blocks, representing Saudi Arabia’s macroeconomic and energy linkages (see Figure 8). It uses more than 700 annual time series variables and more than 330 behavioral equations and identities. The long-run and short-run relationships among the variables are estimated using cointegration and equilibrium correction modeling, respectively. Details of the KGEMM can be found in Hasanov et al. (2020).

Table 8 summarizes the results of the macroeconomic analysis. In Table 8, Panel A shows the responses of employment, value added, private investment in the non-oil sector and inflation sectors to the injection of saved diesel revenues into the economy. Panel B shows the responses of value added and employment in the agriculture and utilities sectors to this injection. Before proceeding to a discussion of the aggregate or sectoral variables, two general observations are made from the results presented in Table 8.

First, the impact of saved diesel revenue spending on the economy is positive, but it is very small in magnitude. This is expected given that the amount the government spends or allocates in the agriculture and utility sectors is very small (see above). Moreover, we consider the impact in 1 year, which is very short run, and the short-run impact is usually smaller than the long-run impact. For example, Al Moneef and Hasanov (2020) find that the short-run (2-year) multiplier of government investment on the value added of the Saudi non-oil private sector is 0.08, while it is 0.47 in the long run. They also find that the multipliers of total government spending in the short and long run are 0.11 and 0.41, respectively. Thus, the diesel saved revenue is expected to have a higher impact in the coming years.

Second observation is that the Agri-utility scenario produces slightly higher non-oil employment and output values than the General-spending scenario (see Panel A of Table 8). This is especially true when it comes to sectoral employment and output effects (see Panel B of Table 8). In other words, the results of the scenarios might imply that the targeted sectoral supply-side effect is more growth-enhancing, albeit marginal, than the effect of general governmental spending. One explanation for this finding could be that empirical studies examining the impact of government spending on economic growth have concluded that the efficiency of this spending can be improved in Saudi Arabia, as in other Gulf Cooperation Council and developing countries (Al-Abri, Genc, and Naufal 2018; Al-Faris 2002; Alshahrani and Alsadiq 2014; Eid and Awad 2017; Espinoza, Fayad, and Prasad 2013; IMF 2019; Joharji and Starr 2011). To address this issue, the government established the Spending Efficiency Realization Center, in line with the former Fiscal Balance Program (recently launched as the Fiscal Sustainability Program), one of the main realization programs of the Saudi Vision 2030 (FBP 2019).
Figure 8. A schematic illustration of the KGEMM. For abbreviations, please refer to Appendix A.

Table 8. Percentage change deviations in \textit{General spending} and \textit{Agri-utility} compared with \textit{BaU} in 2021.

<table>
<thead>
<tr>
<th>Panel A: Aggregate Indicators</th>
<th>Variable</th>
<th>Scenario</th>
<th>\textit{General spending} (Scenario 1)</th>
<th>\textit{Agri-utility} (Scenario 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GVANOIL</td>
<td></td>
<td>0.037</td>
<td>0.050</td>
<td></td>
</tr>
<tr>
<td>ETNOIL</td>
<td></td>
<td>0.017</td>
<td>0.019</td>
<td></td>
</tr>
<tr>
<td>IFNOILP</td>
<td></td>
<td>0.032</td>
<td>0.240</td>
<td></td>
</tr>
<tr>
<td>INF</td>
<td></td>
<td>-0.003</td>
<td>-0.006</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Panel B: Sectoral Indicators</th>
<th>Variable</th>
<th>Scenario</th>
<th>\textit{General spending} (Scenario 1)</th>
<th>\textit{Agri-utility} (Scenario 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GVAAGR</td>
<td></td>
<td>0.001</td>
<td>0.224</td>
<td></td>
</tr>
<tr>
<td>ETAGR</td>
<td></td>
<td>0.003</td>
<td>0.109</td>
<td></td>
</tr>
<tr>
<td>GVAU</td>
<td></td>
<td>0.001</td>
<td>0.126</td>
<td></td>
</tr>
<tr>
<td>ETU</td>
<td></td>
<td>0.002</td>
<td>0.042</td>
<td></td>
</tr>
</tbody>
</table>

Source: Authors’ calculations.

Notes: IFNOILP = Investments in non-oil private sector, real, SAR Millions, 2010 prices. ETNOIL = Employment in non-oil sector, thousands. GVANOIL = Gross value added in non-oil sector, real, SAR Millions, 2010 prices. INF = Consumer price index (2010 = 100) inflation, %. GVAAGR = Gross value added in agriculture and forestry, real, SAR Millions, 2010 prices. ETAGR = Employment in agriculture and forestry, thousands. GVAU = Gross value added in utility sector, real, SAR Millions, 2010 prices. ETU = Employment in utility sector, thousands.
4. Results and Discussion

The second observation is that the Agri-utility scenario produces slightly higher non-oil employment and output values than the General-spending scenario (see Panel A of Table 8). This is especially true when it comes to sectoral employment and output effects (see Panel B of Table 8). In other words, the results of the scenarios might imply that the targeted sectoral supply-side effect is more growth-enhancing, albeit marginal, than the effect of general governmental spending. One explanation for this finding could be that empirical studies examining the impact of government spending on economic growth have concluded that the efficiency of this spending can be improved in Saudi Arabia, as in other Gulf Cooperation Council and developing countries (Al-Abri, Genc, and Naufal 2018; Al-Faris 2002; Alshahrani and Alsadiq 2014; Eid and Awad 2017; Espinoza, Fayad, and Prasad 2013; IMF 2019; Joharji and Starr 2011). To address this issue, the government established the Spending Efficiency Realization Center, in line with the former Fiscal Balance Program (recently launched as the Fiscal Sustainability Program), one of the main realization programs of the Saudi Vision 2030 (FBP 2019).

Regarding the impact of export revenues from saved diesel on the agriculture and utilities sectors, these revenues create positive employment and value-added effects in both sectors, albeit marginal ones. The effects are higher in magnitude when the injected money is directed into the sectors’ capital stocks through investment. This is expected, as sector-targeted spending should create more value added in these sectors than the general government spending. Another notable observation of the sectoral effect is that in the Agri-utility scenario, employment in agriculture increases much more than in utilities (0.11% versus 0.04%) compared with BaU. This is because the utilities sector is generally less labor intensive than the agricultural sector, even though the latter is not labor intensive in Saudi Arabia compared with global averages. For example, in their sectoral employment analysis, Hasanov et al. (2021) estimated that in the long run, a 1% increase in income leads to a 0.42% increase in employment in the utilities sector, while this elasticity is 0.93 for the agricultural sector. They find that the short-term income elasticities of employment are 1.98 and 0.55 for agriculture and utilities, respectively.

As for the aggregate non-oil employment, investment and value-added effects of the saved diesel export revenues, the positive values created in the General-spending scenario are mainly due to the demand effects resulting from the government’s additional spending, while those in the Agri-utility are mainly because of supply side (capital stock) effects in the agriculture and utility sectors. The increase in non-oil private investment is much higher in the Agri-utility scenario compared with that in the General-spending scenario: 0.03% versus 0.24%. This is expected because in the General-spending scenario only a portion of the general government spending can go to private investment, whereas in the Agri-utility scenario the government allocates all the saved diesel export revenues to the capital stocks of these sectors and this leads to a higher output, as predicted by the production function theory. Last, we observe that consumer price index inflation is almost unchanged across the scenarios, although it becomes negligibly negative. The negative effect, which again is negligible, in the Agri-utility scenario can be explained by the supply-side effects, while that in the General-spending scenario can be the result of the supply-side effects overbalancing the demand-side effects. Both explanations are theoretically expected.
5. Conclusion and Policy-relevant Insights

A detailed analysis is conducted to assess the financial, emission and macroeconomic implications associated with electrifying water pumping activities in the Saudi agricultural sector. The technoeconomic energy assessment is carried out with the aid of two mainstream software packages, HOMER and PLEXOS. The macroeconomic assessment, in contrast, is carried out using KGEMM, which is a hybrid-type general equilibrium econometric model extended to include the energy sector. The study also collected primary data.

To replace the diesel engines currently used for lifting water from aquifers, three alternatives are assessed: powering each individual farm with a dedicated hybrid microgrid, powering the entire cluster of farms with central generation and connecting the entire cluster of farms to the national grid. We find that connecting the farms to the national transmission grid is the most economic option, irrespective of the opportunity cost assumed. The national grid connectivity option can bestow other benefits, especially in the northern part of the Kingdom, as transmission interconnection plans with Iraq and Jordan can be considered. For example, right-of-way studies and civil works can be combined to reduce costs, or the same transmission line can serve both farming activities and the exporting/importing of power. Powering the entire cluster of farms with central generation comes in second place, even when considering different gas prices and opportunity costs.

Depending on the opportunity cost assumed, the hybrid renewable microgrid option can possess a positive NPV. However, it requires the highest amount of capital, totaling more than $2 billion dollars, with battery storage being responsible for most of this amount. As a result, even if the NPV of the hybrid renewable option are comparable with the other projects, the other two options would be considered more attractive given the lower capital costs needed. Note, however, that the renewable option reduces emissions by around 1.1 million tonnes of carbon dioxide. Considering that total Saudi emissions are 620 million tonnes, the emission-reduction argument should not be considered as a main driver for electrifying the agricultural sector. While renewables may be deemed economically viable in other agricultural applications, the unique situation of the case study considered herein (i.e., deep aquifers and high flow rate) translated to a high energy requirement and hence high capital.

Another policy-relevant finding that stemmed from this study is that the NPV of all electrification options is positive, even with a relatively low agricultural electricity tariff. In fact, as the analysis showed, the opportunity cost is high to the extent that the agricultural electricity tariffs could be lowered and the government could obtain an outcome that has a positive NPV. Governments generally resort to raising fuel and/or electricity prices to promote efficiency and rationalize consumption. In this study, alternatives to raising diesel prices used for agriculture are offered. The considered scenarios, which require investment, garner considerable benefits.

Regarding the macroeconomic and sectoral implications of the diesel displacement, there are two main points that can inform policymaking. First, the impact of spending saved diesel export revenues on the economy is positive, but it is very small in magnitude. This might imply that the more diesel is displaced the more benefits would be realized. Note that the analysis herein focuses on one agricultural cluster only. However, the macroeconomic and
5. Conclusion and Policy-relevant Insights

sectoral analyses conducted here do not take into consideration any associated direct or indirect costs of diesel displacement. Second, the targeted sectoral spending effect is more growth-enhancing, albeit marginally so, than the effect of general spending by the government. This suggests implementation of additional measures to further improve the efficiency of general government spending. This policy recommendation can be seen as support for the already established Spending Efficiency Realization Center highlighted in the Fiscal Balance Program (recently renamed the Fiscal Sustainability Program), which is one of the main realization programs of the Saudi Vision 2030.

Some lessons can be extended to other countries. Specifically, renewables can contribute considerably to the agricultural sector in countries where water aquifers are not deep, where non-water-intensive crops are grown and/or where the weather is not arid (see examples in section 2). Otherwise, considerable investment (i.e., to meet the considerable capital and land requirements) would be needed. One solution to this challenge would be to resort to a hybrid renewable-plus-diesel microgrid. The latter serves as a midway point between two extremes but is not considered in the analysis here because the intention of the paper is to quantify the costs of fully retiring diesel. A hybrid renewable-plus-diesel microgrid may serve, nonetheless, as a transitional stage before full diesel retirement is realized.
Notes


2 Not all the $273.6 million is available for the government to spend, as some costs and taxes are deducted from this amount, which averages to 20% of oil export revenues (Hasanov et al. 2020; Oxford Economics 2021). The Saudi Riyal, abbreviated SAR, is pegged to the U.S. dollar, where 1 USD is equivalent to 3.75 SAR.

3 We projected that the investment deflator in 2021 will be 110.57, considering 2010=100.

4 The version of KGEMM used in this study differs slightly from that documented by Hasanov et al. (2020) as the data have been updated, the behavioral equations have been re-estimated through 2019 and the projections account for COVID-19 and post-COVID-19 recovery effects.
References


References


Appendix A

Abbreviations for the KGEMM parameters and variable, as shown in Figure 8 (in alphabetical order):

- **CPI**: consumer price index, 2010=100
- **entoil**: employment in non-oil sector
- **gap_lgvanoil**: output gap in the non-oil sector production function
- **gap_lgvaser**: output gap in the services sector production function
- **gc**: government consumption
- **gcgpe**: government transfer to households
- **GDP**: gross domestic product
- **gdpnoil**: value added in the non-oil sector
- **gi**: government investments
- **grevoth**: other government revenues (non-oil revenues)
- **gvacon**: value added in the construction sector
- **gvadis**: value added in the distribution sector (wholesale, retail, cafes and restaurants and hotels)
- **gvafibu**: value added in the financial, insurance and other business services
- **gvamanno**: value added in the non-oil manufacturing sector
- **gvaminoth**: value added in the non-oil mining sector
- **gvaoths**: value added in other service sectors
- **gvaser**: value added in the service sector
- **gvatracom**: value added in transportation and communication sector
- **M**: real imports
- **M2**: broad money aggregates
- **oilmbd**: oil production in Saudi Arabia
- **oiluse**: domestic oil use in Saudi Arabia
- **oilx$$_z$$**: oil export revenues, in USD
- **pengind**: price of energy in industry
- **popmig**: migrated population
- **popw**: population of working age
- **Rxd**: exchange rate
- **TFE**: total final expenditure
- **X**: total exports
About the Authors

Amro Elshurafa

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

Hatem Alatwi

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

Fakhri Hasanov

Fakhri is a senior research fellow leading the KAPSARC Global Energy Macroeconometric Model (KGEMM) project. Previously, he was an associate professor and director of the Center for Socio-Economic Research at Qafqaz University, Azerbaijan. He has served as a deputy director of the Research Institute at the Ministry of Economic Development, and a senior economist at the Research Department of the Central Bank of Azerbaijan Republic. He received a Fulbright Post-Doctoral Scholarship and conducted a research on building and applying a macroeconometric model for policy analysis at the George Washington University. Fakhri is a member of the research program on forecasting at the George Washington University and the editorial board of the Asian Journal of Business and Management Sciences. His research interests and experience span econometric modeling and forecasting, building and applying macroeconomic models for policy purposes, energy economics with a particular focus on natural resource-rich countries.
Frank Felder

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

About the Project

The Saudi agricultural sector relies on diesel for irrigation, which is provided to farmers at a much lower price than the average global price, implying significant opportunity costs. With the aid of soft-coupled power and macroeconometric models, we assess in this study the cost and macroeconomic implications of retiring diesel and electrifying irrigation activities in the Saudi agricultural sector.