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Assessing Residential Solar Rooftop Potential in Saudi Arabia Using Nighttime Satellite Images: A Study for the City of Riyadh

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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.

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Key Points

The Saudi National Renewable Energy Program aims to substantially increase the share of renewable energy in the Kingdom's power generation mix, targeting 3.45 gigawatts (GW) of installed renewable energy capacity by 2020 and 9.5 GW by 2023. This study explores the extent to which renewable energy, specifically solar rooftop deployment at the residential scale in Riyadh, could be cost-efficient and could accelerate the decarbonization of the Saudi Arabian power generation mix.

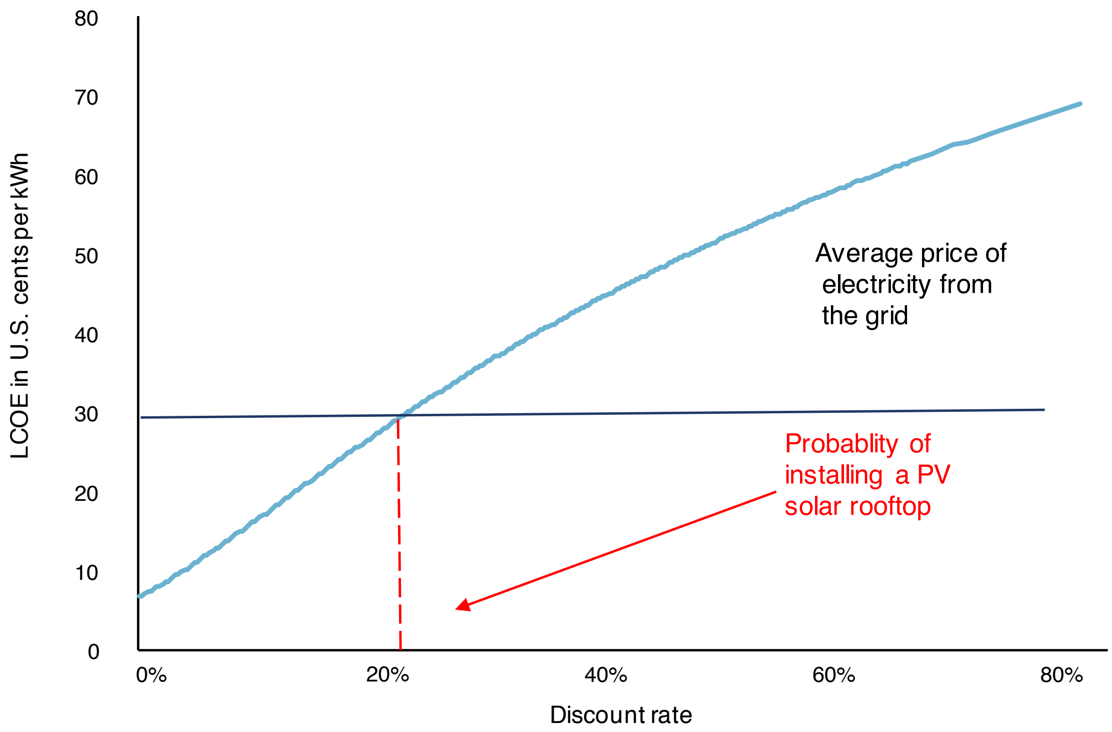
This study found that the maximum aggregate solar power capacity in Riyadh at the residential level would be around 400 megawatts (MW). Also, the current residential electricity tariff does not incentivize photovoltaic (PV) solar rooftop deployment. Despite an increase in Saudi residential electricity prices in January 2018, rooftop solar PV cannot compete with electricity from the grid, even assuming aggressive reductions in the investment cost of solar technology. The study suggests:

- Residential PV solar energy is uneconomical for households based on current electricity tariffs in Saudi Arabia, although PV at utility scale is a cost-efficient alternative.

- An intermediate business model that takes simultaneous advantage of the proximity to the final consumer, economies of scale and is managed professionally, might be economically competitive.

- This new business model would be based on neighborhood-scale solar fields. This would allow investors to spread the infrastructure costs over a larger number of subscribers, thereby reducing the fixed cost per unit.

Figure 6. Methodology to assess the probability of households installing PV.



Source: KAPSARC.

Note: *LCOE: Levelized cost of electricity.

Summary

Saudi Arabia is developing utility-scale solar power projects as a first step toward diversifying its electricity generation mix, currently based almost entirely on crude oil, refined oil products and natural gas. The Saudi National Renewable Energy Program aims to substantially increase the share of renewable energy in the Kingdom's power mix, targeting 3.45 gigawatts (GW) of installed renewable energy generation capacity by 2020 and 9.5 GW by 2023.

This study explores the extent to which renewable energy, specifically solar rooftop deployment at the residential scale in Riyadh, could be cost-efficient and could accelerate the decarbonization of Saudi Arabia's power generation mix.

This study uses a typical cost-benefit analysis to explore the viability of solar rooftop installations in Riyadh, based on multiple heterogeneous households rather than on a single representative household, as is standard. The study groups households according to their level of electricity consumption. This approach aligns with residential electricity pricing, which is based on a sliding scale according to consumption.

The objective of this study is to assess the potential deployment of solar energy at the residential scale in Riyadh. To do this, we developed an innovative approach based on satellite nightlight images combined with spatial layers of the population and the degree of urbanization of the metropolitan area of Riyadh. Using this approach, we can segment households in different areas of the city, according to their level of electricity consumption. This study suggests that the maximum aggregate solar power capacity in Riyadh at the residential level would be around 400 megawatts (MW), based on different household characteristics. The study also finds that Saudi Arabia's current residential electricity tariff does not incentivize solar photovoltaic (PV) rooftop panel deployment. The discount rate used by households to assess the value of investing in solar PV technology is also highly uncertain. Accordingly, the policy cost of promoting residential solar deployment is unclear. Promoting solar PV at the residential scale is a better option from a financial perspective. However, there are scenarios in which it is possible to incentive residential solar rooftop installations at no direct cost to the government.

Introduction

In February 2018, Saudi Arabia awarded its first utility-scale solar project to ACWA Power: a 300 MW project that will start commercial operations in 2019. This is the first step toward diversifying the Kingdom's power generation mix, currently based almost entirely on crude oil, refined oil products and natural gas. The Saudi National Renewable Energy Program aims to substantially increase the share of renewable energy, targeting 3.45 GW of installed renewable energy capacity in the country by 2020 and 9.5 GW by 2023. This study explores the extent to which renewable energy, namely solar rooftop deployment, at the residential scale in Riyadh could be cost-efficient and could accelerate the decarbonization of the Saudi Arabian power generation mix.

This study uses a typical cost-benefit analysis to explore the viability of rooftop solar PV in Riyadh, but bases it on multiple heterogeneous households rather than on a single representative household, as is standard. The study groups households according to their level of electricity consumption. This approach aligns with residential electricity pricing, which is based on a sliding scale according to consumption. This study uses data published by the National Oceanic and Atmospheric Administration (NOAA) from its Visible Infrared Imaging Radiometer Suite (VIIRS) Day and Night Band (DNB), the Esri's World Population Estimate spatial layer, and the Global Human Settlement Layer (GHSL) developed by the European Commission's Joint Research Centre (JRC), to identify 58 homogenous clusters of nighttime light intensity and population density in Riyadh. Since the publication of the foundational paper by Elvidge et al. in 1997, a growing number of studies have used the NOAA's nighttime lights images as a proxy for economic and human activity. This methodology has been used in previous studies to assess economic growth, regional income distribution and consumption of electricity, including Henderson et al. (2010), Elvidge et al. (2012), Pinkovsky et al. (2016), Doll et al. (2006), Townsend et al. (2010), Chen et al. (2011) and Shi et al. (2014). However, as far as the authors are aware, this study is the first to have used this methodology in the field of energy transitions. The variables that will determine the pace of residential solar deployment are: households' electricity consumption, the structure of the electricity tariff, the cost of the technology, the solar conditions, and house types.

The deployment of solar technology in Saudi Arabia would also have a positive macroeconomic impact (Blazquez et al. 2017). Crude oil and refined oil products together represent around 50% of the Saudi power generation fuel mix. Additionally, the price of oil used for power generation in the Kingdom is below the international price, creating an economic opportunity to use that oil more efficiently — any decrease in residential electricity consumption from the grid would reduce domestic oil consumption, positively impacting oil export revenues. For this reason, Saudi policymakers might be interested in the costs and benefits of incentivizing a faster deployment of solar power at the residential scale.

The rest of this paper is organized as follows: the first section explores the published literature on residential solar energy, with a focus on the Middle East and Gulf Cooperation Council (GCC) countries; the second section describes the methodology and the selection of the different clusters of the metropolitan area of Riyadh; the third section details the study's results and discusses their policy implications; and the final section presents the conclusions of the study.

Literature Review

Some academic papers have analyzed the economic viability and prospects of solar technology in the Middle East. For example, Nematollahi et al. (2016) suggest that strong growth in energy demand and good solar conditions are the key drivers for the deployment of solar technology in the region, especially in Saudi Arabia and Egypt. Abdmouleh et al. (2015) also find that the big increase in energy demand in GCC countries creates an opportunity for deploying renewable technologies.

A key issue affecting the promotion of renewable energy in GCC countries is the low prices currently in force for most electricity consumers. As Griffiths (2013) points out, low electricity tariffs discourage the deployment of solar technology in the absence of an incentivizing policy package. Likewise, Matar et al. (2017) argue that the low administered prices of fossil fuels harm the competitiveness of solar photovoltaic (PV) power at utility scale in Saudi Arabia. Martin-Pomares et al. (2017) suggest that new regulations and more incentives are needed to offset the lack of commercial competitiveness of PV technology in Qatar, partly due to the low prices of electricity. Ramli et al. (2017) assess the viability of solar and wind power technologies in Saudi Arabia, suggesting that a renewable portfolio standard policy might be an appropriate mechanism through which to introduce these technologies. Shaahid and El-Amim (2009) explore the role of hybrid PV for rural electrification in Saudi Arabia, while Almasoud and Gandayh (2015) find that solar energy could be a serious competitor to fossil fuel power generators in Saudi Arabia when indirect costs are included.

Khan et al. (2017) estimate the maximum potential solar rooftop deployment in 13 cities in Saudi Arabia. They find that these cities combined can produce 51 terawatthours (TWh) of electricity annually, or 30% of the Kingdom's annual domestic power demand. Griffiths and Mills (2016) focus on the United Arab Emirates (UAE), highlighting that it is possible to develop solar power technology if there is clear governmental support, although, currently, PV technology cannot compete with power from the grid in UAE. Byrne et al. (2015) explore the potential for solar rooftop installations in Seoul, South Korea. They estimate the number of rooftops suitable for PV panel deployment and find that the city could install around 11 GW. Peng and Lu (2013) conduct a similar analysis for Hong Kong, finding that PV-suitable rooftops allow for 6 GW of solar panel deployment there. They also find that PV technology needs public support to make it competitive with electricity from the grid. Cole et al. (2016) study the substitutability between PV solar rooftop technology and the bulk power system from a central planner perspective in the United States (U.S.). They find an almost perfect substitution between distributed PV and utility-scale PV.

Other studies have taken a macro approach to solar deployment in the Middle East at the utility scale. Blazquez et al. (2017) find that PV solar technology has a positive macroeconomic effect on aggregate welfare in Saudi Arabia. Elshurafa and Matar (2017) analyze the cost of solar energy to the Saudi power system. They suggest that PV solar deployment at the utility scale can reduce system costs. Finally, Matar et al. (2015) and Matar and Anwer (2017) suggest that the deregulation of fossil fuels, or a different structure of administered prices, could stimulate PV solar deployment in the Kingdom at the utility scale.

Methodology

This paper first analyzes the metropolitan area of the city of Riyadh to identify clusters of households and nightlight intensity in urban zones that have a consistent presence of people. It then transforms nightlight intensity into electricity consumption and estimates the average electricity consumption per household in different clusters. It estimates the cost of electricity generated using solar PV rooftop technology, based on the cost of the technology and the irradiation conditions of Riyadh. Lastly, it discusses the economic cost and benefits of deploying this technology. It does not take into consideration the potential benefits of a reduction in carbon emissions.

This study assumes an economic approach to PV technology. Households compare the cost of electricity from the grid with the cost of electricity from a residential PV system. They will install a solar rooftop system if its total cost is below the cost of purchasing electricity from the grid. This implies that all households facing the same electricity tariff make the same decision on deployment. In other words, only the financial cost matters.

Dividing Riyadh into homogenous clusters for nightlight intensity and population

Initially, the metropolitan area of Riyadh is split into 100 zones using the Spatially Constrained Multivariate Clustering methodology.[1] This procedure identifies a given number of polygons (clusters) in an image where the population and intensity of nightlights (captured by the satellite radiometry) within the same cluster have the lowest possible variability, while ensuring that the resulting clusters are as different as possible from each other.

This paper uses the Esri World Population Estimate spatial layer 2015 [2] and the Household Expenditure and Income Survey of 2013 to assess population distribution. The final distribution of the population across clusters is established using a dasymetric interpolation technique, following Vittorio (2016).

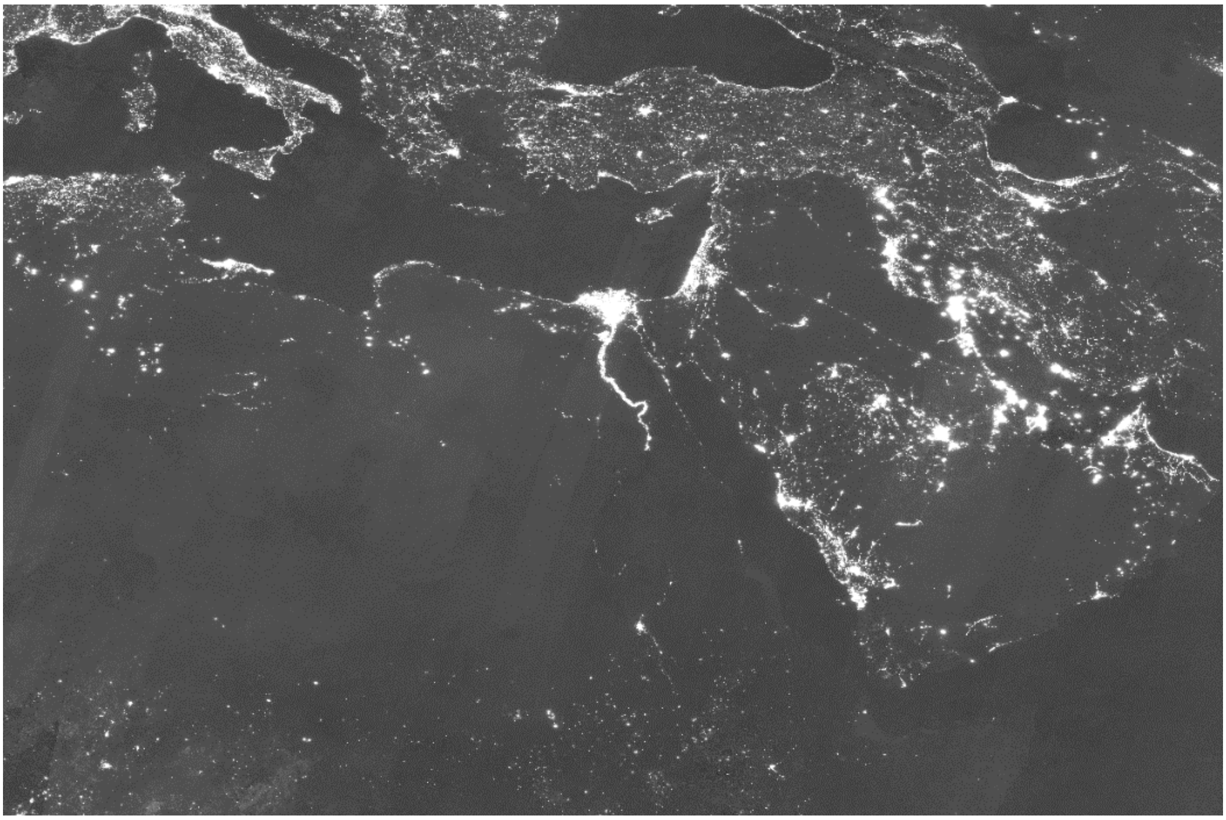
The data published by NOAA from its VIIRS provides monthly information on nighttime lights. This study used the yearly composites and the monthly composites provided by NOAA for 2015. The images used in this study are based on multiple daily snapshots of Riyadh. Consequently, they portray the average monthly radiance of Riyadh, eliminating outliers and gas flares. Figure 1 shows NOAA's VIIRS image of the region for March 2015.

Once Riyadh is divided into 100 homogenous clusters of population density and nighttime light, this analysis uses the Global Human Settlement Layer (GHSL), developed by the European Commission's JRC, to assess the degree of urbanization in the resulting cluster zones (EC JRC 2016). The GHSL is based on the JRC's global analysis of Sentinel satellite images. The GHSL presents a graphic distribution of urban settlements and built-up areas. This study uses this tool to eliminate inhabited cluster zones that do not represent a residential area.[3] The use of GHSL allows for a more precise selection of zones with household electricity consumption. The analysis finds 65 relevant residential clusters in Riyadh.

Estimation of the energy consumption by households in the city of Riyadh

This study uses an econometric regression to link the consumption of electricity for a representative household (dependent variable) in three different

Figure 1. Satellite VIIRS DNB data for March 2015.



Source: NOAA.

regions of Saudi Arabia with the average monthly temperature and nightlight intensity (independent variables). Monthly electricity consumption during 2015 is based on annual statistics published by the Saudi Arabian Monetary Authority.[4] The average monthly consumption of electricity per household in each region is calculated accordingly. The source for the average temperature is the World Bank's Climate Change Knowledge Portal.[5] The satellite VIIRS DNB data provided by NOAA is used to construct the independent variable nightlight intensity. There are 36 observations corresponding to three regions and the 12 months of 2015. The analysis estimates the parameters using standard least squares estimate (LSE) regression. Table 1 shows the results.

The average household consumption in each of the cluster zones of Riyadh can be estimated using the parameters calculated in the estimation. This approach has a potential weakness: the methodology of this paper attributes all nighttime lights to residential consumption, but a residential area could also house commercial or industrial activity. To minimize potential errors, this study eliminates clusters with a very high consumption per household and clusters of less than 100 households, assuming that these are mainly commercial or industrial areas. In particular, the analysis eliminates clusters where monthly electricity consumption exceeds five times the national average consumption. Table 2 shows the main statistics relating to electricity consumption in Riyadh.

For the sake of illustration, Figure 2 shows the clustered population distribution of Riyadh and Figure 3 shows the average consumption of electricity per capita per cluster.

Table 1. Estimation of parameters for this study.

	Coefficients	Standard Error
Intercept	-1.24	0.56
Nightlight	1.41	0.13
Temperature	1.01	0.13
R Square	0.82	
Adjusted R Square	0.81	
Standard Error	0.22	

Source: KAPSARC.

Table 2. Main descriptive statistics of the study.

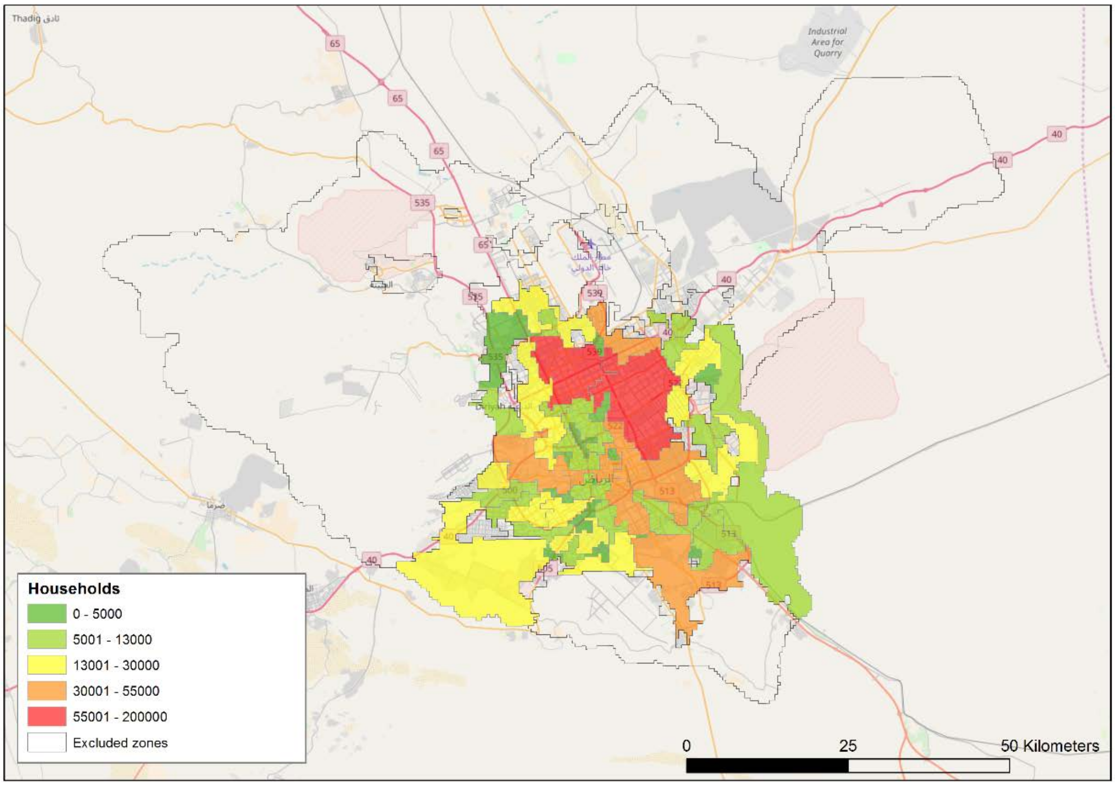
Number of clusters	58
Total households in 2015 [6]	798,090
Mean of monthly consumption per household (kWh) in 2015	2,327
Median of monthly consumption per household (kWh) in 2015	1,923
Standard deviation	1,757
Adjusted R Square	0.81
Standard Error	0.22

Source: General Authority of Statistics, Saudi Arabian Monetary Authority.

Estimation of the levelized cost of electricity for residential solar rooftops

Currently, the deployment of PV solar technology in Saudi Arabia at the residential scale is limited, and no standardized commercial information exists on the investment cost. For this reason, this analysis uses information on the cost of rooftop PV solar technology from other countries. The cost of PV solar investment at the residential scale was between $2.15 per watt (W) and $5.25/W in 2015, according to the KAPSARC Solar Photovoltaic Toolkit.[7] KAPSARC's public database provides the capex (investment cost) for six different projects in Australia, China, Germany, Italy, Japan and the U.S. in 2015. The average cost of residential solar PV systems in Australia, France, Germany, Italy, Japan and the U.S. is declining at 10.7% annually (Renewable Power Generation 2017). Using the average capex in 2015 ($3.32/W) as a benchmark and assuming an annual decline in the cost of residential solar PV systems of 10.7% in both 2016 and 2017, produces an estimated investment cost of $2.36/W in 2018. The typical capacity range of a residential PV rooftop system is between 1 kilowatt (kW) and 5 kW.[8] This study will use 2.2 kW

Figure 2. Population distribution of Riyadh for 2015.

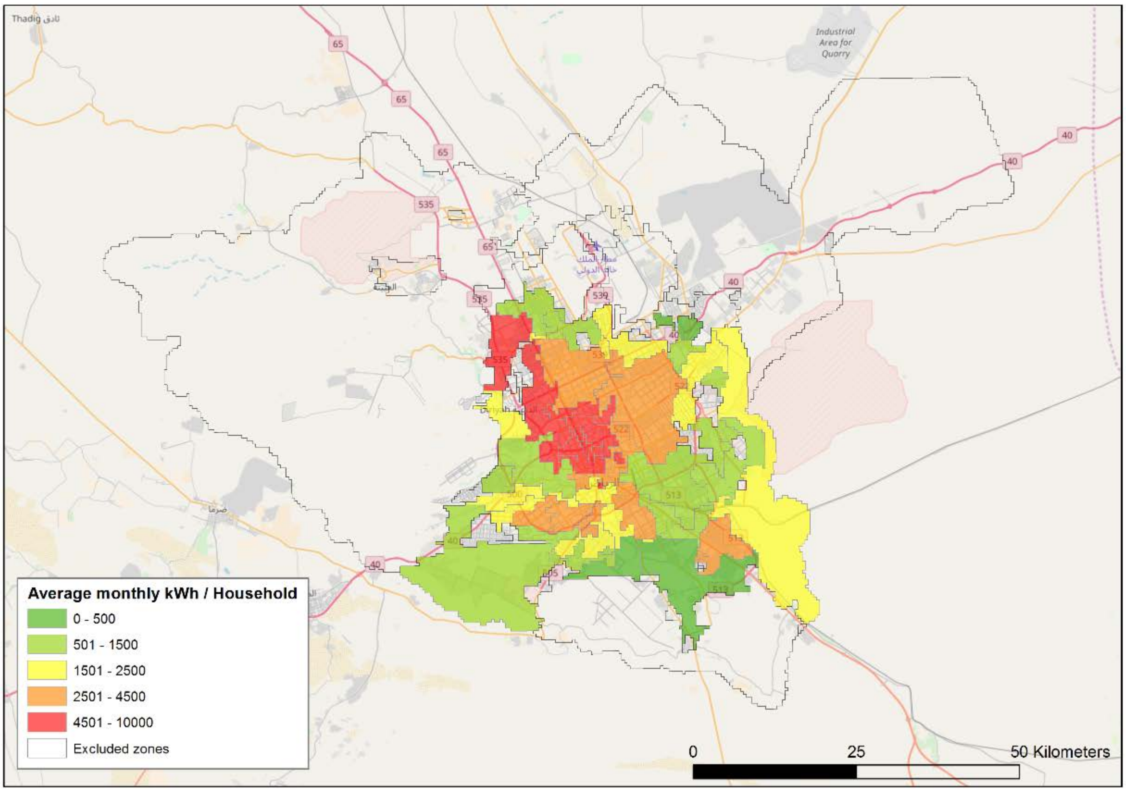


Source: Esri World Population Estimated layer, 2015.

as a benchmark figure. The standard lifespan of a PV solar panel is around 25 years. The capacity factor in Riyadh is around 21%, due to the city's high solar irradiation of around 2.130 kilowatthour (kWh)/per square meter per year (Zell 2015). Nevertheless, high temperatures and dust can negatively impact the efficiency of PV cells (Baras 2012). This study does not consider these factors. Finally, the technical degradation of PV cells is 0.9% annually and the system derating factor is 85%.

The discount rate is critical in calculating the levelized cost of electricity (LCOE). Companies' standard discount rate for evaluating a project is the weighted average cost of capital (WACC). For example, the International Renewable Energy Agency (IRENA) (2017) estimates the LCOE for the different renewable technologies at the utility scale using a discount rate of 7.5% in OECD countries and 10% for the rest of the world. There is no obvious discount rate for households because the discount rate is a reflection of subjective time preferences, which would differ between individuals. Harrison et al. (2002) conducted an experiment for the Danish government, finding that the overall individual discount rate is around 28%. Bruderer et al. (2014) found that the mean discount rate of the Swiss population is approximately 27% if extreme values are excluded. Hausman (1979) finds an average discount rate of 26% for individual purchases of air conditioners. On the other end of the spectrum, Camilo et al. (2017) use a discount rate of 4%, consistent with the social discount rate

Figure 3. Electricity consumption per household, Riyadh, 2015.

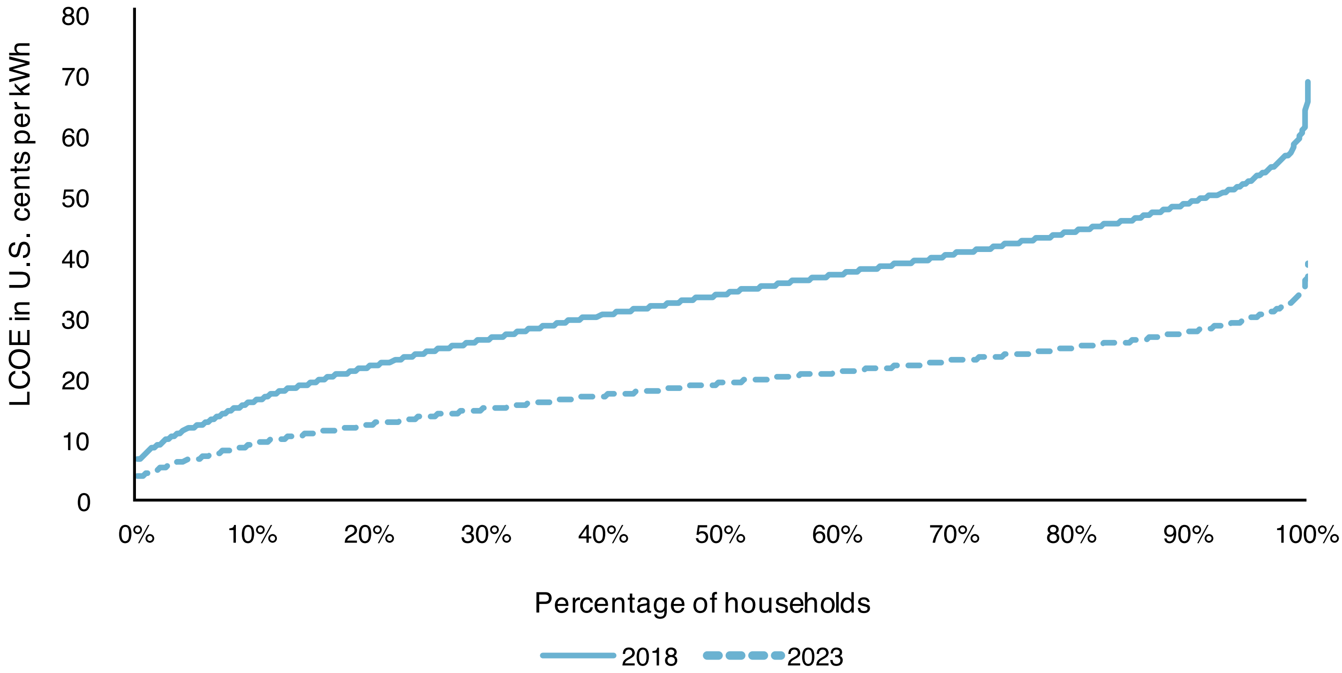


Source: KAPSARC.

used in macroeconomic models. Hartman and Doane (1986) suggest the discount rate depends on the age and wealth of each individual and can vary from 156% to close to zero. Samwick (1998) uses the U.S. Survey of Consumer Finances 1992 to provide a distribution of the discount rate using data on financial assets and net worth, with the mean being 7.4%.

Rather than assuming a representative discount rate for the whole population of Riyadh, this study assumes that the discount rate follows a normal distribution, with 27% as the average (consistent with Baras [2012]; IRENA [2017]; and Harrison [2002]), and 15% as the standard deviation. Samwick (1998) finds that the first percentile of the population has a discount rate of 0.6 times the average. The proposed normal distribution in this study also has that property. This approach generates a different LCOE for each household, depending on its discount rate. For this reason, and to avoid confusion, this variable is termed 'perceived LCOE' in this study. It is important to highlight that a normal distribution for the discount rate does not generate a normal distribution for the perceived LCOE. For this reason, this analysis randomly generates 5,000 discount rates, using N(0.27,0.15), and then computes the perceived LCOE for each discount rate. Figure 4 shows the perceived LCOE generated using this methodology for two years. The 2018 line represents the perceived LCOE for the estimated cost of the investment in 2018 ($2.36/W), while the 2023 line shows the perceived LCOE, assuming a constant

Figure 4. Perceived LCOE generated using a normal distribution.



Source: KAPSARC.

reduction in the cost of the investment of 10.7% annually until 2023. The minimum perceived LCOE in 2018 is 6.8 (U.S.) cents/kWh for households with a discount rate of 0%, and the maximum is 61.9 cents/kWh for households with a discount rate of 82.7%. Perceived LCOE numbers generated with negative discount rates were removed.

Analysis of the Results and Policy Discussion

Estimation of the 'reasonable' maximum solar PV deployment at residential scale

The standard approach for estimating the potential deployment of small-scale solar energy in a city is to assess the number of square meters (m^2) suitable for the installation of rooftop PV solar panels. However, this study follows a different approach, estimating the number of households that are suited to the installation of rooftop PV solar panels. This approach is useful for evaluating the potential effectiveness of policies designed to promote solar energy at the residential scale.

The Saudi Housing Survey[9] classifies five different types of Saudi housing units: an apartment, a floor in a traditional house, a floor in a villa, a villa, and a traditional house. Khan et al. (2017) estimate the total floor area of each of Riyadh's house types. The average floor area of a traditional house is 116 m^2, and the average floor area of a villa is 268 m^2. For this study, a residential rooftop PV installation comprises of 10 PV panels with a combined power capacity of 2.2 kW and needs a minimum roof installation space of 16 m^2. Both the villa and the traditional house types have sufficient roof space on which to install solar panels. This study assumes that householders living in apartments or occupying a floor of a house or villa do not have sufficient space to install a solar rooftop panel. Villas and traditional houses represent 66.2% of all housing units in Riyadh. It is reasonable to assume that only those residents who own their homes would install PV solar panels, given the long maturity time (about 25 years) of such renewable investments. According to the Housing Survey, 56% of housing units occupied by Saudi families are owner-occupied. In this study, the residential areas of Riyadh contain 798,090 households, including Saudi and non-Saudi families. The Housing Survey does not report information on housing units occupied by non-Saudi families. The non-Saudi population is significant enough (37.4% of the total) to be taken into consideration. Any analysis focused only on Saudi electricity consumers could be misleading as it would miss a significant share of the city's electricity demand. However, the vast majority of non-Saudi householders do not own their dwellings and, as such, will not invest in solar energy.
Using the information above, this study estimates that there are 185,213 Saudi-owned villas or traditional houses in Riyadh. These are the types of households most likely to install a residential rooftop PV facility if it yields a positive economic value.

If all 185,213 households install a rooftop PV solar facility with a power capacity of 2.2 kW, the maximum aggregate residential solar power capacity in Riyadh would be 407 MW, and the total cost of the investment would be around $1 billion. This deployment would produce around 0.7 TWh annually.

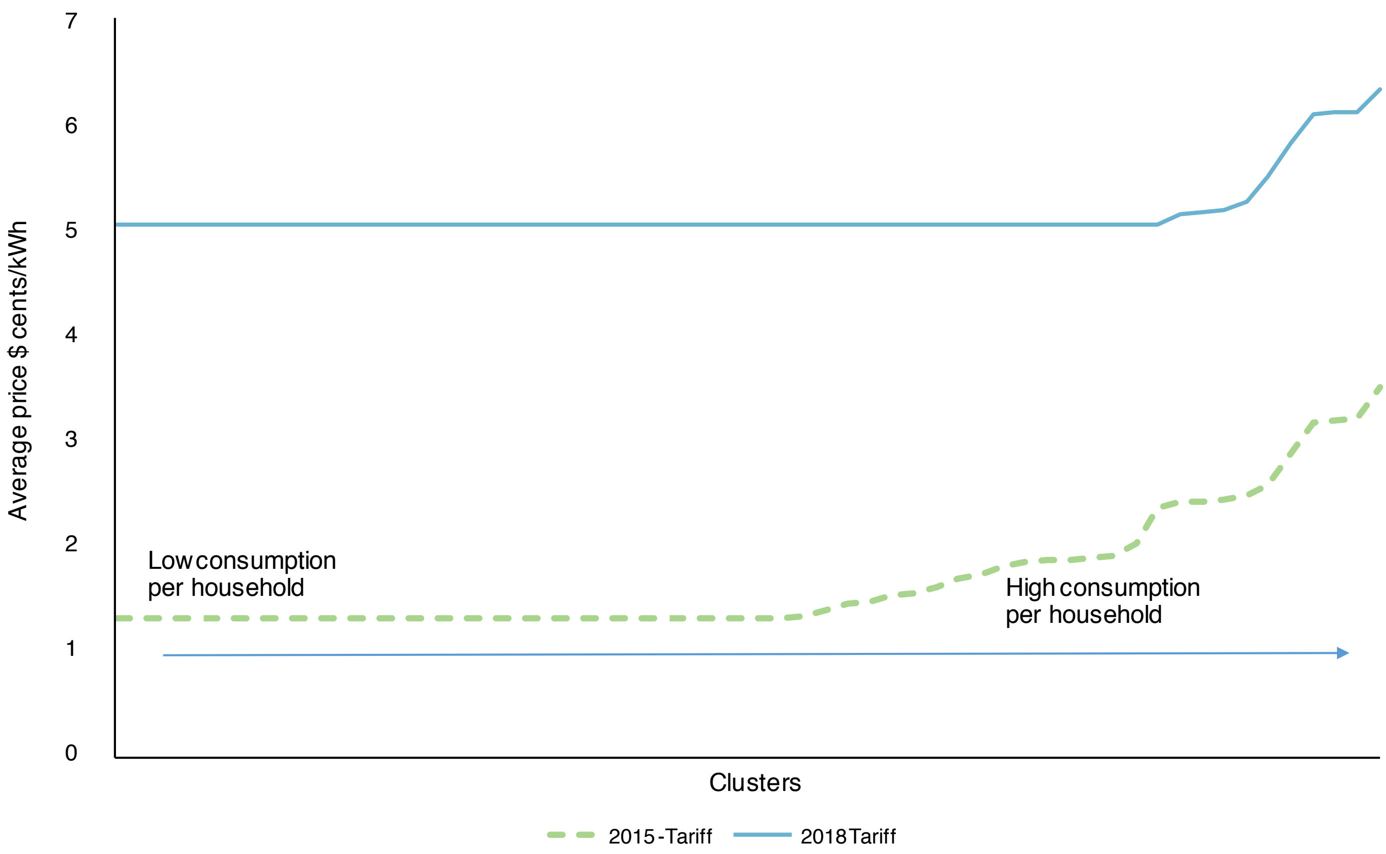
Assessing residential solar deployment in Riyadh for economic reasons

In 2015, electricity in Saudi Arabia was priced on a sliding scale, according to consumers' monthly consumption. Tariffs were increased in 2016 and again in 2018[10]. The 2018 sliding scale has two rates: 0.18 Saudi riyal (SAR)/kWh (4.8 U.S. cents/

kWh per month) for the first 6,000 kWh consumed and 0.3 SAR/kWh (8 cents/kWh per month) for the following kWh consumed (Council of Ministers' Decree dated 12/12/2017[11]). A 5% value-added tax, introduced on Jan. 1, 2018, further increased electricity prices in the Kingdom. To make this study relevant for policymakers, it re-estimates households' energy consumption for 2018, taking into consideration the new electricity tariff and Saudi Arabia's economic growth between 2015 and 2018.[12] Energy consumption in 2018 is evaluated using a long-run income of 0.48 and a price elasticity of -0.16 (Atalla 2016). The estimated aggregate consumption of electricity for the 58 clusters analyzed in 2018 is 15.7% lower than in 2015. Once the 2018 consumption per household in different clusters has been estimated, the average price per kWh consumed can then be calculated. Figure 5 shows the electricity tariff in 2015 and 2018 for the different clusters, from the lowest level of consumption per household to the highest level.

To assess the potential deployment of residential rooftop PV systems for economic reasons, this study compares the cost of the electricity from the grid for all the clusters with the perceived LCOE. As previously outlined, households are given a discount rate by a probability function which generates the perceived LCOE. The average

Figure 5. Saudi Arabia residential electricity tariff in 2015 and 2018.



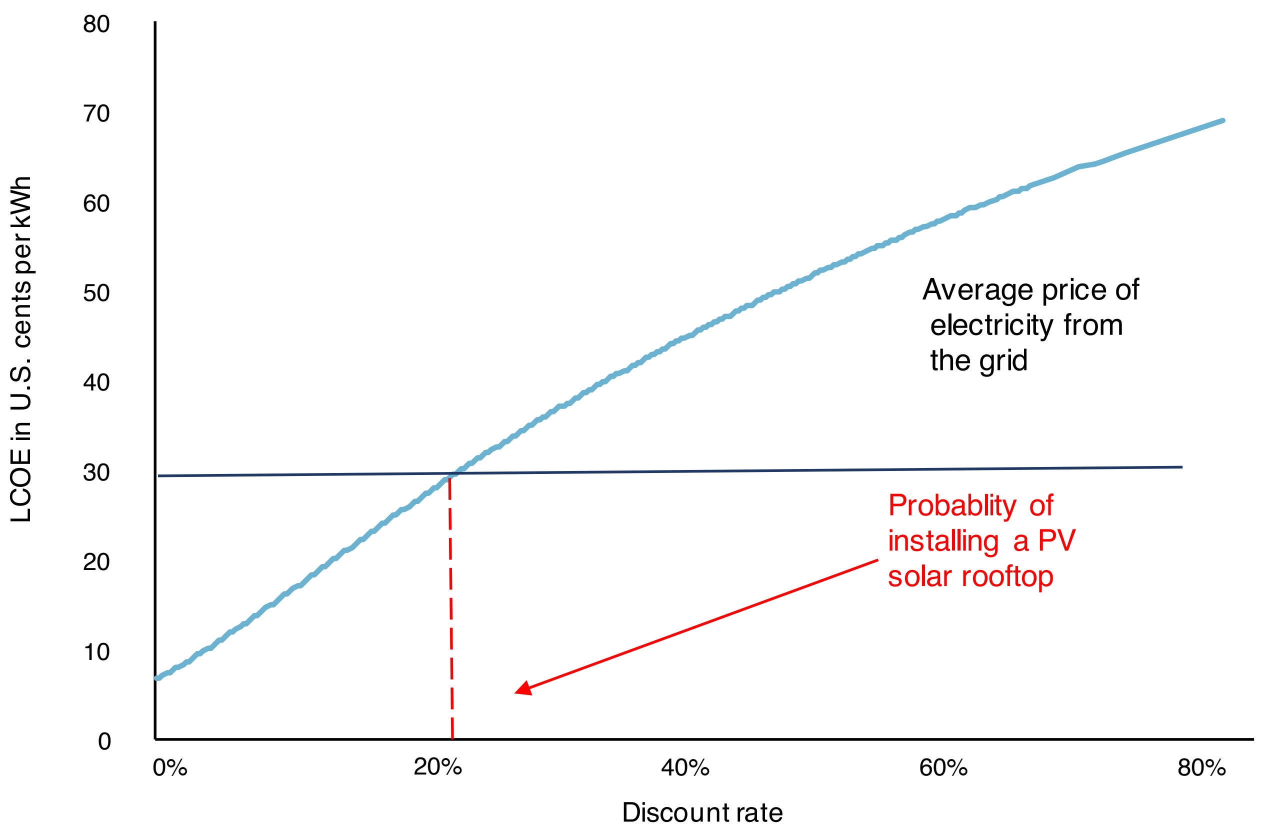
Source: KAPSARC.

electricity tariff determines the probability of a household installing a solar rooftop, shown in Figure 6.

Households in cluster 59 are those with the highest levels of consumption and the highest average price per kWh consumed, of 6.34 U.S. cents/kWh. This price is below the minimum perceived LCOE in 2018, implying no financial incentive to install rooftop solar PV panels. A key policy insight from this data is that current electricity prices for residential consumption in Saudi Arabia are still too low to incentivize the deployment of rooftop solar PV for economic reasons.

However, this does not mean that rooftop PV deployment has to be nil. Schelling (1978) contended that everyday choices made by individuals are privately-optimized decisions carried out according to personal motives. The aggregation of these micro-decisions will ultimately determine the deployment of solar PV rooftop systems at the residential scale. In this sense, households can install rooftop solar panels for a variety of reasons, such as environmental concerns, an ecological lifestyle, or the adoption of market innovation, as pointed out by Chen (2014), Fraj and Martinez (2006), and Sommerfeld et al. (2017). This study ignores the potential impacts of peer-effect, or social influences, on rooftop PV deployment. For example, Bollinger and Gillingham (2012) found strong statistical evidence of a peer-effect on PV adoption at the residential scale in California.

Figure 6. Methodology to assess the probability of households installing PV.



Source: KAPSARC.

In 2019, the decrease in the perceived LCOE due to lower investment costs could potentially favor a marginal deployment in the clusters with the highest level of consumption per household. However, the expected total number of families that would install solar PV in 2019 in Riyadh is extremely low, at just three households overall.

Repeating the analysis for 2020, the number of households in Riyadh potentially interested in installing a solar PV system for economic reasons is still extremely low, at only 24 overall. When this analysis is repeated for 2021, 2022 and 2023, the number of households interested in installing a solar PV system for economic reasons rises to 55, 97, and 145, respectively. The main insight is that the Kingdom's residential electricity prices are low and do not favor the deployment of residential solar energy systems, even after big reductions in the costs of PV technology.

Saudi Arabia, in common with other GCC countries, has embarked on a process of electricity reform to improve the power sector's efficiency, attract new investments and remove fuel subsidies (Elshurafa et al. 2017). Matar and Anwer (2017) suggest that the price of electricity would be around 7.1 U.S. cents/kWh in a scenario of deregulated fuel prices and dynamic pricing. There is some deployment of residential PV under this scenario, at around 2.5 MW in 2018, rising to 26.5 MW in 2023.

According to the California Distributed Generation Statistics (2018), the city of Los Angeles, with 3.3 million households, has 342 MW of installed PV solar capacity at the residential level. The average price of electricity for residential consumers in the city was 18.8 cents/kWh in November 2017, according to the U.S. Energy Information Administration (EIA 2018). According to the model used in this study, and using the same average electricity price, residential solar deployment in Riyadh would have been around 56.1 MW in 2018.

Blazquez et al. (2017) point out that shifting power generation from using oil as fuel to using solar power has a positive impact on the Saudi Arabian economy. Matar and Anwer (2017) find that PV becomes cost competitive when the price of crude oil reaches $30 per barrel. For this reason, policymakers might consider policies to incentivize residential PV deployment. Regardless of the type of policy instrument, households will install a rooftop solar PV system if the net present value of the investment is positive, or at least zero. Financing the difference between the LCOE and the average price per kWh consumed would make the solar rooftop installation financially attractive. It would not matter to the household whether it consumed electricity from the grid or solar cells. In other words, the solar rooftop system would be financially attractive if the government covered the difference between the electricity tariff and the perceived LCOE. There are two elements to consider from the perspective of policymakers. First, the uncertainty of the households' discount rates creates a lack of clarity as to the cost of the policy and its effectiveness in terms of MW installed. Second, PV solar at utility scale is much cheaper. According to IRENA (2018), the global utility-scale LCOE was around 10 U.S. cents/kWh in 2017. Record low auction prices in Abu Dhabi, Chile, Dubai, Mexico, Peru and Saudi Arabia in 2016 and 2017 suggest that the LCOE of PV technology can be reduced to 3 U.S. cents/kWh from 2018 onward. For these two reasons, the government of Saudi Arabia could focus on PV at the utility scale to accelerate the decarbonization process.

Conclusions

This paper explores the potential deployment of residential rooftop solar PV panels in Riyadh from a financial perspective. The study analyzed nighttime light intensity and temperatures to estimate households' electricity consumption in different areas of the city. The variables used to assess electricity consumption at the household level are NOAA's VIIRS-DNB, the Esri World Population Estimate spatial layer 2015, and the Global Human Settlement Layer (GHSL) developed by the European Commission's JRC. This granular data enables the mapping of household electricity consumption and an assessment of the potential demand for solar rooftop technology.

Riyadh is divided into 58 areas comprising 798,090 households. The average consumption of electricity is 2,327 kWh per household per month and the standard deviation is 1,923 kWh. According to the study's estimates, 69% of households in Riyadh consume less than 3,000 kWh per month.

This study found that the maximum aggregate solar power capacity in Riyadh at the residential level would be around 400 MW. This figure is based on households' characteristics and house types. Around 185,000 households have the right characteristics for the installation of PV solar panels on their rooftops. Second, the current residential electricity tariff disincentivizes PV solar rooftop deployment. Despite the increase in residential electricity prices in January 2018, rooftop PV systems cannot compete on price with electricity from the grid, even assuming aggressive reductions in the investment cost of PV technology. This is because households tend to have a discount rate, penalizing the perceived LCOE of solar technology. Third, the policy cost of promoting residential solar deployment is uncertain because the discount rate used by households to assess the value of investing in solar technology is unclear. For these reasons, PV at the utility scale seems a better solution to accelerating the Kingdom's decarbonization process.

This study finds that current electricity tariffs in Saudi Arabia and other GCC countries preclude financial motivations from being a driver for residential PV deployment. However, as the study shows, households install rooftop PV panels for different reasons, including environmental concerns, to maintain an ecological lifestyle, or for social influence.

Residential PV solar energy is not economically viable for households in Riyadh based on current electricity tariffs; PV at the utility scale is a cost-efficient alternative. However, an intermediate business model that takes simultaneous advantage of the proximity to the final consumer, to economies of scale, and is managed professionally, might be economically competitive. This new business model would be based on neighborhood-scale solar installations. It would allow investors to spread the infrastructure costs over a larger number of subscribers, thereby reducing the fixed cost per unit. Such schemes would be particularly cost-effective in large condominiums. This business model for residential PV solar is one option that could be tested and explored further.

Endnotes

[1] The Spatially Constrained Multivariate clusterization is carried out using a tool available in the Geographical Information System (GIS) software ESRI ArcGIS Pro 1.2.

[2] http://www.arcgis.com/home/item.html?id=ac0401d78fa24a10a9151ffe50f35afe

[3] For example, there are some cluster zones in Riyadh that are usually recreational areas with temporary constructions such as weekend tents.

[4] http://www.sama.gov.sa/en-US/EconomicReports/Pages/YearlyStatistics.aspx

[5] http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisRegion=Asia&ThisCCode=SAU

[6] The average Saudi household has 5.7 members, according to the Household Expenditure and Income Survey (2013) by the General Authority for Statistics.

[7] https://www.kapsarc.org/openkapsarc/kapsarc-solar-photovoltaic-toolkit/.

[8] https://energy.gov/energysaver/planning-home-solar-electric-system.

[9] General Authority for Statistics: https://www.stats.gov.sa/en/911-0

[10] This table shows the evolution of the electricity tariff in Saudi Arabia.

Electricity tariff in U.S. cents per kWh.

Category	2015	2016	2018
0-2000	1.3	1.3	4.8
2001-4000	2.7	2.7	4.8
4001-6000	3.2	5.3	4.8
6001-7000	4.0	8.0	8.0
7001-8000	5.3	8.0	8.0
8001-9000	5.9	8.0	8.0
9001-10000	6.4	8.0	8.0
10001-	6.9	8.0	8.0

[11] https://www.se.com.sa/en-us/customers/Pages/TariffRates.aspx

[12] International Monetary Fund (2018).

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Notes

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About the Project

The KAPSARC Transport Analysis Framework (KTAF) studies and models global economic activity and freight transportation. For this, KTAF relies on open-source global data from satellites and the spatial distribution of different economic activities by broad sectors. The main objective of KTAF is to offer quantified insights on the effects of policy measures on transportation activities and energy consumption related to freight mobility.

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