Macroeconomic, Energy and Emission Effects of Solar PV Deployment at Utility and Distributed Scales in Saudi Arabia

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This study assesses the macroeconomic, energy and emissions impacts of solar photovoltaic (PV) deployment in the Kingdom of Saudi Arabia for the period 2021–2030. This is accomplished by linking an energy and environmental sector augmented macroeconometric model with a power model and a distributed generation model. Furthermore, this study distinguishes between the macroeconomic, energy and emissions impacts of PV deployment at the utility and distributed generation scales. To the best of our knowledge, these two aspects make this work novel. We analyze three scenarios: (i) fully government-funded utility-scale PV deployment, (ii) half-government-funded utility-scale PV deployment and (iii) household-funded distributed-generation-scale PV deployment, with some government support alongside a business-as-usual (BaU) scenario.

Based on the scenario analyses, the following main policy options emerge. Scenario (ii) offers more gains related to non-oil economic activity than the other two scenarios, although these have their own merits. Numerically, in scenario (ii), government non-oil revenues, non-oil value added, employment, utilities value added and household consumption increase by 0.06%, 0.01%, 0.02%, 1.76%, and 0.03%, respectively, on average, over 2021–2030 compared to the BaU scenario. These figures are lower or even negative in the other two scenarios. Thus, if the main objective is to improve non-oil fiscal positions, increase non-oil value added, employment and household consumption, scenario (ii) is preferred. However, if the main concern is to reduce energy consumption and associated carbon dioxide (CO₂) emissions to achieve energy efficiency and pollution reduction goals, as well as a better position in international trade, then scenario (iii) would be the best option. Over the projected period, the total energy consumption and CO₂ emissions are both reduced by 0.31%, while net exports increase by 0.52% in this scenario compared to BaU, on average. If the main policy focus is on fiscal expansion and increasing the size of the utility sector, authorities should implement scenario (i), as it offers an average of 0.16% and 1.76% more growth, respectively, compared to BaU for the period in question. The scenario analysis also supports the commonly held view that domestic absorption, especially government investment, plays an important role in the Kingdom’s development. Therefore, it would be desirable for the government to have partners for financing renewable energy deployment projects, as it could save budgetary resources to invest in growth-enhancing areas and promote economic development.
Many governments worldwide have supported renewable energy generation for energy independence (security) purposes (Gökgöz and Güvercin 2018; Lucas, Francés and González 2016), to meet carbon emission reduction targets (Akram et al. 2020; Nguyen and Kakinaka 2019; Saidi and Omri 2020) and/or contribute to domestic economies by creating jobs and establishing industries (Mu et al. 2018). The continuous cost declines of renewable technologies have made them cost competitive compared with conventional forms of energy generation in many jurisdictions. Capacity expansion models choose to build renewables, despite their intermittent nature (Helm and Mier 2019).

The link between energy security and renewables has received significant research attention (Ang, Choong and Ng 2015; Aslani, Helo and Naaranoja 2014; da Silva et al., 2016; Kousksou et al. 2015). This is also the case for the link between carbon emissions and renewables (Dai et al. 2018; Emir and Bekun 2019; Hanif 2018; Jin and Kim 2018; Lee et al. 2018). However, as Andini, Cabral and Santos (2019) highlight, the impact that renewable energy deployment has on macroeconomic indicators has received far less research attention.

Depending on the economic structure prevailing in any country, deploying renewable energy will result in different economic outcomes. The economic benefits that renewable energy deployment can bestow include, for example, creating an industry (Liu, Li and Yao 2019) and generating (direct and indirect) jobs (Garrett-Peltier 2017). Excess production can also be exported if the manufacturing capacity exceeds domestic needs (Cao, Rajarshi and Tong 2018). For fossil-fuel-rich countries, deploying renewables for power generation can free up domestic fossil fuels for export (Atalay, Biermann and Kalfagianni 2016; Elshurafa et al. 2022). Other benefits include boosting industry innovation (Pegels and Lütkenhorst 2014) and relaxing healthcare budget allocations since renewables can contribute to lowering carbon emissions and consequently, reduce illnesses (Buonocore et al. 2016). It is worth noting that some of these benefits, like boosting innovation and improving human health, are difficult to quantify. Further, not all the above-mentioned benefits necessarily apply to all countries. Some countries will opt to import technology rather than manufacture it domestically. Similarly, not all countries are oil rich or oil exporting. Each jurisdiction possesses unique characteristics that warrant a dedicated study.

In addition to the economic environment dominant in a certain country, renewable energy deployment for the same technology can occur in different forms. In the case of solar photovoltaic (PV), which is the focus of this paper, it can be deployed at the utility scale or at the distributed generation scale. Utility-scale PV farms refer to larger plants with capacities of several megawatts (MW) and reaching even the gigawatt (GW) scale. Distributed-scale PV are in the range of a few kilowatts (kW) and are mostly deployed at the residential or commercial scale.

Significant differences exist between utility-scale and distributed-scale PV. Utility-scale PV benefits from economies of scale, and hence can be deployed at lower per-unit capital costs. Further, utility-scale solar PV projects are easier for grid operators and central planners to handle. However, they require large land footprints, which may not always be available or accessible. In contrast, distributed generation solar PV systems, which are typically installed on rooftops, do not occupy land, but they are more costly on a per-unit basis. From a financing perspective, the government (represented by the national electricity company if the electrical sector is government owned) or market players...
(if the electricity market is deregulated) would invest in utility-scale projects. In this case, no household spending is required. At the distributed scale, however, the homeowner would likely bear some of the PV installation cost (regardless of whether the technology is subsidized). These, and other differences mean that deploying the same PV capacity at the utility and distributed generation scales will have different economic impacts. This latter distinction was a major stimulus for this study.

Considering the above, this study introduces a method whereby policymakers can assess the macroeconomic, energy and emission benefits through a set of key indicators that would result from deploying solar PV projects \textit{ex ante}. Such indicators include international trade, fiscal indicators, employment, output and household consumption. An important characteristic of the analysis presented herein is that it can quantify and distinguish between the macroeconomic, energy and emission impacts that stem from solar PV deployment at either the utility or distributed generation scales. This distinction is valuable for policymakers as it allows for better informed decisions in terms of setting renewable deployment targets and allocating financial support (i.e., subsidies). Policymakers can also determine the share that each technology segment should be responsible for with respect to the overall deployment target.

In light of the above, this study attempts to quantify the macroeconomic, energy and emission impacts that stem from solar PV deployment in the Kingdom of Saudi Arabia. This objective is achieved by using an energy- and environmental-sector augmented macroeconometric model, the KAPSARC Global Energy Macroeconometric Model (KGEMM). This model describes energy, environment, and macroeconomic linkages in the Saudi economy. KGEMM is linked with two other models: an optimal power dispatch model and a distributed-generation technoeconomic model. This is the first time that such an approach has been used. It represents an innovative approach for policy analysts and policymakers concerned with the important and pressing issues of how much and what types of PV to deploy, considering the macroeconomic, energy and emission implications. We also note that the Saudi government has announced ambitious renewable energy targets; hence, understanding the macro implications of renewable energy deployment is of interest to policymakers.

We simulated KGEMM for the macroeconomic, energy and emissions impacts of solar PV deployment and associated fuel saving and financing in three scenarios for 2021–2030. In the first scenario, PV deployment at the utility scale is fully financed by the government, and in the second it is half financed. In the third scenario, households mainly finance distributed generation, with a contribution from the government. Policy options derived from the scenario analyses are proposed to support the decision-making process, depending on the priorities of the policy agenda.

This study contributes to the literature in the following ways. First, to the best of our knowledge, it is the first study to link an energy- and emission-augmented macroeconometric model with power and distributed-generation models to assess the macroeconomic, energy and emissions impact of PV deployment, distinguishing between utility and distributed generation scales. Second, unlike many previous studies, and for the first time for Saudi Arabia, a general/full equilibrium macroeconometric model is used to examine the macroeconomic impacts of renewable energy. This specific contribution has two benefits: (1) KGEMM, as a general equilibrium hybrid modeling framework, provides more comprehensive representations (e.g., the impacts of renewable energy
on more than one variable) than single equation frameworks. Moreover, it allows for both feedback loops and the impacts of variables of interest. These include policy levers other than renewables (e.g., fuel switching, government investment, international trade) that are particularly important for forecasting/projections but are missing in single-equation frameworks (e.g., Ballantyne et al. [2020]; Beenstock and Dalziel [1986]; Cusbert and Kendall [2018]; Hasanov [2019]; Hasanov et al. [2021], Bandara [1991], Elshurafa et al. [2022]). (2) As Giacomini (2015), Gurkaynak et al. (2013), Nikas, Doukas and Papandreou (2019, 37–38) and others discuss, hybrid macroeconometric models provide more information than structural models. This is because they not only incorporate theory-guided structural relationships but also data-driven short-term dynamic relationships and deviations from theory-guided equilibrium relationships. Third, this paper projects the macroeconomic, energy and emissions outlook for the Saudi economy under the impact of PV deployment through 2030. Fourth, this is one of a few studies that examines the macroeconomic, energy and emission impacts of PV deployment in Saudi Arabia through broader indicators, accounting for COVID-19 and post-COVID-19 implications, using a general equilibrium framework.

The remainder of the paper is organized as follows. The next section summarizes the relevant literature. Section 3 details the different models utilized, the methodology and the structure of the simulations. Section 4 presents the results and Section 5 summarizes and concludes the paper.
Recently, a growing body of literature has begun to employ general equilibrium hybrid-type macroeconometric models (and coupling them with energy and environmental models) to investigate (macro)economic effects of (renewable) energy, environmental and other policy measures. Examples include but are not limited to Blazejczak, Edler and Schill (2014); Blazejczak et al. (2014); Fläute et al. (2017); Lindenberger et al. (2010); Lehr and Lutz (2016); Lehr, Lutz and Edler (2012); Lutz (2011); Lutz, Lehr and Ulrich (2014); Lutz et al. (2014); Schlesinger, Lindenberger and Lutz (2010) and Welfens and Lutz (2012). None of these studies considers Saudi Arabia. One reason for preferring macroeconometric models to other structural general equilibrium models (such as computable general equilibrium [CGE] and dynamic stochastic general equilibrium [DSGE] models) would be that hybrid macroeconometric models provide more information. This is because they not only incorporate theory-guided structural relationships but also include data driven short-term dynamics (i.e., deviations from theory-guided equilibrium relationships). This is unlike CGE, DSGE or agent-based optimization models, as Giacomini (2015), Gurkaynak et al. (2013), Nikas, Doukas and Papandreou (2019, 37–38) and others discuss. Another reason is that the behavioral representations of the economic agents (such as government, private sector and households) are based on their historical evolutions in the macroeconometric models. In contrast, in CGE or DSGE-type models, they are usually based only on the optimization of a representative agent, imposed parameters and calibration using single-year data and national accounting relationships (e.g., see Blazejczak et al. [2014]; Lehr, Lutz and Edler [2012]; Lutz [2011]).

We find that, unsurprisingly, Germany has received considerable attention from the literature with respect to quantifying the impact of renewable deployment on its economy. Lutz (2011), in addition to using a macroeconometric model, used an electricity optimization model for Europe to inform his analysis. According to Lutz, resorting to a European model was necessary given the nature of the European Emissions Trading System and the future integration of electricity markets that is planned on the continent. He also used a bottom-up energy consumption model. The electricity and energy models were soft linked with an econometric analysis to assess Germany’s gross domestic product (GDP) and employment.

Blazejczak et al. (2014) analyzed and quantified the net balance of economic effects related to renewable energy deployment until 2030 in Germany. The macroeconometric model that was employed contained a representation of industries, including renewable energy sectors. The study showed that renewables can be deployed in Germany without compromising growth or employment. A similar conclusion was reached by Lehr, Lutz and Edler (2012), who also employed a macroeconometric model to assess the impact of renewable energy deployment on job creation.

Fläute et al. (2017) used an environmentally extended macroeconometric model and an input-output model in the context of Germany, concluding that ‘prosumers’ (energy consumers who also produce it) have a positive effect on the macroeconomy. In this model, the parameters are econometrically estimated with a flexible input-output structure.

Blazquez et al. (2021) studied the macroeconomic and welfare impacts of renewable energy deployment in Saudi Arabia using a DSGE model. They found that when renewables are financed through a reduction in government consumption or transfers
to households, no welfare gains are realized. Renewable energy deployment was found to have positive impacts on macroeconomic indicators (e.g., it increases oil exports and non-oil GDP).

Soummane et al. (2019) discussed macroeconomic pathways for the Saudi economy under various scenarios extending until 2030 using a CGE model. This study did not explicitly focus on the impact of renewable deployment on the economy. Rather, it focused on global oil prices. They also considered the impact of increasing domestic energy tariffs and enacting efficiency initiatives. The deployment of renewables was a secondary aspect of their growth modeling.

Blazquez, Hunt and Manzano (2017) employed a DSGE model to assess the interrelations between oil and renewable deployment in the Saudi economy. They found that there would be a positive impact of these interrelations on GDP and household welfare at low renewable penetration levels. However, at high shares of renewable deployment, the Saudi economy’s dependence on oil would increase (because of increased oil exports).

The following papers are examples of studies that used CGE models to assess the (macro)economic effects of renewable energy deployment. Cansino et al. (2014) employed a CGE model to assess the macroeconomic impact of an increase in solar parks in Andalusia, a southern, semi-autonomous independent part of Spain. They estimated that increasing power output by over 300 MW of installed capacity through an increase in solar parks would increase activity by over 3%. Further, they estimated that the total employment generated would be over 215,000 full-time equivalent jobs, and other key macroeconomic indicators would increase.

Timilsina, Pang and Yang (2021) assessed the potential macroeconomic impacts of following a market-based principle to operate the power sector in China. This was achieved by coupling a top-down CGE with a bottom-up energy model. They found that adopting a market-based approach would reduce prices by 20%, and that this price reduction would spill over to the economy and result in a GDP increase of more than 1%. In contrast, Li, Lu and Zhang (2019) found that a renewable energy policy, in the form of renewable portfolio standards, would have a marginally negative impact on the macroeconomy in China. Specifically, for each additional percentage point in the share of renewables in the energy mix in 2030, the loss in GDP would increase by around 9.11 billion Chinese yuan.

Kat, Paltsev and Yuan (2018) assessed the economic impact of Turkey’s 2015 pledges to reduce its greenhouse gas emissions by 21% by 2030. The authors developed a CGE model of the Turkish economy, which combined a macroeconomic representation of the non-electric sectors with a detailed power sector representation. They concluded that these pledges may be possible at a small economic cost of about 1% compared with the business-as-usual (BaU) case. A similar conclusion was reached for Australia (Meng et al. 2018) through a CGE model that integrated an electricity supply model. It was found that a national emissions trading scheme would reduce emissions effectively, with a small impact on the overall economy.

To examine the potential impacts of a carbon tax in South Africa, Nong (2020) developed a CGE model with a more detailed representation of electricity, emission and carbon price mechanisms. It was found that the incorporation of non-carbon dioxide ($\text{CO}_2$) emissions in the model significantly altered the results compared with a scenario that only considered $\text{CO}_2$ emissions. South Africa can reduce its emissions by around 15% at the cost of a real GDP reduction of 1.59%.
Del Granado et al. (2018) discussed the nexus of energy-system and economic modeling to accurately describe energy transitions. They proposed linking top-down and bottom-up models to represent distributed generation, grid operation, dispatch and macroeconomic interactions.

Another method for assessing the impact of renewable deployment on the macroeconomy is via partial equilibrium models, which are more widely adopted than general equilibrium models. Most existing studies that use partial equilibrium, including a single-equation modeling framework, examine the macroeconomic effects of renewable energy by focusing on either parameter estimates or Granger non-causality exercises. Some of these studies are discussed below.

Chien and Hu (2008) used structural equation modelling for over 100 countries in an attempt to understand the mechanism of how renewables improve macroeconomic efficiency. They found that renewables have a significant positive influence on capital formation (but not on the trade balance). Thus, they concluded that there is a “positive relationship between renewable energy and GDP through the path of increasing capital formation” (Chien and Hu 2008, 3050). Kahia et al. (2017) analyzed renewable energy policies for 24 Middle East and North Africa (MENA) economies using probit, logit and tobit econometric estimation. They concluded that the treatment effect of renewable energy policies had a positive impact, increasing economic growth in the countries that implemented the policies.

Two studies, Fang (2011) and Inglesi-Lotz (2016), considered the role of renewable energy consumption in increasing economic welfare for China (based on a Cobb-Douglas production function) and for 34 OECD countries (using panel cointegration), respectively. Both studies concluded a 1% increase in renewable energy consumption would increase real GDP by about 0.1% and GDP per capita by about 0.1%-0.2% in China and the 34 OECD countries, respectively. In addition, Inglesi-Lotz (2016) found that a 1% increase in the share of renewable energy in the energy mix of the OECD countries would increase GDP and GDP per capita by about 0.1%, respectively. Fang (2011), however, found that the impact of a change in the renewable energy consumption share on economic welfare in China was not significant, and that an increasing share might have a negative effect on economic welfare. A study by Andini, Cabral and Santos (2019) used a structural vector autoregression approach for Portugal and found that renewable electricity power generation projects had a positive effect on economic growth in the medium run through the investment and operation stages.

Many studies have used various econometric approaches to determine whether there is Granger causality between renewable energy consumption and macroeconomic indicators such as economic growth. Examples include Apergis and Payne (2010a) for 20 OECD countries; Apergis and Payne (2010b) for 13 Eurasian countries; Tugcu, Ozturk and Aslan (2012) for the G7 countries; Apergis and Payne (2012) for 80 countries; Ocal and Aslan (2013) for Turkey; Rafindadi and Ozturk (2017) for Germany and Tugcu and Topcu (2018) for the G7 countries. The results concerning the impact of renewable energy consumption on economic growth vary. Sebri (2015) undertook a meta-analysis of such studies in an attempt to quantitatively synthesize this literature to investigate the causes of variation in the causality between renewable energy consumption and economic growth. The author found that the variation is “due to a number of characteristics including model specification, data characteristics, estimation techniques …, and development level of
Several studies have analyzed the likely impacts of PV deployment in a micro-economic partial equilibrium framework. One example is Branker and Pearce (2010) who found, based on a financial analysis, that both the provincial government of Ontario and the Canadian federal government benefited from positive cash flows from various subsidies to incentivize PV deployment in less than 12 years. They determined that it was “in the financial best interest of both the Ontario and Canadian federal governments to implement aggressive policy to support PV manufacturing,” and that such policies would “provide substantial economic, environmental and social benefits” (Branker and Pearce 2010, 4301). Richter (2013), who conducted interviews with German utility managers, suggested that utilities do not see distributed PV as a threat to their businesses and do not see distributed PV as a potential market for them. Furthermore, he argues:

*Utilities have to change their perspective on distributed PV to overcome the barriers: The solution lies in not treating distributed PV generation as merely another source of electricity generation in competition with traditional sources, but as a strategic option to enter the emerging distributed generation and service markets.* (Richter 2013, 464).

Some noteworthy observations can be made based on our review. First, to the best of our knowledge, no previous study has used a macroeconometric model to assess the effects of solar energy by distinguishing utility scale from distributed generation scale. Second, although a recently growing body of literature uses macroeconometric models to assess the impacts of energy, environmental and other measures, there are few papers concentrating on renewable deployment in this manner. Third, there are very few studies that link a macroeconometric model with energy sector model(s) to explore the implications of renewable deployment. While some studies incorporated a detailed description of the power sector within a macroeconomic framework, none incorporated the distributed generation piece into a macroeconomic framework. To the best of our knowledge, the modelling linkages we introduce in this study are the first attempt to combine a power model, a distributed generation model and a macroeconometric model to assess the likely macroeconomic, energy and environmental effects of PV deployment. We reiterate that the clear distinction between how utility-scale deployment and distribution-generation-scale deployment impact the economy is among the key contributions of this study, and it is applied herein to the Saudi economy.

The next section introduces the models used here and our approach to simulating the macroeconomic effects of PV deployment at the utility and distributed generation scales.
Overview of Methodology

As outlined in the introduction, the objective of this paper is to assess how differently utility-scale (UTS) and distributed-generation-scale (DGS) PV deployment can contribute to the Saudi economy. This difference stems from several factors such as the source of investments and the impact on government revenues. At the UTS, the government would fund the deployment of PV farms. At the DGS, however, households would make the investment, with possible support from the government via instruments such as investment credits, feed-in-tariffs and tax credits. Further, in the case of UTS PV deployment, the state-owned integrated electricity company would not suffer lost revenues. However, in the DGS case, it would because it would sell less electricity given that the household would consume whatever is generated by the distributed-generation (DG) PV system.

When PV is deployed as part of the energy mix, it would be dispatched first, as per the merit order, because it has a near-zero marginal cost. Another way to view the contribution of PV, or renewables more generally, in the dispatch of power plants, is through the lens of net demand. As a result, a certain amount of fossil fuels would be saved. Saudi Arabia relies mostly on natural gas, crude oil and heavy fuel oil for its power generation needs. Depending on where (i.e., in which region within the Kingdom) and how much PV is deployed, the amount and type of saved fuel would vary. A Saudi power sector model is therefore developed to quantify the amount of saved fuel that would result from PV deployment and then be exported, used by other industries, or otherwise consumed.

On the DGS side, given the low electricity retail tariffs currently prevailing in the Kingdom (ranging from $0.048 per kilowatthour (kWh) for the first consumption slab below 6,000 kWh and $0.08/kWh for the second consumption slab), DG PV is still not considered financially attractive. If DG is to be deployed widely, governmental intervention would be needed to make the business case for DG such that it is attractive for homeowners compared with obtaining electricity solely from the grid. To quantify the amount of incentive required, a technoeconomic DG model is developed.

The output from these two models (i.e., the Saudi power model and the DG model) are then used as inputs into KGEMM. KGEMM is a time series macroeconometric model that integrates data properties with relevant theory and captures new Keynesian demand side features anchored to medium-run equilibrium and long-run aggregate supply. It is used as a policy analysis tool for examining the impacts of domestic policy measures and global economic and energy shocks on Saudi Arabia. This therefore provides a framework for considering the overall impact of the UTS and DGS deployment of PV on the Saudi economy. In particular, we focus on the impact this deployment has on important macroeconomic indicators such as total energy consumption, international trade, government revenues, GDP, household consumption and employment in the year of deployment as well as five years and 10 years later, respectively.

Saudi Power Model (SPM)

We developed a power model that describes the Saudi power sector using the commercially available software package PLEXOS. The Kingdom is divided into six regions with all the generators and their heat rates inputted. Further, the transmission interconnection between the regions is also modeled, and we assign a single load node to each
region. Other inputs to the model include the hourly load profile for each of the six regions and fuel prices. The model is then run in a short-term optimal dispatch mode—minimizing costs—with an hourly resolution (Elshurafa et al. 2021; Elshurafa and Peerbocus 2020).

It is important to bear in mind that the fuel mix within the Kingdom varies significantly among the different regions. For example, the eastern region, which is where the oil and gas fields are found, relies entirely on gas for its power generation needs. Conversely, the southern region is fully reliant on liquid fuels. Hence, the fuel savings that would result from PV deployment is highly dependent on where the PV plant is located. Note also that there are energy flows between the regions through transmission interconnection. All these (and other) intricacies are captured in the power model.

A key output of this model for the purposes of this study is the fuel offtake. In the base case, we run the model given the current status of the power sector in the Kingdom and obtain the fuel offtake. Next, we add a specific PV capacity to the energy mix, as announced by the Kingdom (please see Table A1 in Appendix A for the announced projects), and rerun the model. The fuel offtake in the second run (i.e., with PV) would be lower than in the first run (i.e., without PV). The model would also inform us of the reduction in offtake of each of the fuels (i.e., gas, crude oil and heavy fuel oil). This is an important numerical result as the savings realized from each fuel would be invested back into the economy differently: natural gas would be reallocated to industry while crude oil could be exported, for example.

**Distributed Generation Model**

Despite the significant cost reductions witnessed in the solar industry, solar PV at the distributed scale is not financially attractive in the Kingdom, primarily because of the country’s very low electricity prices. Therefore, for PV to be widely deployed, incentives are required. To properly quantify the incentives required, a technoeconomic model was developed via the Hybrid Optimization of Multiple Energy Resources (HOMER Pro) software. Data inputs to this model include, for example, the capital costs of PV, solar irradiation, temperature, module efficiency and load profile.

As explained earlier, the total costs of obtaining electricity from the grid-plus-PV would be higher than obtaining electricity solely from the grid. For both scenarios to be equivalent, we assume that the government incentivizes the homeowner with an investment credit (i.e., shares part of the PV capital costs), making the net-present cost for both scenarios equal.

By quantifying the amount of incentives required to make the grid-only option financially equivalent to the grid-plus-PV option, the share that the homeowner can bear would also be determined. These two spending items, which result from the DG model, can be inputted into the macroeconomic model. We reiterate that the incentives provided by the government and household spending in the case of DG deployment are not present in the case of UTS deployment.

**Macroeconometric Model**

KGEMM comprises econometrically estimated behavioral equations using time series data and identities to represent economic (macro and sectoral), energy and environmental relationships within the Kingdom. In econometric estimations, it uses a cointegration and equilibrium correction modeling (ECM) framework, in which the estimated long-run relationships follow economic theories, whereas the estimated short-run relationships are
mainly data driven. The econometric estimations of the behavioral equations are performed in the framework of the general-to-specific modeling strategy (Gets) with Autometrics—an automated machine learning econometric modeling algorithm—and encompassing tests. The identities mainly come from the System of National Accounts. They are also used to represent bridge relations and conversions. For further details see Hasanov et al. (2020, 2022).

As Figure 1 below illustrates, KGEMM has nine blocks, namely energy, CO₂ emissions, fiscal, monetary, real, external, labor market and wages, prices, and population and age cohorts, which interact with each other to represent Saudi Arabian energy-economic-environmental relationships. The relationships are based on more than 780 annual time series variables classified as endogenous or exogenous, and more than 360 behavioral equations and identities. The exogenous variables primarily represent domestic policy, global energy and the global economy. The endogenous variables are determined by behavioral equations or identities constructed primarily based on the System of National Accounts.

The behavioral relationships among the variables are modeled using cointegration and ECM. Hence,

Figure 1. Schematic illustration of KGEMM.
these relationships capture long-run (i.e., theory-driven) and short-run (i.e., data-driven) dynamics. In other words, KGEMM represents theoretically coherent relationships, similar to CGE or DSGE models. Additionally, it represents short-run dynamic relationships and deviations from the theoretically-dictated equilibrium relationships, which are mainly data driven and modeled by equilibrium correction equations if cointegration exists among the variables. This is the key advantage of KGEMM-type macroeconometric models over pure structural models, as discussed by Nikas, Doukas and Papandreou (2019, 37–38), inter alia.

The demand-side of the energy block contains 14 behavioral equations for eight primary and secondary energy products across five customer types in Saudi Arabia. These are the consumption of crude oil, heavy fuel oil (HFO), diesel, natural gas and electricity by industry; the consumption of gasoline, diesel and kerosene in transportation; the residential consumption of electricity, kerosene and liquefied petroleum gas; and commercial, government and agricultural electricity consumption. In the equations, energy consumption is usually expressed as a function of price and income (and, where appropriate, the prices of substitute energy types).

On the supply side of the energy block, the total electricity supply in Saudi Arabia comes from fossil fuel generation (oil, HFO, diesel and natural gas) and renewable energy sources. This structure enables KGEMM to quantify the impacts of different policy options, such as 50% of electricity generation from natural gas, a higher share of renewables than fossil fuels or different efficiency ratios in electricity generation. It should also be noted that renewable electricity generation in KGEMM currently only includes solar electricity generation. This is because other renewable energy sources, such as wind, hydro, geothermal and biofuels, are either negligible or their data are not available.

The structure of the model can distinguish between the benefits that would stem from PV deployment at the utility and DG scales. In this study, we focus on output and employment as the main macroeconomic indicators, as they are considered key indicators of any macroeconomic policy. For Saudi Arabia, we particularly chose non-oil value added and non-oil employment. This is because one of the major goals of the country’s strategic long-term policies, per official documentation and announcements such as Saudi Vision 2030, is to further develop the non-oil sectors of the economy to achieve diversification away from oil. We also considered how government revenues can be negatively affected by PV deployment and positively by saved and exported fossil fuels.

**Summarizing the Model Linking**

The three models described above are collectively utilized to compare how UTS and DGS PV deployment would impact the Saudi macroeconomy. Figure 2 outlines the overall linking between the three models. There are tens of thousands of input values, including hourly regional load values, hourly regional solar irradiation values, hourly regional temperature values and many more technical and economic inputs. We only show a sample of these inputs in Figure 1 for illustrative purposes. Each input (or set of inputs) is only relevant to a specific model.

The outputs that we are interested in will be attained from the macroeconometric model block, i.e., KGEMM. However, as shown in Figure 2, some of the outputs calculated from the SPM and DG model serve as inputs to the KGEMM. We reiterate that the conceptual schematic shown in Figure 2 is a representative one. It shows a sample of the possible inputs needed to run the model and a sample of the possible outputs that could be obtained.
Scenario Description

We simulate the joint modeling framework illustrated in Figure 2 to produce multiple scenarios, a base-case and three other PV deployment scenarios, as follows:

**Scenario BC – Base Case**: In this scenario, we calculate all the macroeconomic metrics of interest, assuming the current status of the Saudi economy where no PV deployment exists. As the name of this scenario suggests, it is the base scenario against which all other scenarios will be compared.

**Scenario UTSLF – Utility-Scale Deployment that is Locally Funded**: Here, a solar PV capacity at the utility scale that is fully funded by the government would be deployed. The capacities that would be deployed are based upon recent announcements by the Saudi government. The announcements indicate a total capacity of 3.27 gigawatts (GW) of PV projects would be commissioned in various locations around the Kingdom and deployed at the UTS (please see Table A1 in the appendix).
**Scenario UTSMF – Utility-Scale Deployment with Mixed Funding:** This scenario resembles the previous scenario in terms of the capacity of UTS PV deployed. However, it differs in the method of financing. This scenario assumes that half the funding would be provided by the government, and the other half would be secured via foreign direct investment (FDI).

**Scenario DGD – Distributed-Generation Deployment:** The final scenario assumes that the announced capacity of 3.27 GW would be completely deployed at the distributed scale. Recall that, in this scenario, households would bear a considerable share of the capital costs. In addition, the government would provide incentives in the form of investment credits to make the grid-plus-PV option financially equivalent to the grid-only option.

Table 1 summarizes the key assumptions for capital expenditure (capex) and incentives used in the above scenarios. The results are discussed in the next section.

Table 1. Key spending scenario assumptions.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Parameter</th>
<th>Value ($ million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTSLF</td>
<td>Government investment</td>
<td>2,298</td>
</tr>
<tr>
<td>UTSMF</td>
<td>Government investment</td>
<td>1,144.5</td>
</tr>
<tr>
<td></td>
<td>Foreign direct investment</td>
<td>1,144.5</td>
</tr>
<tr>
<td>DGD</td>
<td>Incentives from government</td>
<td>817.5</td>
</tr>
<tr>
<td></td>
<td>Payments by household</td>
<td>2,452.5</td>
</tr>
</tbody>
</table>

Source: Authors’ own calculation.
Figure 3. Transmission channels from renewable deployment to the macroeconomy.

Source: Authors’ own construction.
Note: The blue and red arrows indicate a given process leads to an ‘increase’ or ‘decrease,’ respectively. In the interests of brevity and simplicity, we do not illustrate feedback effects in KGEMM (e.g., an expansion of economic activity leads to higher domestic oil consumption, which results in lower oil exports and government revenues and thus, lower expenditure).
### Scenario Results

#### Overview

Although results are available for all years from 2021 to 2030, for brevity, in Table 2 we only present the results of the model scenarios for the first year (2021), the fifth year (2025) and the tenth year (2030). Specifically, Table 2 presents the level of the key macroeconomic, energy and emission indicators in the BC scenario and their percentage change deviations for the three scenarios: UTSLF, UTSMF and DGD. Overall, as would be expected, the impact across the board is relatively small. This is expected as the magnitudes of the introduced renewable deployment and the associated fossil fuels savings, government and private investment spending, and resulting changes in the reported indicators are quite small. For example, the share of the introduced 5.5 terawatt hours (TWh) of renewables in total energy consumption is about 0.4% in 2021, the base-case scenario. Therefore, we report results in Table 2 up to six decimals. However, the objective of the study is to assess the differences between these scenarios and how the different expenditures in various channels create changes within the economy. Overall, two takeaways from Table 2 can be noted: (i) The deployment of renewables, regardless of the financing options, leads to economic gains, i.e., higher total government revenue, expenditure, non-oil value added and employment and thus higher household consumption; (ii) Renewable deployment through utility farms results in high energy consumption and CO₂ emissions, whereas distributed generation results in low energy consumption and CO₂ emissions over time. The following section briefly discusses the key indicators in turn before considering the overall picture.

### Table 2. Scenario results. Percentage change deviation of the scenarios (UTSLF, UTSMF, DGD) from the base case (BC).

#### Panel A. Centralized Energy Consumption*

<table>
<thead>
<tr>
<th></th>
<th>BC</th>
<th>UTSLF</th>
<th>UTSMF</th>
<th>DGD</th>
</tr>
</thead>
<tbody>
<tr>
<td>(MTOE)</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>2021</td>
<td>142.6</td>
<td>-0.103</td>
<td>-0.007</td>
<td>-0.448</td>
</tr>
<tr>
<td>2025</td>
<td>169.7</td>
<td>0.003</td>
<td>0.003</td>
<td>-0.276</td>
</tr>
<tr>
<td>2030</td>
<td>208.1</td>
<td>0.020</td>
<td>0.020</td>
<td>-0.206</td>
</tr>
</tbody>
</table>

#### Panel B. Exports

<table>
<thead>
<tr>
<th></th>
<th>BC</th>
<th>UTSLF</th>
<th>UTSMF</th>
<th>DGD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAR 2010 Bn</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>2021</td>
<td>1,111.2</td>
<td>0.330</td>
<td>0.320</td>
<td>0.449</td>
</tr>
<tr>
<td>2025</td>
<td>1,307.0</td>
<td>0.219</td>
<td>0.219</td>
<td>0.293</td>
</tr>
<tr>
<td>2030</td>
<td>1,447.4</td>
<td>0.189</td>
<td>0.189</td>
<td>0.253</td>
</tr>
</tbody>
</table>

#### Panel C. Imports

<table>
<thead>
<tr>
<th></th>
<th>BC</th>
<th>UTSLF</th>
<th>UTSMF</th>
<th>DGD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAR 2010 Bn</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>2021</td>
<td>628.6</td>
<td>1.214</td>
<td>1.455</td>
<td>1.562</td>
</tr>
<tr>
<td>2025</td>
<td>784.2</td>
<td>0.035</td>
<td>0.035</td>
<td>0.029</td>
</tr>
<tr>
<td>2030</td>
<td>928.2</td>
<td>0.032</td>
<td>0.032</td>
<td>0.030</td>
</tr>
</tbody>
</table>

---

*Note: Results are presented up to six decimals for brevity and clarity.*
### Panel D. Government oil revenues

<table>
<thead>
<tr>
<th>Year</th>
<th>BC (SAR 2020 Bn)</th>
<th>UTSLF %</th>
<th>UTSMF %</th>
<th>DGD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>430.2</td>
<td>0.438</td>
<td>0.369</td>
<td>0.585</td>
</tr>
<tr>
<td>2025</td>
<td>564.0</td>
<td>0.301</td>
<td>0.301</td>
<td>0.408</td>
</tr>
<tr>
<td>2030</td>
<td>766.2</td>
<td>0.235</td>
<td>0.235</td>
<td>0.319</td>
</tr>
</tbody>
</table>

### Panel E. Government non-oil revenues

<table>
<thead>
<tr>
<th>Year</th>
<th>BC (SAR 2010 Bn)</th>
<th>UTSLF %</th>
<th>UTSMF %</th>
<th>DGD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>390.3</td>
<td>0.060</td>
<td>0.113</td>
<td>-0.175</td>
</tr>
<tr>
<td>2025</td>
<td>471.3</td>
<td>0.038</td>
<td>0.038</td>
<td>-0.166</td>
</tr>
<tr>
<td>2030</td>
<td>582.9</td>
<td>0.034</td>
<td>0.034</td>
<td>-0.130</td>
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</tbody>
</table>

### Panel F. Government total revenues

<table>
<thead>
<tr>
<th>Year</th>
<th>BC (SAR 2010 Bn)</th>
<th>UTSLF %</th>
<th>UTSMF %</th>
<th>DGD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>820.5</td>
<td>0.258</td>
<td>0.247</td>
<td>0.223</td>
</tr>
<tr>
<td>2025</td>
<td>1,035.4</td>
<td>0.181</td>
<td>0.181</td>
<td>0.147</td>
</tr>
<tr>
<td>2030</td>
<td>1,349.1</td>
<td>0.148</td>
<td>0.148</td>
<td>0.125</td>
</tr>
</tbody>
</table>

### Panel G. Government expenditure

<table>
<thead>
<tr>
<th>Year</th>
<th>BC (SAR 2010 Bn)</th>
<th>UTSLF %</th>
<th>UTSMF %</th>
<th>DGD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>1,083.9</td>
<td>0.219</td>
<td>0.215</td>
<td>0.170</td>
</tr>
<tr>
<td>2025</td>
<td>1,192.4</td>
<td>0.150</td>
<td>0.150</td>
<td>0.104</td>
</tr>
<tr>
<td>2030</td>
<td>1,365.0</td>
<td>0.121</td>
<td>0.121</td>
<td>0.088</td>
</tr>
</tbody>
</table>

### Panel H. Non-oil sector value added

<table>
<thead>
<tr>
<th>Year</th>
<th>BC (SAR 2010 Bn)</th>
<th>UTSLF %</th>
<th>UTSMF %</th>
<th>DGD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>1,534.8</td>
<td>-0.182</td>
<td>-0.015</td>
<td>-0.195</td>
</tr>
<tr>
<td>2025</td>
<td>1,799.0</td>
<td>0.019</td>
<td>0.019</td>
<td>0.015</td>
</tr>
<tr>
<td>2030</td>
<td>2,051.0</td>
<td>0.029</td>
<td>0.029</td>
<td>0.029</td>
</tr>
</tbody>
</table>

### Panel I. Non-oil sector employment

<table>
<thead>
<tr>
<th>Year</th>
<th>BC (Million person)</th>
<th>UTSLF %</th>
<th>UTSMF %</th>
<th>DGD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>12.69</td>
<td>-0.069</td>
<td>0.029</td>
<td>-0.054</td>
</tr>
<tr>
<td>2025</td>
<td>14.13</td>
<td>0.020</td>
<td>0.020</td>
<td>0.018</td>
</tr>
<tr>
<td>2030</td>
<td>15.13</td>
<td>0.023</td>
<td>0.023</td>
<td>0.022</td>
</tr>
</tbody>
</table>

### Panel J. Household consumption

<table>
<thead>
<tr>
<th>Year</th>
<th>BC (SAR 2010 Bn)</th>
<th>UTSLF %</th>
<th>UTSMF %</th>
<th>DGD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>936.8</td>
<td>-0.134</td>
<td>0.051</td>
<td>-0.144</td>
</tr>
<tr>
<td>2025</td>
<td>1,138.5</td>
<td>0.019</td>
<td>0.019</td>
<td>0.023</td>
</tr>
<tr>
<td>2030</td>
<td>1,311.9</td>
<td>0.028</td>
<td>0.028</td>
<td>0.033</td>
</tr>
</tbody>
</table>
## Scenario Results

### Panel K. Utility sector potential output

<table>
<thead>
<tr>
<th>Year</th>
<th>BC (SAR 2010 Bn)</th>
<th>UTSLF %</th>
<th>UTSMF %</th>
<th>DGD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>35.5</td>
<td>2.174</td>
<td>2.174</td>
<td>-0.000</td>
</tr>
<tr>
<td>2025</td>
<td>38.0</td>
<td>1.799</td>
<td>1.799</td>
<td>0.144</td>
</tr>
<tr>
<td>2030</td>
<td>41.0</td>
<td>1.305</td>
<td>1.305</td>
<td>0.139</td>
</tr>
</tbody>
</table>

### Panel L. CO₂ emissions

<table>
<thead>
<tr>
<th>Year</th>
<th>BC (Million metric ton)</th>
<th>UTSLF %</th>
<th>UTSMF %</th>
<th>DGD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>570.42</td>
<td>-0.103</td>
<td>-0.007</td>
<td>-0.448</td>
</tr>
<tr>
<td>2025</td>
<td>678.63</td>
<td>0.003</td>
<td>0.003</td>
<td>-0.276</td>
</tr>
<tr>
<td>2030</td>
<td>832.30</td>
<td>0.012</td>
<td>0.012</td>
<td>-0.206</td>
</tr>
</tbody>
</table>

Source: Authors.

Notes: UTSLF = utility-scale deployment that is locally funded; UTSMF = utility-scale deployment with mixed funding; DGD = distributed-generation deployment; Mtoe = million tonnes of oil equivalent; SAR = Saudi riyal; bn = billion
*does not include off-grid electricity consumption; CPI inflation is not shown in the table since the changes for all scenarios compared to the BC are negligible.
Centralized Energy Consumption

This is the amount of (centralized) total final energy consumed by domestic end users. We term it "centralized" because it does not include off-grid electricity consumption generated by households or the private sector in Saudi Arabia (e.g., electricity generated by solar panels). The indicator covers the total final domestic consumption of natural gas, crude oil, liquefied petroleum gases, motor gasoline excluding biofuels, kerosene-type jet fuel excluding biofuels, other kerosene, gas/diesel oil excluding biofuels, fuel oil, other oil products and electricity, as per the International Energy Agency’s Extended Energy Balances.

Not surprisingly, the scenario results in Panel A of Table 2 suggest that there is very little change over all years for the UTSLF and UTSMF scenarios compared to the BC scenario. This is mainly because energy prices, including electricity, are assumed to remain unchanged. Thus, consumers will continue to use similar amounts of energy, including electricity, compared to the BC (i.e., before the utility-scale PV installation). Therefore, for the fully integrated Saudi utility (known as the Saudi Electricity Company or SEC), the total amount of electricity sold remains very similar (as will the revenues from the sales) since sales are simply replacing about 5.5 TWh produced via fossil fuels, with 5.5 TWh produced via PV.

For the DGD scenario, the last column of Panel A presents a different picture because grid electricity is substituted by about 5.5 TWh of electricity produced locally and consumed by households at the distributed level. Thus, although the actual total amount of electricity consumed by the (new) prosumers would not fall, there would be a reduction of about 5.5 TWh of grid electricity sold. Hence, the reductions in the DGD scenario, which would also result in a loss of revenue for the SEC of almost $264 million, assuming an electricity price of 0.18 Saudi riyals (SAR)/kWh for the Saudi residential sector ($1 is equivalent to 3.75 SAR). It is noteworthy that the revenue loss from the 5.5-TWh electricity cut in household use happens only in the first year of DG deployment, i.e., in 2021. Household consumption, including electricity consumption, increases in the following years because of the expansion in economic activity, and thus household income increases compared to the BC scenario. Consequently, revenue loss for the SEC decreases over time.

Total final electricity consumption as a component of the total final energy consumption follows the same pattern. That is, it increases in the UTSLF and UTSMF scenarios, except in 2021, and decreases in the DGD scenario compared to the BC scenario.

Exports

Panel B of Table 2 shows that for exports, there is no discernable difference between the UTSLF and UTSMF scenarios for all the years shown. Both show a slightly larger increase in the first year than in the subsequent years. This is partly because of the displacement of fossil fuels from power generation, which would be exported, and partly because of the increase in oil exports caused by low domestic consumption in 2021. The low consumption is the result of the decline in economic activity caused by lower government spending for non-oil activity because of the renewable installations. Evidently, the first part is a permanent effect and lasts until the end of the simulation period, whereas the second part occurs only in the first year of the renewable deployment, i.e., in 2021. Over time, increasing economic activity demands more oil (both crude and refined) for domestic consumption and thus, less oil for export. Table 2 therefore shows that the percentage deviations of exports in all three
scenarios (i.e., UTSLF, UTSMF and DGD) from those in the BC scenario decrease over time (e.g., from 0.33% in 2021 to 0.19% in 2030 in the UTSLF). The time profile for exports in the DGD scenario is similar, although the magnitude is slightly higher in all years. This is because of two main reasons. First, marginally more fossil fuel would be saved because transmission losses would be reduced with DGD, which is not the case for the UTSLF and UTSMF scenarios. Second, the electricity sales revenue loss from household distributed generation results in reduced total government revenue and thus, a reduction in spending. This leads to reduced economic activity, which in turn requires less domestic consumption of oil. As a result, more oil is exported in the DGD case compared to the UTSLF and UTSMF cases.

**Imports**

The patterns of imports are quite different from those of exports for all three scenarios (UTSLF, UTSM and DGD), as Panel C of Table 2 shows. This is particularly true if the first year is considered, when imports increased over 1% in the mentioned scenarios compared to the BC. Capital costs of 7,763.1 and 10,620.1 million SAR in 2010 prices are required for the establishment of the utility farm (in the UTSLF and UTSM scenarios) and the distributed generation (in the DGD scenario), respectively. These are one-time costs, which occur only in the first year, 2021. In the scenario design, we assume that all these capital costs will be met by imports, as Saudi Arabia does not currently produce PV-related capital goods. This means that import values are increased by 7,763.1 million SAR in 2010 prices in the UTSLF and UTSM scenarios, and by 10,620.1 million SAR in 2010 prices in the DGD scenario, in addition to the import values determined by the economic activity. The higher cost in the DGD scenario compared to the utility-scale scenarios evidently leads to higher imports. Looking at imports in the utility-farm scenarios, it is slightly higher in the UTSMF than the UTSLF, although the capital cost is the same for these scenarios. This is because of the slightly higher economic activity in the UTSMF compared to the UTSLF. Panel C shows that after 2021, the percentage deviations between the imports in all four scenarios and those in BC significantly decline (e.g., it declines from 1.45% in 2021 to 0.03% in 2025 in the UTSMF case). This is largely expected, as explained above—the capital cost is a one-time cost in 2021 only. For the years after 2021, once utility farms and distributed generations are installed, changes in imports are mostly driven by changes in economic activity across the scenarios.

**Government Revenues and Expenditure**

Table 2 illustrates that, in general, there is an increase in government oil revenues over the BC in all three scenarios (UTSLF, UTSM and DGD), reflecting the increased fossil fuel exports. Exports are increased because of the reduced fossil fuel consumption caused by the renewable deployments. Specifically, the magnitude of the increase is larger in the DGD scenario compared to the UTSLF and UTSM scenarios. This is simply because the amount of saved fossil fuels from electricity generation—and hence, their exports—are higher in the DGD scenario, as we discussed in the exports section above. The increases in the government’s oil revenues are very marginally lower in the UTSMF scenario than in the UTSLF scenario because the economic activity is slightly higher in the UTSMF, which requires more consumption of oil and thus less oil remains for export.

The patterns of non-oil government revenue across the scenarios (reported in Panel E of Table 2) are quite different from those of government oil revenue. The differences are mainly because oil revenues are determined by oil exports, while non-oil revenues are mainly driven by non-oil economic activity. For
example, percentage deviations between the oil revenues in the DGD scenario and those in the BC scenario are negative because it results in less economic activity in the DGD scenario. Energy sale revenues (which are classified as non-oil revenues in KGEMM) are also lower in the DGD scenario compared to the utility-farm scenarios, as discussed in the centralized energy consumption section above. The oil revenue increases both in the UTSLF and UTSMF scenarios compared to the BC scenario. These increases are slightly higher in the UTSMF scenario as economic activity is slightly higher in this scenario. As we mentioned above, non-oil revenues are mainly determined by non-oil activity. Note that there are seven sources of non-oil revenues in KGEMM, and five of them—value added tax, domestic energy sales, expat levies, taxes on income, the profits and capital gains of companies, and tariffs on imported goods—are mainly functions of domestic economic activity. There is a small positive increase over the BC that declines in the latter years.

Changes in total government revenues reflect changes in both non-oil and oil revenues, with more weight noted for the latter (see Panel F of Table 2). To this end, changes in total revenues in the UTSLF and UTSMF scenarios mimic the patterns of the oil revenue changes. The increases in total revenues in the DGD scenario are lower than those in the UTSLF and UTSMF scenarios in all three years shown. This is because the changes in the non-oil revenues in the DGD scenario are negative compared to the BC scenario in these years, as explained above.

Finally, Panel G of Table 2 shows that changes in the government expenditure reflect changes in the government’s total revenues. This is expected as all five government spending components (that is, government wages and salaries, operational expenses, maintenance costs, transfers to households and investment) are econometrically estimated as functions of government revenues.

Non-oil Sector Value Added, Employment and Household Consumption

Panel H of Table 2 reports the scenario results for non-oil value added (or GVA for short). For all three of the scenarios (UTSLF, UTSMF and DGD), the GVA falls in the first year compared to the BC but shows a recovery, albeit a small one, for the subsequent years. The fall in the first year is very minor for the UTSMF scenario, but markedly larger for the UTSLF and DGD scenarios. The differences in the first year are due to the reduction in government expenditure required to fund the capital expenditure (capex) of the utility farms in the UTSLF scenario being twice that required in the UTSMF scenario (with the other half coming from FDI). There is also a noteworthy cut in household spending to finance the distributed generation in the DGD scenario. For similar reasons, this pattern is also seen in non-oil employment and household consumption, with both falling in the first year in the UTSLF and DGD scenarios but showing a slight increase on the UTSMF scenario. These falls are followed by very marginal increases in the following years for all three scenarios.

Non-oil employment follows a similar pattern to non-oil value added (GVA) with an increase in the first year for UTSMF, whereas employment falls for both DGD and UTSLF. For the years after 2021, employment increases for all three scenarios: The UTSLF and UTSMF scenarios have the same employment numbers, which are higher than the those in the DGD scenario. This is because government expenditure is higher in the utility-scale scenarios compared to the DGD. Current government spending increases aggregate demand for non-oil goods and services, while government investment spending creates favorable infrastructure for non-oil activities. Both result in increased employment, among other gains.
Increased employment results in high wages and salaries, and consequently household incomes and consumption increase for 2021 and 2030, as we observe from Panel J in Table 2. However, unlike GVA and employment, we observe that the highest increase in household consumption occurs in the DGD scenario, not in the UTSMF scenario. This is because in each year after 2021, households do not pay for the 5.5 TWh of electricity as they get it from their distributed generation instead of from the SEC. Thus, they have more money to spend on other goods and services. Although again, in the initial year, the UTSMF scenario shows an increase in consumption, whereas the UTSLF and DGD scenarios show a decrease.

Utility Potential Output

For utility potential output, unsurprisingly, there are significant differences between the utility-scale and distributed-generation deployment scenarios. The UTSLF and UTSMF scenarios are almost identical for all years shown—with a large positive increase over the BC scenario. In contrast, given the off-grid deployment of PV, there is almost no change in the utility sector’s potential output in the first year of the DGD scenario compared to the BC scenario. This is followed by a small increase in later years because of general macroeconomic effects working their way through the system. We believe that the increases in the utility sector output are primarily capital driven rather than labor driven for two reasons: (i) the huge investments made in solar utility farm installations, and (ii) in KGEMM, the estimated production function for the utility sector for 1996–2019 has long-run capital and labor elasticities of 0.78 and 0.35, respectively.

CO₂ Emissions

As Panel L of Table 2 shows, percentage deviations of CO₂ in the UTSLF, UTSMF and DGD scenarios from the BC scenario mimic those of centralized energy consumption in Panel A. This is not surprising given that CO₂ emissions in the model are calculated as the multiplication of the consumption of energy products (such as crude oil, diesel and natural gas) and their respective conversion factors. CO₂ emissions in the BC scenario grow by 109 million metric tonnes (MMt) from 570 MMt in 2021 to 679 MMt in 2025. They then grow by 153 MMt, reaching 832 MMt in 2030. These changes are consistent with the changes in the energy consumption in Panel A, which are driven by the developments in Saudi Arabia’s economic activity. It is important to note that the CO₂ emission values in the BC and other scenarios do not reflect the government goal of having 50% natural gas and 50% of renewables in the energy mix used for electricity generation by 2030, while reducing the use of liquid fuel, which would produce lower values than the ones reported here.

Overall Assessment for Policymaking

As highlighted above, although the scenarios’ macroeconomic, energy and emission effects are relatively small, there are some noteworthy differences between the three scenarios. This begs the question: Which scenario should policymakers choose if they are planning to deploy/encourage PV installation? The answer to this question is not straightforward as not all the indicators in Table 2 point in the same direction.

From the international trade balance perspective, one would prefer the distributed-generation deployment of renewables, that is, the DGD scenario, as it provides the highest exports and the lowest imports of all the scenarios.

In the UTSMF scenario, government non-oil revenue increases the most. However, for total government revenue, the largest increases are recorded in the UTSLF, but they are only slightly above those
of UTSMF, which indicates a similar picture for government expenditure. Thus, the fiscal indicators suggest that utility-scale deployment would be preferred over distributed-generation deployment. Moreover, a centrally funded approach (the UTSLF scenario) would be preferable to a mixed funded approach (the UTSMF scenario)—though the difference is very marginal. However, in terms of increased exports and increased government oil revenues, distributed generation (the DGD scenario) clearly comes out on top.

Turning to the non-oil value added and non-oil employment, Table 2 shows that in the first year, UTSMF would result in the smallest reduction in GVA. It also shows an increase in non-oil employment (compared to a reduction for both the UTSLF and DGD scenarios). The UTSMF scenario also provides the highest increase for non-oil value added and employment compared to the UTSLF and DGD scenarios. Thus, from the non-oil activity perspective, utility-scale deployment using mixed funding (i.e., the UTSMF scenario) is preferred.

From the household consumption standpoint, one might also give preference to utility-scale deployment using mixed funding (i.e., the UTSMF scenario) as it provides the highest consumption for all the years, including the first year. In contrast, consumption is negative for utility-scale deployment fully funded by local government and for the distributed generation case (i.e., the UTSMF and DGD scenarios).

From the perspective of the utility sector, one would prefer utility-scale deployment (either fully locally funded or with mixed funding as the differences between the two are very minor) over the DGD.

Lastly, if policymakers are predominantly concerned with energy saving and mitigating environmental pollution, then the DGD case is the best option. Table 3 summarizes all the preferences discussed above. We can conclude that the UTSMF option is the most preferred according to Table 3. However, we also note that this choice may change, depending on the specific policy objective.

<table>
<thead>
<tr>
<th>Table 3. Policy preferences for the scenarios.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policy preference</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>International trade balance</td>
</tr>
<tr>
<td>Fiscal expansion</td>
</tr>
<tr>
<td>Government non-oil revenues</td>
</tr>
<tr>
<td>Non-oil value added</td>
</tr>
<tr>
<td>Non-oil employment</td>
</tr>
<tr>
<td>Household consumption</td>
</tr>
<tr>
<td>Utility sector activity</td>
</tr>
<tr>
<td>Energy and CO₂ reduction</td>
</tr>
</tbody>
</table>

Source: Authors’ own construction.
Note: BC = base case; UTSLF = utility-scale deployment that is locally funded; UTSMF = utility-scale deployment with mixed funding; DGD = distributed-generation deployment.
To the best of our knowledge, this study is the first attempt to bring together and integrate a power model, a distributed generation model and a macroeconometric model to analyze the macroeconomic effects of PV deployment by distinguishing the solar farm scale from the distributed generation scale. In particular, three scenarios are produced for 2021–2030 to quantify the macroeconomic, energy and emission effects of deploying PV. The three scenarios are (i) the utility-scale, totally funded by the government, (ii) utility-scale, jointly funded by the government and private investors, and (iii) distributed generation scale funded by households with some government support.

Some interesting and important differences are revealed across the three different PV deployment options. The simulations show that no one deployment scenario is an obvious clear ‘winner’ that performs the best across all key macroeconomic, energy and emission indicators. Instead, they all perform better in some indicators. The main policy options can be outlined as follows. The utility-scale renewable deployment scenario jointly financed by the government and private investors offers greater benefits for non-oil sector economic activity compared to the other two scenarios, although both scenarios have their own merits. Thus, if the agencies’ primary concerns are improved non-oil fiscal positions, increased non-oil value added, increased employment and increased household consumption, they should prefer this scenario. If their main concern is to reduce energy consumption and associated CO₂ emissions to meet energy efficiency and pollution reduction goals, and if they seek a better position in international trade, then the distributed generation scenario for renewable deployment financed by households with some government support would be the best option. If the main policy focus is on fiscal expansion and increasing the size of the utility sector, then authorities should implement the utility-scale scenario in which renewable deployment is fully government financed, as it offers more growth. Finally, the scenario analysis supports the common view in the literature that domestic absorption, especially government investment, plays an important role in the Kingdom’s development. Therefore, it would be preferable for the government to have partners for financing renewable energy projects, as it could save budgetary resources for investment in growth-enhancing areas and promote economic development.
By linking, we mean that the results/output from the power model and distributed generation model is used as the input to KGEMM. To avoid confusion, we do not use the terms ‘soft-linking’ or ‘soft-coupling,’ as they have been used in previous papers to represent iterations. The term ‘link’ or ‘linking’ will be used throughout the paper.

We focus on macroeconomic variables in this study, although the KGEMM can assess the impact of renewable energy on 14 economic sectors (see Hasanov et al. 2020). This would be an interesting topic for future research.

The sum of the fossil fuels measured in million tonnes of oil equivalent is multiplied by the average efficiency ratio of these fuels to determine the total electricity generation from fossil fuels.

This is because the Saudi oil production level is exogenous in the KGEMM as it is mostly determined by the OPEC+ agreements and in this setup, more domestic use of oil leaves less for export.

We consider transmission losses in our analysis. For grid electricity, we need to generate 1.0638 kWh of energy to deliver 1 kWh to consumers assuming that the transmission losses within the network are 6%. However, at the distributed scale, there are no losses since the energy is consumed at the point of generation.

It is understood that other assumptions also can be made, such as over time, some portions of this capital cost will be met by the domestic production indicating development in local content. Or some items of the renewable installment will be provided by the domestic production. These assumptions can be considered in future KGEMM simulations for renewables.
References


References


References


References


Sebri, Maamar. 2015. “Use Renewables to be Cleaner: Meta-Analysis of the Renewable
References


Appendix

Abbreviations for the KGEMM parameters and variables shown in Figure 1 (in alphabetical order):

**CPI**: consumer price index, 2010 = 100

**CPI**: consumer price index, 2010 = 100

**entoil**: employment in the non-oil sector

**gap_lgvanonoi**: output gap in the non-oil sector production function

**gap_lgvase**: output gap in the services sector production function

**gc**: government consumption

**gcpe**: government transfer to households

**GDP**: gross domestic product

**gdpnoil**: value added in the non-oil sector

**gi**: government investments

**grevoth**: government other 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)

**gvafib**: value added in the financial, insurance and other business services

**gvaamanno**: value added in the non-oil manufacturing sector

**gvaaminoth**: value added in the non-oil mining sector

**gvaoth**: value added in other service sectors

**gvase**: value added in the service sector

**gvastracom**: value added in the transportation and communication sector

**M**: real imports

**M2**: broad money aggregates

**oilmb**: oil production in Saudi Arabia

**oiluse**: domestic oil use in Saudi Arabia

**oilx$**: oil export revenues in US$

**pengind**: price of energy in industry

**popmig**: migrated population

**popw**: working age group population

**Rxd**: exchange rate

**TFE**: total final expenditure

**X**: total export
Table A1. Announced solar PV projects in Saudi Arabia as per the Saudi Ministry of Energy, totaling 3,270 MW.

<table>
<thead>
<tr>
<th>Project</th>
<th>Capacity (MW)</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sudair</td>
<td>1,500</td>
<td>Central</td>
</tr>
<tr>
<td>Shuibah</td>
<td>600</td>
<td>Western</td>
</tr>
<tr>
<td>Jeddah</td>
<td>300</td>
<td>Western</td>
</tr>
<tr>
<td>Rabigh</td>
<td>300</td>
<td>Western</td>
</tr>
<tr>
<td>Madinah</td>
<td>50</td>
<td>Western</td>
</tr>
<tr>
<td>Sakaka</td>
<td>300</td>
<td>Northeastern</td>
</tr>
<tr>
<td>Qurayat</td>
<td>200</td>
<td>Northeastern</td>
</tr>
<tr>
<td>Rafha</td>
<td>20</td>
<td>Northeastern</td>
</tr>
</tbody>
</table>

Source: Authors’ own calculation.
Note: MW = megawatt.

Table A2. Key assumptions for the PV system used for the distributed-generation modeling.

<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>Operation and maintenance cost</td>
<td>$10/kW/year</td>
</tr>
<tr>
<td>Electricity export price</td>
<td>$0.019/kWh</td>
</tr>
<tr>
<td>Project lifetime</td>
<td>25 years</td>
</tr>
<tr>
<td>Discount rate</td>
<td>10%</td>
</tr>
<tr>
<td>Total PV system losses</td>
<td>15%</td>
</tr>
<tr>
<td>Solar cell efficiency</td>
<td>17%</td>
</tr>
<tr>
<td>Nominal operating cell temperature</td>
<td>47 °C</td>
</tr>
<tr>
<td>Temperature effect on power</td>
<td>-0.5%/°C</td>
</tr>
<tr>
<td>Solar irradiation</td>
<td>Hourly data for each respective region</td>
</tr>
</tbody>
</table>

Source: Authors’ own calculations.
Note: kW = kilowatt; kWh = kilowatthour; °C = degrees Celsius.
About the Authors

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Amro is an expert with over 20 years of experience in energy and technology garnered on three continents. His research interests lie in renewable energy policy, power systems modeling, net-zero power, and hybrid microgrid design and optimization. He has led and executed several national modeling initiatives both at the distributed and utility scales. Some aspects of his research have been adopted by BP in creating their seminal annual Statistical Review of World Energy. Amro is the author of 50+ papers and the inventor of several patents. He holds a Ph.D. in Electrical Engineering and an MBA in Finance.

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Lester C. Hunt

About the Projects

This study is part of the KGEMM Policy and Research Studies and KGEMM Model Development projects.

The KGEMM Policy and Research Studies project produces policy and applied research studies that can provide Saudi Arabian decision makers with a better understanding of domestic and international macroeconomic-energy relationships. The project mainly employs KGEMM, an energy-sector augmented general equilibrium macro-econometric model, as well as partial equilibrium frameworks.

The KGEMM Model Development project extends, enhances and customizes KGEMM’s internal and international representations, in line with the initiatives and targets of Saudi Vision 2030 and the requirements of the Saudi energy ecosystem entities. The goal of the project is to address policy options for the development of the Saudi economy. Its activities also include constructing small-scale models, tools and dashboards.