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The Upper Limit of Distributed Solar PV Capacity in Riyadh: A GIS-Assisted Study

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Abstract: Rooftop solar photovoltaic (PV) systems, commonly referred to as distributed generation (DG) solar systems, are deemed important contenders in future sustainable cities. Because deploying DG systems is associated with technical, financial, policy, and market implications that impact utilities, governments, and businesses, quantifying the potential of DG systems that could be deployed in a certain jurisdiction ex ante helps inform the decision-making process for all stakeholders. To that end, the upper limit of rooftop PV systems that could be deployed in Riyadh, the capital of Saudi Arabia, was assessed with the aid of geographic information systems (GIS). By relying on urban land lot data for different categories, i.e., zones, and the maximum allowable area that could be built within a certain lot using prevailing building codes and regulations, the rooftop area suitable for PV deployment within Riyadh Metro was quantified. The analysis was restricted to rooftops in residential, mosque, shopping mall, and health care buildings only. Following the quantification of the rooftop area, the upper limit of rooftop solar PV capacity that can be deployed in the city of Riyadh was found to be 4.34 GW. This capacity represents nearly 22% of the peak load and can satisfy approximately 9% of the energy requirement in the central region, the region in which Riyadh resides.

Keywords: GIS; distributed generation; solar photovoltaics; rooftop solar; land parcel; Saudi Arabia

1. Introduction

The global demand for electricity is increasing steadily. The International Energy Agency, through its 2018 World Energy Outlook, projects that electricity demand will grow to at least 37,000 TWh by 2040 compared to the 2017 level of 25,700 TWh [1]. With heightened environmental concerns [2], governments are facing pressure to meet this growth in demand while curbing, to the extent possible, fossil fuel use and hence carbon emissions [3]. As such, a considerable percentage of the increase in demand is envisioned to be met by clean energy technologies including, and not restricted to, solar photovoltaics (PV), wind, and storage [4,5].

The solar PV industry, in particular, has progressed well in the past two decades. Strong policy support, financial and otherwise [6,7], coupled with technological cost declines [8,9] have contributed to the rapid deployment of PV. While there was no mentionable installation capacity of solar PV in the early 2000s, the cumulative global installed capacity reached over 500 GW by the end of 2018. In addition to requiring no fuel and being carbon-free, solar PV enjoys low operation and maintenance (O&M) costs. However, it suffers from being an intermittent source, i.e., non-dispatchable [10].

With respect to their size [11], solar PV systems can be mostly categorized as residential (2–10 kW), commercial (20–200 kW), or utility-scale systems (1 MW and above). Residential and commercial systems are also classified as distributed generation (DG) systems [12], where DG indicates that these systems are installed within the distribution network or near the load [13]. DG systems are generally installed on rooftops, but can also be ground-mounted if the area is available. However, utility-scale systems are always ground-mounted and require a relatively large land area.

Akin to any technology, both DG and utility-scale PV bring about strengths and weaknesses. Utility-scale solar farms, for example, benefit from economies of scale and are easier for electricity companies to manage from a central planning perspective [14]. However, land availability makes utility-scale deployment difficult within cities and even more so in city centers.

On the other side of the spectrum, DG scale solar systems surmount the large land area requirements, and empower the consumer [15]. As the homeowner (or industrial facility, for example) self-consumes whatever is generated, this reduces the electricity bill. Further, if exporting energy back to the grid is possible and is compensated for, then the homeowner, depending on his consumption level [16], can receive credit for the exported energy [17]. This consumer empowerment [18], which transforms him/her to a prosumer (i.e., a consumer and a producer simultaneously), is of particular appeal especially in countries where the prevailing electricity prices are high. On the other hand, DG systems could cause instabilities in the distribution network [19], and hence, the electric utility has to adopt new operational procedures to avoid such incidents.

Governments that have promoted renewable energy deployment were generally propelled by three main drivers: Reducing carbon emissions, boosting the economy by creating a renewable energy industry and creating jobs, and achieving higher energy security levels [20]. These objectives would be achieved by tying them to a renewable energy target installation capacity, and this target would have stemmed from a grand strategic plan that encircled financial, legal, industrial, economic, trade, and other goals, considerations, and constraints. The renewable energy targets would also specify the share that each renewable technology would shoulder from the overall target.

One consideration that informs the decision of the utility-scale PV capacity to be installed is land availability, accessibility, and suitability [21]. Explicitly, the latter looks into land proximity to loads [22], land proximity to transmission line infrastructure [23], whether the land is natural habitat for certain (endangered) species [24], and potential interference with agricultural activities [25]. However, once the land is identified and deemed suitable for a PV project, it is easy to estimate, with a high level of confidence, the size of the PV farm that could be constructed.

Arriving at the potential of DG installations, however, is not as easy. Cities comprise homes, residential buildings, shopping centers, governmental buildings, religious buildings, etc., with starkly different area footprints. Further, different neighborhoods have different electricity infrastructure capability and population densities (which translates to different levels of load consumption). As such, the preparedness of various urban geographical locations to absorb DG will vary significantly [26], and trying to quantify this potential helps policymakers better plan for their targets and the share that DG can contribute to this target, and better budget for the financial commitments required [27].

The deployment of renewables, whether at the utility or distributed scales, affects and depends on infrastructure investment within a country. As the energy mix in a country changes, the cost of providing energy changes, which in turn, affects consumption behavior. Ultimately, energy intensity developments [28] and targets [29] would be impacted. The latter is particularly important for the industrial sector [30]. Education becomes a key factor in raising awareness of such changes [31].

In light of the above, we quantify, for the first time, the upper limit of DG potential in the city of Riyadh, the capital of Saudi Arabia, using a geographic information system (GIS) approach. Explicitly, we rely on land-lot data for the city of Riyadh. The areas of the land-lots along with their dedicated use (i.e., residential, commercial, mosque, etc.), and the maximum allowable area that could be built within a land lot were relied upon and to assess the suitable area that could be used for PV deployment. Based on the power to area ratio of solar PV modules, it was found that the maximum rooftop PV capacity that can be deployed in Riyadh is 4.34 GW, where this capacity includes residential, mosque, mall, and health care buildings only. The latter numerical finding is an upper limit that does not account for economic or technical limitations. Given that Saudi Arabia announced its 2030 renewable energy targets recently, and as the regulator has also released the provisional bylaws that will govern how DG would be treated/compensated within the kingdom, this analysis comes as timely to help in shaping the discussion around DG as the kingdom moves forward in its renewable energy plans.

2. Review and Motivation

Many governments around the world have realized the potential that DG possesses with respect to meeting growing electricity demand and simultaneously combating climate change. As mentioned earlier, the value that DG offers increases in highly dense and populous cities where land, for utility-scale deployment, is scarce.

Assessing the feasibility of DG deployment encircles a number of factors to be considered including the spatial component of the analysis. Hence, not surprisingly, we see that numerous research papers rely heavily on GIS to inform the studies and findings. Note that using GIS is not restricted to DG penetration only. Utility-scale PV siting efforts are also being guided by GIS analysis [32,33], though the need for GIS for DG deployment is higher.

The nature of studies that involve GIS and DG comes in different flavors. One type of studies that relate DG to GIS focuses on the natural resource [34], where the solar irradiation levels would be collected down to a certain area resolution with other climate factors (e.g. dust and cloud cover) also considered. With such data, the electricity generation potential would be estimated for a specific geographical location. A sample of these studies includes analysis for Africa [32], Bangladesh [33], and Slovakia [35].

DG and GIS do not only find application in urban locations but are considered an attractive workforce for rural electrification purposes [36], given that connecting these remote areas to the grid with transmission lines network is often prohibitively costly. Rural areas throughout the world are mostly powered by diesel, and although diesel generation provides the required energy, the inhabitants of these areas suffer carbon pollution, noise pollution, diesel price fluctuation, diesel transportation/delivery costs, and lack of diesel supply reliability [37]. GIS proves to be a vital tool to support rural community energy planning [38,39] and PV system fault detection and monitoring [40].

As mentioned, with DG penetration several engineering considerations rise to the surface and require new modes of operation from the utility. GIS has been adopted in technical studies to inform the siting of DG systems to satisfy a certain technical objective function including voltage profile improvement [41] and loss minimization [42]. Among the technical issues that GIS has also been used for is to complement supply and demand studies to offset peak loads and improve grid stability [43].

Beyond resource and engineering studies, GIS has also steered other social studies, including solar DG diffusion in neighborhoods. If a household installs a PV system on its rooftop, the neighboring household might follow suit. The rest of the neighborhood may follow suit as well. This phenomenon has been studied by coupling GIS and agent-based modeling to describe the adoption rates, i.e., diffusion, of DG systems and how the perception and behavior of neighbors towards PV may change if a nearby house installs a DG system [44,45].

In addition to the above types of studies, GIS can play a crucial role in assessing the potential capacity that can be deployed in a certain location. This location can be as small as a neighborhood, or as big as a country as will be shown. As mentioned earlier, when a certain land has been identified as suitable for utility-scale deployment, the capacity of the PV system that could be erected would be known with a high degree of certainty. The same does not apply to DG.

While a single homeowner can assess what his roof can accommodate in terms of capacity, this piece of information is not considered enough for macro-scale deployment. There are at least three entities that would be interested in understanding the potential of DG deployment within a certain city, state/province, or country. First, policymakers would like to know what the potential capacity that could be deployed as this would aid them in better planning for targets and better assessment of policy support requirements, be it financial or otherwise [46]. While both utility and DG scale PV can be offered support, both the nature and type of support offered to both types of installations are different [47]. Policymakers also use the potential capacity information in estimating new employment opportunities that would be created. Second, the grid operator and/or the electric utility, knowing the potential DG capacity that could be introduced into the system, can better plan for grid upgrades and ramping capabilities [48]. Further, the electricity provider, whether a private company or run by the government, can evaluate the financial implications that would result from the foregone revenues, as homeowners buy less electricity from the grid [49], and possibly cause the death spiral. Third, the DG potential provides valuable information to solar PV providers and/or installers as they can evaluate the market potential for their business [50].

Given the impact that capacity estimation of DG deployment can have on a number of decisions, it is not surprising to see this topic receiving research attention. For example, and on a relatively small scale, a simulation framework using GIS was developed to optimally size and locate solar PV in a campus environment [51]. We also find GIS heavily used on a larger scale, i.e., capacity assessment for city-wide deployment. The solar energy potential in Hong Kong was estimated to be 2.66 TWh annually on building rooftops. The latter result was achieved by integrating GIS, solar irradiation data, and remote sensing technologies [52].

Similarly, a study was performed for Dhaka, Bangladesh, whereby the authors put into consideration the capacity of the substation available in the neighborhoods of interest [53]. With the aid of GIS, coupled with light detection and ranging technology (i.e., LiDAR), the actual rooftop area that is suitable for DG installation was estimated for several parts of Dhaka. Similar to this aforementioned analysis, another study was conducted for the city of Georgetown, Malaysia. In this study, however, an additional layer of detail was incorporated into the analysis which was the slope of the roof [54]. Explicitly, GIS, once again with the aid of LiDAR, was used to identify the roofs that were facing south and their slope.

Moving even to a larger scale, GIS can be used to estimate the potential of solar PV deployment for nation-wide studies. The National Renewable Energy Laboratory (NREL) in the US, estimated the technical potential of specific renewable energy generation technologies for the United States while keeping in mind resource availability, topography, and constraints associated with land-use as explained earlier. Not only did they consider solar PV, but also incorporated onshore and offshore wind, hydropower and geothermal technologies. For PV in particular, the study concluded that around 664 GW of rooftop solar could be installed, compared to 154,000 GW of utility-scale PV [55].

The above review has served as a confirmation that GIS is considered a reliable technique to assess DG deployment potential. Following this, there were two main motivators that triggered pursuing this work. The first was the recent renewable energy target that was announced in Saudi Arabia. Explicitly, the Saudi target aims at installing around 57 GW of renewable generation technologies by 2030, where 40 GW of this target is solar PV. Currently, there is no mentionable DG installed capacity in the kingdom. Secondly, Saudi Arabia has also embarked on an energy price reform journey. Electricity prices have changed twice in the past few years, and further raises to prices are possible. As electricity prices increase, and technology costs simultaneously drop, DG becomes more attractive. Hence, households may resort to PV installations to reduce their electricity bills. The Saudi Regulator has issued the bylaws that would describe how DG would be governed in anticipation of increased DG growth.

3. Method

Saudi Arabia lies in the Southern West corner of Asia. The city of Riyadh, with a population of over seven million people, is the largest city in Saudi Arabia by area and is also the political capital. From a solar irradiation perspective, the global horizontal irradiance (GHI) in Riyadh averages to about 2200 kWh/m^2/year, which is considered significantly high [56]. These observations make Riyadh a city that holds significant potential for DG installations. For comparison, Southern Germany, for example, possesses an average GHI of about 1200 kWh/m^2/year.

We provide in Figure 1 the average monthly solar irradiation levels in Riyadh. As expected, solar irradiation levels increase during the summer months given the longer days. The average irradiation for Riyadh is around 5.8 kWh/m^2/day. In Figure 2, the average temperatures in Riyadh are provided. Both the irradiation and temperature levels are important parameters that significantly affect the output of solar PV systems as will be discussed.

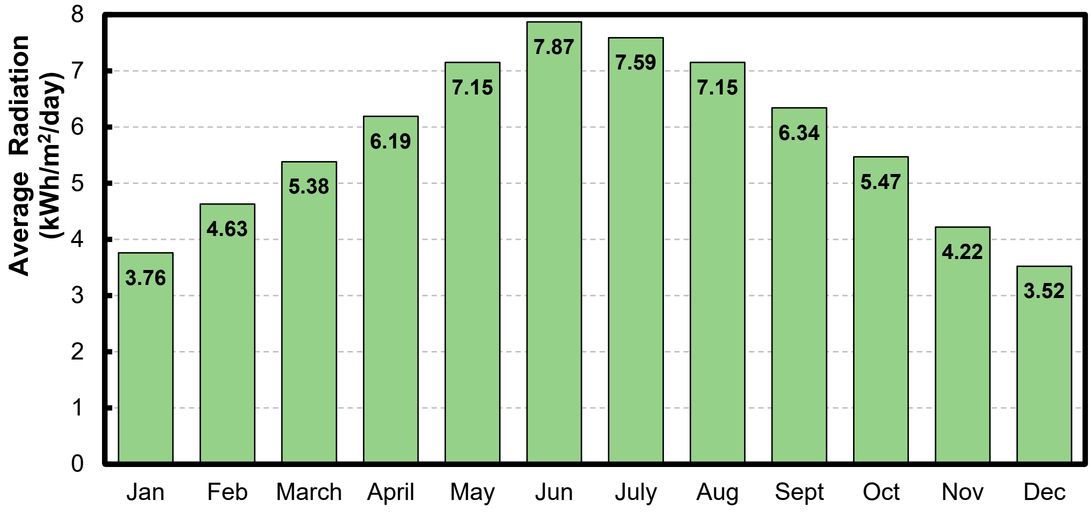


Figure 1. The average radiation, reported monthly, for the city of Riyadh. This data has been collected from the Surface Meteorology and Solar Energy open data source at the National Aeronautics and Space Administration (NASA): https://data.nasa.gov.

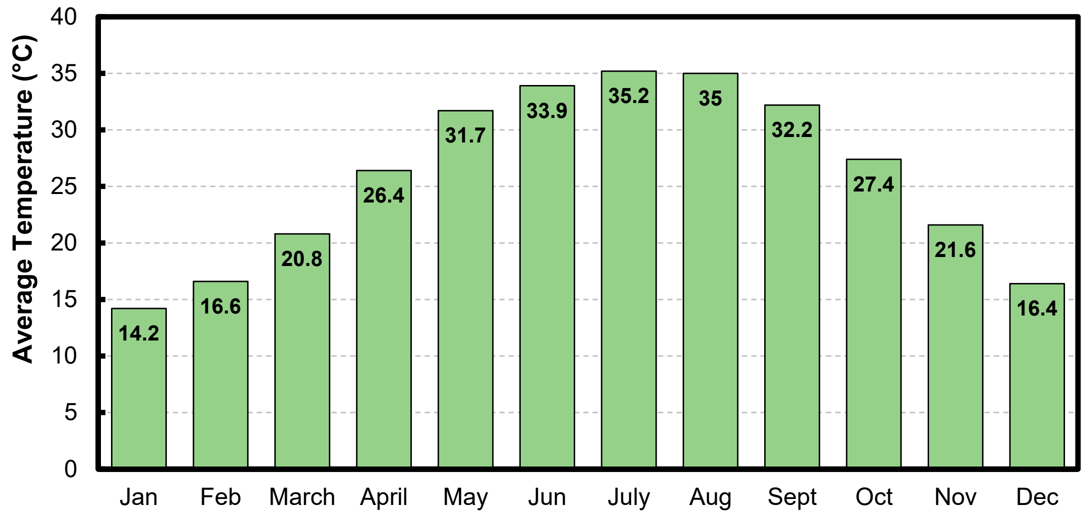


Figure 2. The average monthly temperatures for the city of Riyadh. It is important to note that the temperatures during the daytime in the summer months rise well above 40 °C. This data has been collected from Energy Plus Weather Data: https://energyplus.net/weather.

3.1. Data and Scoping

Ideally, it is desired to employ high-resolution aerial imagery or LiDAR data to identify suitable roof space that satisfies the requirements of solar PV installation and mounting. Unfortunately, and for the geographical area of interest, i.e., the city of Riyadh, none of these data are readily available. Instead, in this study, we rely on utilizing land lots, also referred to as land parcels, as identified in land-use and zoning datasets. A land parcel, or a land lot, is a piece of land that would be used for a specific purpose depending on the governmental and/or municipal zoning. Land parcel designations can include, and are not restricted to, residential, commercial, industrial, or governmental, for example.

A GIS layer representing parcel-lots and their designation, for the city of Riyadh, has been obtained from the Riyadh Development Authority (http://rda.gov.sa). This layer is a static snapshot of land use codes in the city of Riyadh for 2016, and includes a spatial representation (i.e., geographic location and shape) of every land parcel in the city. The total number of parcels included in the data set was a little less than one million. Each land parcel is designated a land-use code based on zoning regulation and is also assigned a building type, if a building exists. Otherwise, the land is tagged as vacant. Possible land-use codes and building types are detailed in Tables 1 and 2, respectively.

Table 1. The range of unique land use codes that could be assigned to a parcel.

Land Use Code
Residential
Industrial
Storage and Warehouse
Transport Services
Communication and Public Services
Commercial
Business Services
Government Services
Grave Yards
Health Services
Education Services
Mosques
Social and Cultural
Amusement and Parks
Agricultural
Vacant Land
Unknown

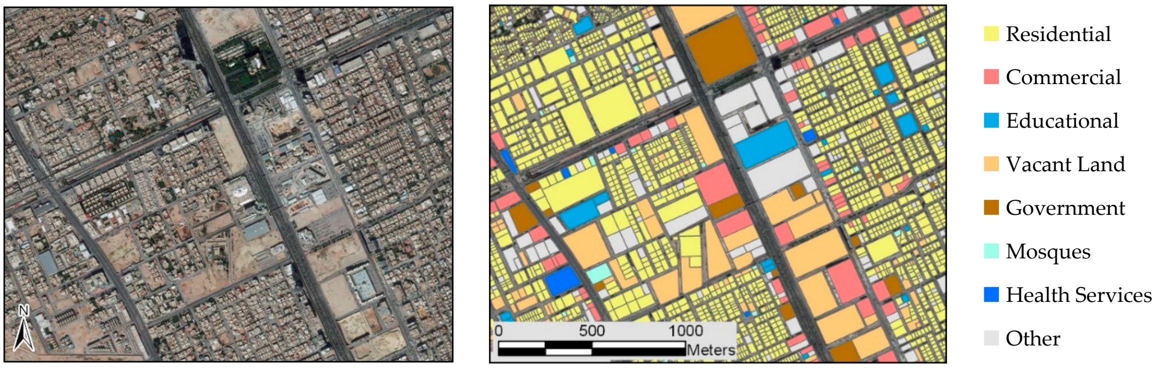
Table 2. Range of unique building types that can exist on a land parcel.

Building Type
Tent or cottage
Traditional Arabic House
Villa
Mansion
Apartment Building
Urban Building
Office Building
Commercial/Retail Building
Market
Warehouse
Factory
Public Service
Complex/Unknown Building Type
Mixed Use (not in a multistory building)
Mixed Use (in a multistory building)
Commercial Center
Other
Vacant Land

The land-use GIS layer has been analyzed using the commercially-available software package ArcGIS Pro. In addition to visualizing and interrogating the layer, it has been employed to supplement the land-use parcel data with additional attributes. For the purposes of this paper, and because the area is of chief importance, the geo-processing engine of ArcGIS Pro was used to arrive at the area of parcels in square meters. Then, the resulting data was exported into tabular form to be processed further via Python scripting language. For more information, please refer to Appendix A. To accommodate for the uncertainty that is inevitable in any modeling and/or data analysis exercise, we consider two extreme cases that serve as a best-case-scenario and a worst-case scenario for deployment.

Figure 3 shows a snapshot of this geographical data, where a raw image for a neighborhood in Riyadh is shown in Figure 3a, and the corresponding zoning categorization is shown in Figure 3b.

Note how each land parcel is color-coded for ease of identification. For more details, please refer to Appendix A.



(**a**) (**b**)

Figure 3. A sample of the geographical data available for a neighborhood in Northern Riyadh. (**a**) This figure shows the neighborhood as it appears in satellite imagery using ArcGIS base-map. (**b**) The same figure that is in (**a**) but categorized as land parcels, and each land parcel is color-coded based on its zonal designation. For example, yellow parcels represent residential land lots, while a light-blue parcel represents a lot that is designated as an educational institution.

As can be seen from Table 1, and given that the focus of this paper is rooftop distributed generation, some land parcel categories will be excluded from the analysis. The reasons for exclusion are summarized in the following points:

- **Inapplicability:** Land parcels denoting agricultural, amusement and parks, grave yards, and transport services (i.e., parking) would clearly not qualify as suitable for DG installation, as these parcels will generally contain no, or little, buildings.
- **Broad Activities:** The same category may be representative of a number of activities that are too broad in nature, and many of these activities will result in the land containing no buildings. For example, the government services category can assign lands for military bases and training camps.
- **Actual built-area Variability:** The variability in the built area within the same category can be significant. For example, the actual rooftop area available varies considerably in the Educational Services category for example. In the latter category, schools, colleges, and universities are all included. However, all these educational institutions vary significantly in how land is utilized (number of buildings, presence and size of playgrounds, indoor sports court, parking, etc.).
- **Lack of Structural Preparedness:** Although a building may exist, the roof may not be structurally suitable for PV installation. For example, the storage and warehouse categories, would contain a structure possessing a roof typically made out of metal sheets. Such a roof would not be capable to host PV installation. The same rationale applies to tents.

Based on the above, the focus of this study has been centered at the following categories: Residential, mosque, health services along with a specific sub-category of commercial which has a specific building type erected on it flagged as commercial centers, indicating malls.

3.2. Rooftop Area and PV Capacity Calculation

Buildings that reside within a certain parcel will not fully occupy the area of that parcel. Buildings and/or structures need to be a minimum distance away from streets, fences, and/or the parcel boundary. This minimum distance is referred to as the land use setback. Through building codes, local municipalities and/or governments specify the value of the setback depending on the parcel type.

Although setback values differ across countries, their implementation ensures, among other reasons, architectural uniformity within the same neighborhood, access around the building, access to sunlight, and availability of space for landscaping.

Using the same reasoning, building codes also specify the maximum allowable area that can be built (MAAB) within a land parcel. While the setback is mostly concerned with the distance that separates the building from the parcel boundaries, the MAAB sets an upper limit to the overall area that can be built in a specific land lot. Akin to the setback, the MAAB varies across categories. For the purposes of this paper, the MAAB constitutes a realistic estimate to the maximum possible rooftop area that can exist in any parcel.

Expectedly, a PV system cannot always be deployed to fully cover the rooftop. The rooftop may not be flat or may be covered with shingles that disallow mounting of PV modules. Further, parts of the roof can be occupied with satellite dishes, water tanks, clothes lines, air conditioners, ducts, or other service units—all reducing the area that can be devoted to PV installations. Parts of the roof may also be shaded by a balustrade or by adjacent buildings, deeming these parts of the roof as not suitable for PV installation [57]. As expected, this information is not available for each and every building. Hence, an assumption will have to be made, and sensitivity analysis can account for the variation that exists between buildings.

By knowing the area of the land parcel, the MAAB, and an assumption regarding the area that can be utilized for solar modules, the potential PV capacity that can be installed can be calculated. The size of the PV system that can be installed would depend on the power rating of the module (i.e., W/m^2) and the angle at which the modules are mounted. Because Saudi Arabia lies in the northern hemisphere, the calculations in this paper assumes that the modules would be installed facing south, and would create an acute angle of 25 degrees with the horizon.

4. Results and Discussion

4.1. Rooftop Area Calculations

The summary of all the land parcels that were used to calculate the PV deployment potential is included in Table 3. As can be seen, there were four categories that were deemed as fit: Residential, mosques, commercial, and health centers. Each category was further sub-categorized, if needed, to cater for differences in MAAB or the percentage of the roof that could be utilized. For all these sub-categories, a mean area was calculated to serve as an indicator of the validity of the obtained analysis.

The residential segment was divided into three sub-categories: Villa, apartment building, and mansion. Note that the mean value for the villa segment is significantly lower than that of the mansion as expected. Similarly, the mosque segment comprises small and large categories, where the former represents smaller mosques that serve for the daily prayers, whereas the latter represents larger mosques that hold the Friday congregation and other social and festive activities. Lastly, the category of health centers contains public hospitals, private hospitals, and clinics, where clinics represent smaller health care providers that cater to simple medical checkups and procedures.

The MAAB was obtained from the official authority: Saudi Authority for Industrial Cities and Technology Zones (www.modon.gov.sa). Note that all MAAB values are equal to 60% with the exception of the MAAB value for small health care centers (i.e., clinics). The percentages of the roof that are available for PV deployment was obtained from [57]. For the available area of the rooftop, we have used two scenarios: An optimistic scenario, where the area available for PV deployment is large, and a conservative scenario, where the area available for PV deployment is small. These two extremes provide policymakers with a realistic range to the potential capacity that can be installed within Riyadh. The optimistic and conservative ratios are both used to calculate a median value.

From the total land parcel area, the maximum rooftop area that would be available can be estimated with the MAAB. Then, the percentage of the roof that can be used for PV installation would be a share of this maximum rooftop area available. All these calculations are summarized in Table 3.

Table 3. The land parcel data, maximum allowable area that can be built within a parcel (MAAB), and rooftop area available for PV deployment for the city of Riyadh.

	Residential			Mosques		Commercial	Health Care		
	Villa	**Apartment Building**	**Mansion**	**Small**	**Large**	**Mall**	**Public Hospital**	**Private Hospital**	**Clinic**
Land Parcel Count	276,862	38,009	1688	3098	1063	82	30	54	84
Total Land Area (m^2)	171,626,281	22,689,746	17,557,758	5,472,329	3,177,452	2,261,226	3,172,713	712,802	1,803,029
Mean Parcel Area (m^2)	620	597	10,420	1766	2989	27,576	105,757	13,200	21,465
MAAB [1]	60% [2]	60%	30% [3]	60%	60%	60%	60%	60%	45%
Maximum Roof Area (m^2)	102,975,768	13,613,848	5,267,327	3,283,397	1,906,471	1,356,736	1,903,628	427,681	811,363
Percentage of Roof Available for PV Deployment (Optimistic) [4]	50%	50%	60%	20%	50%	50%	50%	50%	40%
Percentage of Roof Available for PV Deployment (Conservative) [4]	10%	10%	20%	10%	10%	10%	10%	10%	10%
Roof Area Available for PV Deployment in m^2 (Optimistic)	51,487,884	6,806,924	3,160,396	656,679	953,236	678,368	951,814	213,841	324,545
Roof Area Available for PV Deployment in m^2 (Conservative)	10,297,577	1,361,385	1,053,465	328,340	190,647	135,674	190,363	42,768	81,136
Roof Area Available for PV Deployment in m^2 (Median) [5]	30,892,730	4,084,154	2,106,931	492,510	571,941	407,021	571,088	128,304	202,841

[1] The maximum allowable area that can be built (MAAB) on a certain parcel. The values were extracted from the Saudi Authority for Industrial Cities and Technology zones (www.modon.gov.sa). [2] As of 2019, the MAAB for villas has increased to 70%. However, we use 60% as this was the MAAB in place before the change. [3] The MAAB here is also 60%. However, it is highly unlikely that a mansion would occupy 60% of the land area. Mansions generally enjoy pools, playgrounds, and gardens. As such, the MAAB was assumed to decrease from 60% to 30%. [4] These values were chosen based on the analysis in [57]. [5] The median value is the value that will be used for calculations.

4.2. PV Capacity Calculations

Table 3 summarized the available area that is suitable for PV installation in each category based on the land parcel, the MAAB, and the percentage of the roof that could be utilized for deployment. For convenience and ease of reference, the median areas for all zones (i.e., the last row in Table 3), are summed and recapitulated separately in Table 4. As can be seen in Table 4, the total rooftop area available for DG installation in Riyadh is nearly 39.5 million square meters. Recall that this area stems from the median values that were calculated from Table 3. As expected, we also note that the residential sector is the one that is responsible for nearly all the available area. Within the residential category, the 'Villa' category contributes the largest share.

Table 4. The area available for PV installations in Riyadh based on the zonal category, the sum of the area for each category, the overall subtotal for all categories combined, and the potential PV capacity that could be installed on these areas. Discrepancies are due to rounding.

Land Parcel Category	Land Parcel Subcategory	Area (m^2)	PV Capacity (MW) That Can Be Deployed
Residential	Villa	30,892,730	3398
	Apartment Building	4,084,154	449
	Mansion	2,106,931	232
	Residential Total	37,083,816	4079
Mosque	Small	492,510	54
	Large	571,941	63
	Mosque Total	1,064,451	117
Commercial	Mall	407,021	45
	Mall Total	407,021	45
Health Care	Public Hospital	571,088	63
	Private Hospital	128,304	14
	Clinic	202,841	22
	Health Care Total	902,233	99
	Grand Total	**39,457,521**	**4340**

Note: The rows that contain totals are shaded in grey for convenience and ease of identification.

Now that the available rooftop areas available for PV installations have been estimated, the corresponding PV capacity that can be deployed within these rooftop areas can also be calculated. The overall capacity of the PV system and the area that is required to achieve a certain capacity depends primarily on the PV module that will be used. Further, when installing two or more rows of modules, i.e., strings, each string should be separated from the neighboring string by a minimum distance. This separating distance ensures that each string is not shadowed by the neighboring string, and also allows access to the modules for maintenance and cleaning purposes.

Module capacity and sizes vary across manufacturers. For the purposes of this paper, we consider silicon-based solar PV modules, as silicon modules accounted for 95% of global production in 2017 [58]. Thin-film technologies accounted for the remaining 5%. Silicon technologies (poly-crystalline and mono-crystalline) are dominating the global market and several projects in the Arabian Peninsula have adopted this technology, including the 1.177 GW solar project recently commissioned in Abu Dhabi, United Arab Emirates, which is considered the largest solar plant in the world. The ubiquity of silicon-based solar modules is attributed to three main reasons: Their high power conversion efficiency, the abundance of silicon, and the nontoxicity of silicon.

By consulting the specification sheets for a number of (silicon) PV module manufacturers worldwide, it was found that the power to area ratio ranges typically from 0.15 to 0.2 kW/m^2. This ratio excludes the separating distance between strings as mentioned above, and also excludes the area required for the inverter which transforms the direct current generated by the modules to an alternating current. Assuming a separating distance of one meter between strings, the power to area ratio drops to 0.10 to 0.12 kW/m^2.

Using the areas in Table 4 and a median value of 0.11 kW/m^2 for the power to area ratio, the potential capacity of PV that could be deployed is calculated on the rightmost column. As shown, it is 4340 MW (or 4.34 GW). The residential sector contributes most to this capacity, as expected, because it possesses the largest rooftop area among all sectors considered.

4.3. Contextualizing Results: A Power System Perspective

Based on the analysis presented in this paper, it was found that the city of Riyadh can deploy a maximum of 4.34 GW in the form of rooftop PV systems. In order to put this finding in perspective, it is important to contextualize the magnitude of deployed within the Saudi System, and more specifically, within the central region, i.e., the region in which Riyadh resides.

According to the electricity regulator in the kingdom, the peak load of the central region is 20 GW, whereas the available generation capacity, however, is 16 GW [59]. The deficit in supply is shouldered by the generation capacity available in the eastern region. Given that the high demand hours are generally correlated with the temperature (i.e., AC demand), DG systems can contribute in narrowing the gap between the load and available generation in the central region. This contribution, however, has to be considered carefully as many utilities do not consider the renewable capacity, justifiably, as firm capacity [60].

The energy consumption in the central region totaled 91 TWh. The share that the DG systems can be responsible for can be calculated via (1) the rooftop area arrived at in the previous section, or via (2) the capacity deployed. Using the rooftop area that was concluded, i.e., 39.46 million m^2, and a solar irradiation value of 2200 kWh/m^2/year, the annual generation can be computed as 8.46 TWh assuming a module efficiency of 15%, and an aggregate loss factor of 35% for the PV system that accounts for losses from the inverter, cables, soiling, temperature, maintenance downtime, and other factors [57].

Alternatively, the annual generation can be computed from the deployed capacity that was calculated, i.e., 4.34 GW. Assuming a capacity factor of 21.4% [61], the annual generation becomes 8.14 TWh, which is comparable to the value calculated above using the available area. This generation represents nearly 9% of the total load present in the central region.

4.4. Contextualizing Results: Upper Limit vs. Pragmatic Considerations

The analysis presented in this paper yields an upper limit for the potential capacity of rooftop PV systems that can be deployed. The upper limit is not to be confused with a practical limit that is governed by a number of constraints.

Among the constraints that would impede reaching the full potential of DG deployment is the infrastructure preparedness, and whether the utility can accommodate the uncontrollable nature of PV rooftop generation. Quantifying the power losses associated with DG deployment in order to assess the network efficiency is an important step that aids in optimizing the network performance [62].

Another obvious impedance that stands in the way of achieving the calculated upper limit is the financial constraints of households. A 5-kW residential PV system for example, at 1.5 $/W, would cost $7500—a nontrivial amount that cannot be borne by everyone. Coupling this factor with the infrastructure preparedness factor mentioned earlier, one can envision a scenario where DG deployment may be concentrated in neighborhoods that are tagged as affluent. The inhabitants of these neighborhoods would likely live in relatively large homes (hence possess a rooftop area), and be financially capable of installing a PV system if desired. The electricity provider can predict those deployment pockets and the actual capacity that can result in a certain spatial location with the same methodology implemented in this paper. It is also worth noting that some dwellers may not own the estate they reside in. This segment will most likely not invest in rooftop PV since their presence is governed by short-term circumstances and will not be able to reap the financial benefits of the investment.

In some instances, the rooftop area may be available, but the homeowner may be adopting a not-in-my-back-yard (NIMBY) behavior [63]. This behavior has been witnessed in many countries around the world and describes how individuals conceive and interact with technology. Finally, we note that there will be instances where the homeowner would opt not to install rooftop solar due to esthetic reasons, i.e., if the architectural beauty of the building is going to be compromised.

As mentioned, the peak load of the central region (i.e., which is the region where Riyadh exists) is 20 GW. In other words, if the maximum distributed PV capacity of 4.34 GW were to be fully deployed, then distributed PV would contribute to around 22% of the peak capacity. Realistically, the actual deployment would be significantly less than 4.34 GW for the reasons discussed above.

Within the central region in Saudi Arabia, nearly 70% of the energy demand is satisfied with natural gas. It is well-known that gas is considered among the most flexible forms of power generation. Furthermore, the eastern region, which provides some energy to the central region through transmission lines, is almost entirely powered by gas as well. Thus, from a stability standpoint, the central region possesses a flexible power system that can accommodate a reasonable amount of distributed generation penetration sustainably.

5. Conclusions

In this paper, the potential solar rooftop photovoltaic capacity that can be installed in Riyadh has been quantified. By considering the residential sector, mosque, malls, and health care buildings, it was found that a distributed generation capacity of around 4.34 GW can be deployed. This capacity is considered significant as the peak load in the central region, i.e., the region in which Riyadh lies is 20 GW. The capacity was calculated based on land-parcel data for the city of Riyadh. By knowing the maximum allowable area that can be built within a specific land lot, the maximum area of the roof was estimated. At a capacity factor of 21.4%, the calculated capacity would be capable of meeting nearly 9% of the energy needs of the central region.

The upper limit that was calculated in this paper is not to be confused with a pragmatic limit. As expected, a number of factors would hinder achieving such a capacity. These reasons include technical grid limitations, dweller financial status, and/or esthetic desires. These, and other, factors make the actual capacity that can be deployed significantly lower than the upper limit. With the results presented in this paper, more detailed spatial analysis can be conducted at the neighborhoods that exhibit high readiness to PV deployment.

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Appendix A

This section describes the steps undertaken to process the land use data to produce the tables and figures presented in the paper. This is done by including selected Python code snippets. Before showing the code, the list of acronyms used in the coding is summarized in Table A1 below.

Table A1. List of acronyms.

Variable or Parameters	Description
AREA_GEO	Original column name as imported from raw data. It contains land parcel area in square meters. Later in the process, and for enhanced readability, it was renamed to land_area_m2
Btype	Integer value denoting the building type code
bType_desc_eng	Building type description. This is the original column name as imported from the raw data. Later, it was renamed to building_type.
building_type	Type of building erected on a parcel
detailed_use	Detailed land use type assigned to a parcel
land_area_m2	Land parcel area in square meters
land_area_m2_mean	Average land parcel area in square meters
land_area_m2_sum	Total sum of land parcel areas
land_id	Unique identifier for each land parcel
land_id_count	Count of unique land parcels involved in a category
landuse_type	Land use type
ParcelUse	Integer value denoting the detailed land use type
RULEID	Integer value denoting the land use type
Unnamed: 0	Unique identifier for each land parcel. Later, it was renamed to land_id
use_code_desc	Original column name as imported from raw data. It holds detailed land use type assigned to a parcel. Later, it was renamed to detailed_use.

Appendix A.1. Acquire the Landuse Layer from RDA GIS Portal

```
import pandas as pd
import numpy as np
from arcgis.gis import GIS
ago_gis = GIS("http://www.arriyadhmap.com/adagis", verify_cert=False)
search_subset = ago_gis.content.search("Land use", item_type = "Feature Layer")
landuse_item = search_subset[0]
landuse_item
```

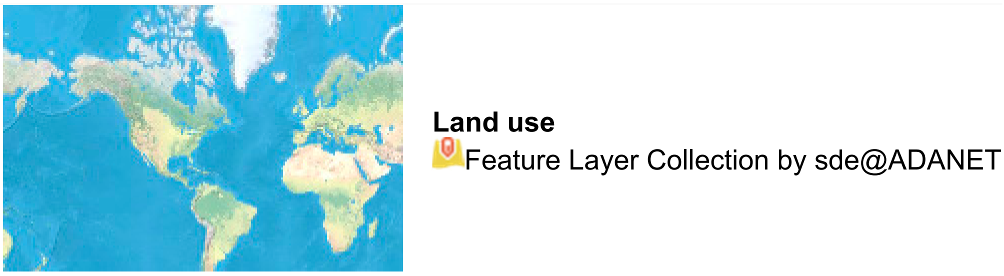

Figure A1. The standard output returned after calling a 'mapping' resource hosted on ArcGIS.

Open the above layer in ArcGIS Pro, add the land area attribute (in square meters) for each parcel by executing the "add geometry attributes" tool. Then export the data into a tabular CSV format. It should be noted since most of the fields are populated in Arabic language, additional steps were also carried out to translate values in pertinent attributes, such as land use code and building type, to English.

Appendix A.2. Import Raw Landuse Data as Exported From GIS

```
landuse_raw = pd.read_csv(r'.\KSA\output\landuse_raw_solar_use_v2.csv')
landuse = landuse_raw[['Unnamed: 0',
                       'RULEID',
                       'Btype',
                       'ParcelUse',
                       'AREA_GEO'
                      ]]
```

```
landuse.head(1)
```

Table A2. Sample of landuse type analysis.

	Unnamed: 0	RULEID	Btype	ParcelUse	AREA_GEO
0	0	1	4	1110	779.494

Appendix A.3. Data Preperation, Step 1: Import Landuse Categroies

```
landuse_type = pd.read_csv(r'.\KSA\domains\landuse_types_DG_categories.csv')
landuse_type.Landuse_type = landuse_type.Landuse_type.str.strip()
landuse_type.drop(columns=['OID', 'DG_Category'], inplace=True)

landuse = landuse.merge(landuse_type, how='inner', on='RULEID')
landuse.head()
```

Table A3. Sample of data preparation for the residential sector.

	Unnamed: 0	RULEID	Btype	ParcelUse	AREA_GEO	Landuse_type
0	0	1	4	1110	779.494	Residential
1	1	1	4	1110	651.353	Residential
2	2	1	6	1110	724.642	Residential
3	3	1	4	1110	643.559	Residential
4	4	1	4	1110	1130.485	Residential

Appendix A.4. Data Preperation, Step 2: Import Building Types and Detailed Parcel Use Categories

```
btype = pd.read_csv(r'.\KSA\domains\Btypes.csv')
btype[["bType_desc_eng","bType_desc"]]= btype[["bType_desc_eng","bType_desc"]].
applymap(np.str.strip)
landuse = landuse.merge(btype, on="Btype")

pUse = pd.read_csv(r'.\KSA\domains\ParcelUse_domain.csv')
pUse.use_code_desc = pUse.use_code_desc.str.strip()
pUse.drop(columns=['OID'], inplace=True)
pUse.rename(columns=[64], inplace=True)
landuse = landuse.merge(pUse, on="ParcelUse")

landuse.head()
```

Table A4. Sample of category analysis.

	Unnamed: 0	RULEID	Btype	ParcelUse	AREA_GEO	Landuse_type	bType_desc_eng	use_code_desc *
0	0	1	4	1110	779.494	Residential	Villa	Villa/Apt
1	1	1	4	1110	651.353	Residential	Villa	Villa/Apt
2	3	1	4	1110	643.559	Residential	Villa	Villa/Apt
3	4	1	4	1110	1130.485	Residential	Villa	Villa/Apt
4	5	1	4	1110	1052.932	Residential	Villa	Villa/Apt

* This column appears in Arabic in the original dataset, but was translated to English herein for convenience.

Appendix A.5. Data Preperation, Step 3: Rename Fields and Keep Relevant Fields Only

```
landuse.rename(columns={'Unnamed: 0';:'land_id',
                        'AREA_GEO':
                        'land_area_m2',
                        'bType_desc_eng':
                        'building_type',
                        'use_code_desc';:'detailed_use'}, inplace=True)

landuse = landuse[['land_id',
                   'landuse_type',
                   'buildingType',
                   'detailedUse',
                   'land_area_m2']]

landuse.head()
```

Table A5. Sample of renaming.

	land_id	landuse_type	building_type	detailed_use	land_area_m2
0	0	Residential	Villa	الفلل والشقق	779.494
1	1	Residential	Villa	Villa/Apt	651.353
2	3	Residential	Villa	Villa/Apt	643.559
3	4	Residential	Villa	Villa/Apt	1130.485
4	5	Residential	Villa	Villa/Apt	1052.932

Appendix A.6. Data Preperation, Step 4: List Unique Landuse Codes and Building Types (Source of Tables 1 and 2)

```
list(landuse.landuse_type.unique())
['Residential',
  'Mosques',
  'Business Services',
  'Commercial',
  'Vacant Land',
  'Unknown',
  'Amusements & Parks',
  'Edu. Services',
  'Health Services',
  'Transport Services',
  'Storage & Warehouse',
  'Gov. Services',
  'ICT & Public Services',
  'Social and Cultural',
  'Industrial',
  'Agricultural',
  'Grave Yards']

list(landuse.building_type.unique())
['Villa',
  'Urban building',
  'Apartment Building',
  'Mixed use (in a multistory building)',
```

```
  'Commercial/Retail Building',
  'Mansion',
  'Other',
  'Complex/ Unknown Building Type',
  'Vacant land',
  'Tent or cottage',
  'Public Service',
  'Mixed use (not in a multistory building)',
  'Commercial center',
  'Traditional Arabic house',
  'Office building',
  'Warehouse',
  'Factory',
  'Market']
```

Appendix A.7. Data Preperation, Step 5: Filter out All Parcels Which Are Flaggd with Empty Buildings, i.e., Vacant

```
landuse = landuse[landuse.building_type.str.upper()!='Vacant land'.upper()]
```

Appendix A.8. Data Preperation, Step 6: Constraint the Data to Include Only Parcels with Landuse_code Tagged as Residential, Mosques, Commercial, and Health Services

```
landuse = landuse[landuse.landuse_type.isin(['Residential','Mosques','Commercial',
'Health Services'])]
```

Appendix A.9. Aggregate the Data Based on Landuse Codes

```
agg = {'land_id': ['count'],
      'land_area_m2':['sum', 'mean'],
      }
totals = landuse.groupby(['landuse_type']).agg(agg)
totals.columns = ["total_"+"_".join(col) for col in totals.columns.values]
totals.sort_values(["landuse_type", "total_land_area_m2_sum"], ascending=[False,
False], inplace=True)
totals
```

Table A6. Aggregation of data.

	total_land_id_count	total_land_area_m2_sum	total_land_area_m2_mean
landuse_type			
Residential	382,472	272,387,977.486	712.178
Mosques	4452	9,675,650.631	2173.327
Health Services	826	7,222,285.302	8743.687
Commercial	9441	22,961,228.784	2432.076

Appendix A.10. Aggregate the Data Based on Landuse Codes and Building Types

```
agg = {'land_id': ['count'],
      'land_area_m2':['sum', 'mean']
      }
grouped_LU = landuse.groupby(['landuse_type','building_type']).agg(agg)
grouped_LU.columns = ["_".join(col) for col in grouped_LU.columns.values]
grouped_LU.reset_index(inplace=True)
```

```
grouped_LU.sort_values(["landuse_type","land_area_m2_sum"], ascending=[False, False],
inplace=True)
```

Through "grouped_LU" data frame, we can compute the total land area occupied by the residential sector in Riyadh, particularly by: Villas, mansions and apartment buildings.

```
res_LU = grouped_LU[grouped_LU.landuse_type=="Residential"]
res_LU = res_LU[res_LU.building_type.isin(['Villa','Mansion','Apartment Building'])]
res_LU
```

Table A7. Further aggregation of data.

	landuse_type	building_type	land_id_count	land_area_m2_sum	land_area_m2_mean
38	Residential	Villa	276,862	171,626,280.502	619.898
40	Residential	Apartment Building	38,009	22,689,745.934	596.957
39	Residential	Mansion	1688	17,557,757.849	10,401.515

Appendix A.11. Aggregate the Data Based on Landuse Codes and Detailed Use Code

```
agg = {'land_id': ['count'],
      'land_area_m2':['sum', 'mean'],
      }
grouped_dUse = landuse.groupby(['landuse_type', 'detailed_use']).agg(agg)
grouped_dUse.columns = ["_".join(col) for col in grouped_dUse.columns.values]
grouped_dUse.reset_index(inplace=True)
grouped_dUse.sort_values(['landuse_type', "land_area_m2_sum"], ascending=[False,
False], inplace=True)
```

Through "grouped_dUse" dataframe, we can arrive at the total land area used for mosques in Riyadh.

```
mos_LU = grouped_dUse[grouped_dUse.landuse_type=="Mosques"]
mos_LU = mos_LU[mos_LU.detailed_use.isin([
'مساجد جمعة','مساجد صغيرة بالأحياء (مساجد محلية)'])]
mos_LU
```

Table A8. Further aggregation of data.

	landuse_type	detailed_use	land_id_count	land_area_m2_sum	land_area_m2_mean
122	Mosques	مساجد صغيرة بالأحياء (مساجد محلية)	3255	5,811,737.911	1785.480
121	Mosques	مساجد جمعة	1089	3,237,236.049	2972.669

Note that in the above code and table related to the mosque category: the Arabic wording refers to "small local mosques in neighborhoods" and "large Friday prayer mosques". Similarly, total land area for malls (i.e., commercial buildings) and health services facilities, such as clinics and private/public hospitals can be calculated.

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