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Rooftop PV Potential in the Residential Sector of the Kingdom of Saudi Arabia

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Abstract: The Kingdom of Saudi Arabia (KSA) has a fast growing building sector driven by factors like burgeoning population, economic and infrastructure development and modernization. Buildings, owing to their energy intensive operation, are imposing significant energy, environmental and economic burdens for the country. To overcome these challenges and improve the sustainability levels in the building and energy sectors, it has been decided to develop 9500 MWs of renewable energy projects by 2023. Given the annual solar radiation level of over 2200 kWh/m^2, solar energy is expected to play the predominant role in achieving this target. Traditionally, KSA's emphasis has been to pursue large-scale energy projects. Globally, however, small scale and building related projects have significantly contributed to the rapid growth of solar energy. Application of solar technologies in buildings is one of the important areas that has been ignored in the country. This paper explores the potential for rooftop solar photovoltaic (PV) in KSA's residential sector. Taking into account appropriate PV design considerations and local building construction and cultural practices, it calculates the power generation potential for 13 major cities. It is found that a total of 51 TWh of electricity can be annually generated from these cities, accounting for 30% of the total domestic demand. Findings of a case study on application of the PV system on 248,452 m^2 of rooftop area of the residential buildings in the King Fahd University of Petroleum and Minerals undertaken with the help of ArcGIS 10.2 and PVsyst modeling have also been provided.

Keywords: buildings; sustainability; solar energy; residential sector; rooftop PV; Saudi Arabia

1. Introduction

Renewable energy is playing an ever important role in meeting energy requirements across the world. It exhibits favourable credentials like an abundant and widely available resource base, inexhaustibility and environmental friendliness contributing to its fast growth over the last two decades. Factors like technological advancements, conducive policies and economy of scale have also helped the rapid uptake of renewable energy. The annual capacity addition of renewable energy is reported to have exceeded that of combined oil, gas and coal. In 2015, renewable technologies attracted $286 billion in new investment and contributed to more than 23% of the worldwide power generation in the year. According to the International Energy Agency, renewable energy is now making a bigger contribution to global power generation mix compared to coal [1]. Solar photovoltaic (PV) is one of the most promising renewable technologies. With a capacity addition of 50 GW in 2015, its aggregate global capacity reached 227 GW [2]. Records suggest that during the year around half a million of solar panels were installed every day [3]. Statistics suggest that 22 countries are having over 1% of their total power requirements met by PV. Italy is the leading country in the world in terms of contribution of PV in total power generation with a share of 7.8%, followed by Greece and Germany with respective shares of 6.5% and 6.4% [4].

Small and building related applications have been an active part of recent PV developments across the world. The leading countries referred to above in the world in terms of installed capacity have benefited from building related utilization of the technology. Germany, for example, having pioneered the concept of feed-in-tariff in the early 1990s, has established a large base of small scale and building integrated PV power generation. The feed-in-tariff policy has been implemented across the world with countries like Spain, Italy, UK, the USA and Japan experiencing rapid growth in their PV markets. A government-backed feed-in-tariff policy for small-scale producers has already been implemented in more than 50 countries in the world [5]. In the developed world, other types of business models including micro-credit based mechanisms have helped PV make significant contributions.

Kingdom of Saudi Arabia (KSA) is the most prominent country in the Middle East in terms of population, economy and geographic outreach. Its rich oil and gas reserves, amongst the largest in the world, coupled with highly subsidized energy prices have contributed towards making the Saudi society energy intensive. Since the 1950s, the country has experienced a complete transformation from a Bedouin to a modern lifestyle driven by massive economic and infrastructure development, as can be seen in the form of rapid growth in the building sector [6,7]. The KSA building sector consumes about 80% of the total national electricity. Domestic buildings alone account for almost 51% of the national electricity use. It is reported that, compared to 2009, the power demand in the domestic sector is expected to double by 2025 [8–12]. With nearly 70% of the population being under 30 years of age, the annual demand for new homes is estimated to be 2.32 million by 2020 [13–15]. KSA is already one of the leading countries in the world in terms of per capita energy consumption and carbon dioxide (CO_2) emissions, and in a business as usual scenario, the fast growth in the building sector is set to substantially increase the energy and environmental burdens it faces [4]. The situation demands a paradigm shift in the energy consumption practices and trends in buildings.

Saudi Arabia is keen to reduce its dependence on oil and gas based energy sector by diversifying the supply mix. Renewable energy is an attractive option and the country has aimed to develop 9500 MW of renewable energy projects by 2023 [16]. Solar energy is the main renewable resource the country can tap and hence is projected to be the main contributor towards meeting the set target. There have been a few solar energy initiatives in the country in the past; however, the focus has been on large scale projects overlooking small scale and building integrated applications. The use of PV systems in the building sector, especially in residential buildings, needs to be taken on board.

Understanding the available potential is key to formulating appropriate policy framework for any considerable nationwide program to promote PV systems in buildings. This study aims to investigate the prospects of PV systems in the residential sector of KSA focusing on the building rooftop areas. The key objectives of the work are as follows:

- Establish the importance of PV application in the building sector of KSA;
- Calculate the total rooftop areas in the residential sector;
- Estimate the net area utilizable for PV application taking into account obstructive structural and utilities related features such as balustrade walls, heat ventilation and air-conditioning (HVAC) systems, water tanks, sky light openings, satellite dish antennas, staircases and vents for plumbing or mechanical installations;
- Determine the power generation potential from rooftop PV application.

Based upon the latest census data on building stock and taking into account building typology, building rooftop areas in all of the 13 administrative areas in the country is estimated. The power generation potential is calculated for corrected rooftop areas taking into account local building construction and cultural practices. A case study of residential buildings in King Fahd University of

Petroleum and Minerals, Dhahran has also been undertaken with the help of ArcGIS 10.2 and PVsyst software tools to validate the findings of the estimates at the national level.

2. PV Initiatives in KSA

The geographic location of Saudi Arabia is well placed for capitalizing solar energy with the average daily solar radiation level reaching 6 kWh/m^2 and 80–90% of clear sky days over the year [17]. The annual solar radiation level reaches over 2400 kWh/m^2 as shown in Figure 1 [18]. Despite such a rich potential and having initiated a sizeable solar village electrification project as early as 1981, the country is yet to make a meaningful utilization of solar energy. Under the *Vision 2030*, however, solar energy is being planned to contribute the most of the 9.5 GW renewables target.

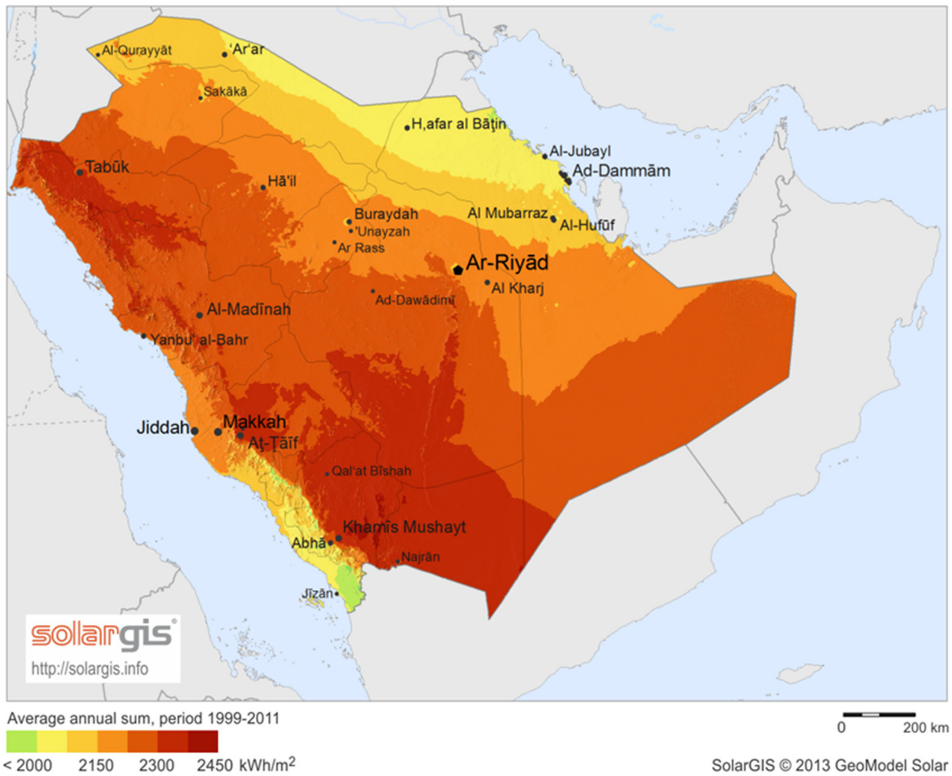


Figure 1. Global horizontal irradiation map of Saudi Arabia.

Over the last few years, KSA has set up a number of government departments and institutions to promote solar energy, the most important of which is the King Abdullah City for Atomic and Renewable Energy (KACARE) established in 2010. Agreement has also been signed with SunEdison to establish a $6 billion PV manufacturing facility in Saudi Arabia [19]. An overview of the solar energy projects developed in the Kingdom is provided in Table 1 [20,21], The focus of initiatives has mainly been on large scale projects. It can also be observed that the developed projects are isolated initiatives rather than being part of a coordinated program. A number of other projects currently under development are also of multi-MW scale.

Table 1. Overview of solar energy projects in Saudi Arabia.

Project	Capacity	Commencement Date
King Abdulaziz International Airport Development Project	5.4 MW	2013
KAPSARC Project	3.5 MW	2013
Saudi Aramco Solar car Park	10.5 MW	2012
Princess Noura Bint Abdul Rahman University	25 MWt	2012
King Abdullah Financial District Project	200 kW	2012
KAUST Solar Park	2 MW	2010
PV Hydrogen Project	350 kW	1993
Solar Village	350 kW	1981

King Abdullah Petroleum Studies and Research Center (KAPSARC), King Abdullah University of Science & Technology (KAUST).

3. Calculations of Rooftop Area

3.1. Survey Values

The rooftop area for PV application has been calculated with the help of the latest data available on residential buildings through the 2010–2014 Housing Census [22]. The housing census database gives the number/type of housing units in each administrative area as shown in Table 2.

Table 2. Housing Units occupied with households by Administrative Areas, 2010 and demand forecast by 2014.

Region	Apartment	Villa	Traditional House	Other	Demand Forecast 2014
Al-Riyadh	434,533	299,243	132,819	117,744	325,000
Makkah Al- Mukarramah	719,305	100,888	399,322	41,758	370,000
Al-Madinah Al-Monawarah	158,064	26,149	98,570	13,417	81,200
Al-Qaseem	43,925	59,410	51,752	19,448	51,000
Eastern Region	287,402	161,911	103,175	22,413	166,300
Aseer	88,530	58,526	130,800	17,611	83,100
Tabouk	61,762	15,112	38,314	5813	38,900
Hail	13,380	24,404	44,205	5468	20,500
Northern Borders	9810	14,381	8598	2580	11,500
Jazan	26,793	19,902	133,679	8612	50,100
Najran	23,776	12,308	33,234	8090	21,600
Al-Baha	23,298	8943	28,998	3731	17,300
Al-Jouf	20,670	23,328	15,364	4926	13,500
Sum	**1,911,248**	**824,505**	**1,218,830**	**271,611**	**1,250,000**

The above given census is now outdated due to procedural actions taken by the Ministry of Economy and Planning. According to the approved Ninth Development Plan (2010–2014) [23] and the 5-year action plan to accommodate the growing population [24], the government has taken a few precautionary steps to provide housing to its citizens forecasting the demand. The considerations taken into account are crucial to make the base assumptions in calculating the total roof area of different administrative areas. The demand forecast took into consideration the following assumptions, which, in our case study, will be helpful to concatenate the values given in Table 2 for the year 2014.

- The annual growth rate of Saudi population is 2.23%, which require about 800,000 housing units by the end of 2014.
- The growth rate of non-Saudi population is at 1.86%, which require about 200,000 housing units.
- Meeting the unsatisfied cumulative demands of Eight Development Plan, replacing dilapidated housing, and covering a research housing stock (10% of demand) will require about additional 250,000 housing units by the end of 2014.

The above assumptions add another 1.25 million housing units as shown in Table 2 in order to find estimated housing units by administrative area by the end of 2014. Accordingly, the demand forecast value of 1.25 million was calculated and distributed among the administrative areas according to the representative population percentage of that administrative area. With the population growth rate of 2.23%, an estimated additional 850,000 units are required by the end of 2016.

A simple cross-check calculation can be done to validate the estimations made above: the population of Saudi Arabia (28.8 million) can be divided into the number of housing units, which gives us the household size. The housing crowd for the above made estimate is 5.7, which agrees well with the Ninth Development Plan.

The actual size of housing units is very difficult to know. According to the Ninth Development Plan (Ministry of Economy and Planning), a total of 350 million square meters of land is required to build the estimated 1.25 million housing units, assuming the average total area required for each housing unit to be 280 square meters. It is difficult to know the actual size of the housing units as per categories, but an excerpt from the Study of the National Housing Strategy in the Kingdom of Saudi Arabia, 2012 gives us a brief estimate as in Table 3 [25], which shows the range of floor area distribution of living space of each type of housing unit.

Table 3. Distribution of living space by floor area.

Floor Area (m^2)	Mean (m^2)	Apartment	Villa	Traditional House
Less than 50	25	3%	0%	6%
50–99	74.5	32%	3%	41%
100–149	124.5	39%	7%	29%
150–199	174.5	16%	13%	13%
200–249	224.5	7%	22%	10%
250–299	274.5	3%	18%	1%
300–349	324.5	0%	16%	0%
More than 350	400	0%	21%	0%
Total	-	100%	100%	100%

The housing unit type "others" constitutes about 5% of the total number of housing units. This space can be assumed having an average of 192 square meters of area per housing unit according to the study done previously. Hence, an additional 52 million square meters of area can be added to the total roof area. Similarly, we add the *demand forecast* total area, which is fixed at 280 square meters of area per housing unit as per the Ninth Development Plan.

Each *traditional housing unit* is usually comprised of a ground floor, but a villa or apartment has several floors. Hence, the number of housing units, especially villa and apartment, need not project the total usable roof area. This correction of reducing the number of housing units under one building is to be made before proceeding further.

According to the Housing Census of 2010 database, the number of housing units for each floor in a villa is almost half the value of the number of villas in a particular administrative area. For example, in the Riyadh region, if the number of villas are 299,243, then a floor in a villa consists of 159,612 housing units. Hence, we assume that each villa consists of an average of two floors (also seen in Figure 2). Similarly, for the apartment housing units, it is a norm in Saudi Arabia to build a three floor building unit with four to six housing units on each floor [26,27]. A large housing unit like 175 m^2 (and 225 m^2) of area reduces the total usable roof space drastically, which is half in this case. Similarly, a smaller living space of 125 m^2 and 75 m^2 per housing unit, the total usable roof area is reduced to one fourth. Hence, the number of housing units for all areas with usable roof areas, can be recalculated as in *Corrected Area* row Table 4. Thus, the ratio between the new corrected area to the original area are found to be 2.55 and 2 for apartment and villa type housing, respectively; while traditional house area is unchanged.

Table 4. Total floor area of each housing type as per the living space for each administrative area.

Region	Apartment (m^2)	Villa (m^2)	Traditional House (m^2)	Demand Forecast (m^2)
Al-Riyadh	54,323,143	80,303,355	15,410,989	91,000,000
Makkah Al-Mukarramah	89,923,914	27,073,799	46,333,332	103,600,000
Al-Madinah Al-Monawarah	19,760,370	7,017,215	11,437,077	22,736,000
Al-Qaseem	5,491,283	15,942,971	6,004,785	14,280,000
Eastern Region	35,929,56	43,449,626	11,971,395	46,564,000
Aseer	11,067,577	15,705,745	15,176,724	23,268,000
Tabouk	7,721,176	4,055,381	4,445,573	10,892,000
Hail	1,672,700	6,548,935	5,129,106	5,740,000
Northern Borders	1,226,397	3,859,213	997,626	3,220,000
Jazan	3,349,526	5,340,801	15,510,774	14,028,000
Najran	2,972,356	3,302,913	3,856,141	6,048,000
Al-Baha	2,912,599	2,399,899	3,364,638	4,844,000
Al-Jouf	2,584,060	6,260,185	1,782,685	3,780,000
Sum	**238,934,668**	**221,260,039**	**141,420,845**	**350,000,000**
Corrected Area	**93,462,416**	**110,630,020**	**141,420,845**	**350,000,000**

It is therefore estimated that the total area to study the feasibility of rooftop PV potential in residential buildings in Saudi Arabia is about 750 million square meters. However, this value is not the effective rooftop area. Shadows due to rooftop constructions, balustrades, satellite dishes, patio covers, etc. should be considered along with the cultural aspects to find the final real usable area for PV installation.

3.2. Assumptions

The Kingdom of Saudi Arabia has a rapidly changing cross-cultural society experiencing the new technological era and a huge influx of expatriate labor. Although courtyard houses have been considered wide spread among the middle-eastern culture, the last few decades have seen major changes in the building sector. Now, cities are mainly divided into two types of constructions; commercial and residential. The residential settlements are further divided into various housing types as mentioned in the previous section i.e., traditional houses, villas and apartments. Traditional houses and villas are mostly Saudi national inhabited. Thirty percent of the Saudi population owns traditional houses, whereas apartments are usually accommodating expat populations [24]. In our case study, we approach the constructional considerations concerning traditional houses, villas and apartments separately, due to the uniqueness of the architecture and inhabitants. Following are the observations considered in further calculation of usable rooftop area in residential buildings in the Kingdom of Saudi Arabia:

- **Balustrades**: Balustrade height varies with the type of buildings. Traditional houses usually do not have roof access, hence a very negligible balustrade height is observed. People living in villas, on the other hand, are more concerned with their privacy. Hence, they construct a balustrade of at least six feet (1.8 m), occasionally adding on it with high houses in close proximity. Apartments have roof access only for various utility and maintenance needs of multiple tenant families living in the building. Usually, these types of buildings have a balustrade height of 1 m.
- **Patio covers:** This type of construction is seen in villa houses only. Due to lack of data and unpredictable assumption basis, only a small safe amount of roof area is assumed. Nonetheless, the patio covers can also be used as potential usable areas.
- **Satellite dishes and water tanks:** All types of houses are fitted with satellite dishes and water tanks. These cover large proportions of roof areas in apartment buildings while having a relatively modest presence on villas and traditional houses roofs.
- **Air-conditioning units:** Window Air-conditioning systems that fit in the wall are traditionally used in the country for the ease of their installation. Apartments and traditional houses mainly have window units though the trend is fast shifting towards split systems that occupy some space

on walls or roof. Majority of villas use central air-conditioning systems that occupy a considerable roof space i.e., 4–6 m^2.

- **Building orientation:** Most of the assumptions vary in their value when building orientation is considered. The balustrade shadow can be considered on three sides of the roof of properly oriented buildings, or four sides of a non-oriented building construction. This assumption is very difficult to make due to unstructured planning in most of the cities. Using satellite images, this factor can be calculated to some extent. In the present study, a nominal three-sided shadow is considered.
- **Commercial shadows:** City constructions are a mix of both residential and commercial buildings in many areas. Tall commercial towers easily overshadow neighboring apartments. Villas and traditional houses are usually away from commercial areas.
- **Staircase room:** Roof access to apartments and villas require an enclosed secure room above the staircase of the building. In general, they have a footprint of about 16–20 square meters.
- **Inter-panel distance:** In order to avoid overshadowing of PV panel rows, a considerable space between the rows has to be given. A typical PV panel of 1.65 m length inclined at 25° and the incident ray angle (sun altitude) of 30° casts a 1.25 m long shadow. A minimum of 1 m aisle width is needed for maintenance, cleaning and shadow protection.

Table 5 summarizes the applicability of potential parameters that affect the utilization of rooftop area for PV, also indicated in Figure 2.

Table 5. Assumptions applicable to housing types.

Assumption	Apartment	Villa	Tradition Houses
Balustrades	√	√	
Patio covers		√	
Satellite dishes & water tanks	√	√	√
Air conditioning units	√	√	
Inter-panel distance	√	√	√
Pent house	√		
Building orientation	√	√	√
Commercial shadow	√		
Staircase room	√	√	

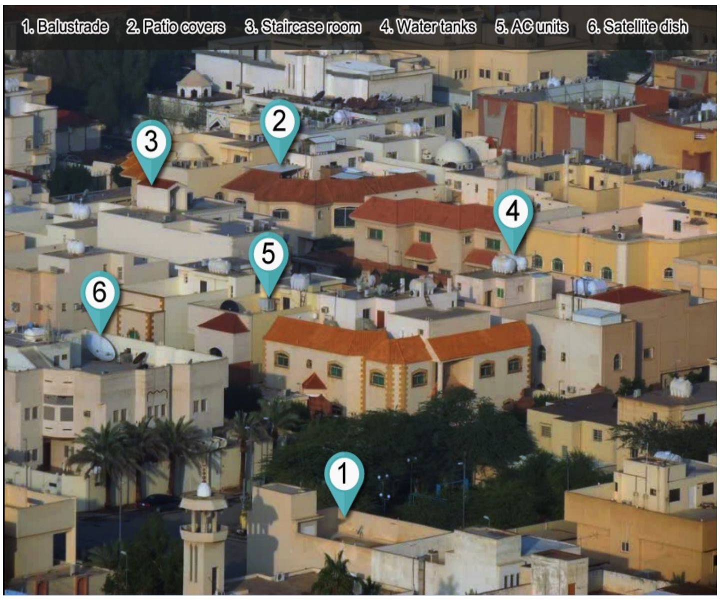


Figure 2. Typical residential villas in Saudi cities [28].

3.3. Usable Area Calculations

Balustrades are the foremost and obvious correction that has to be made in any PV usable rooftop area calculations. Balustrade shadow calculation is undertaken for villas and apartments at the lowest possible sun inclination of 30° (Figure 3).

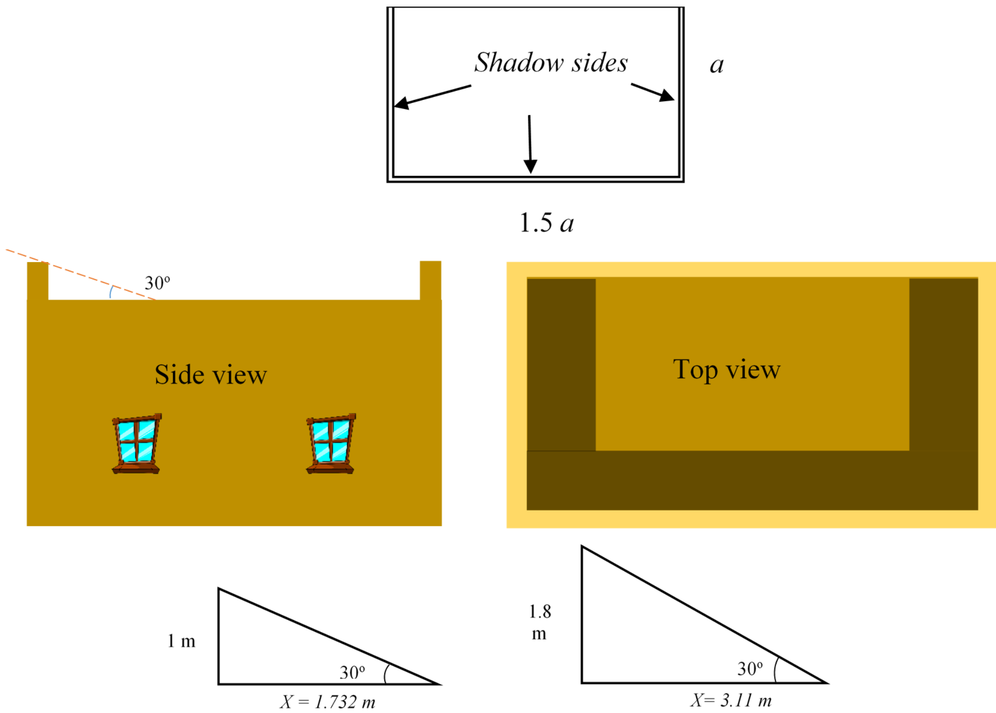


Figure 3. Shadow length (x) for apartment and villa balustrade height and length.

Assuming a rectangular shape of the building with length 1.5 times the width, using basic trignometry, the area of balustrade can be determined by the following equation:

$$\text{Area of balustrade shadow } = 3.11 \times 3.5\left(\sqrt{\frac{A}{1.5}}\right), \quad (1)$$

where 3.11 is the length of shadow casted with a balustrade height of 1.8 m (6 ft) at 30 degrees sun inclination. Therefore, the sum of total corrected villa roof areas (for all floor areas) considering the balustrade shadow is 27,603,566.41.

Similarly, the calculation of apartment housing units using Equation (1) with the balustrade shadow length of 1.732 m for 1 m height of balustrade results in the total usable apartment roof area. A dividend of 2.55 was used in this case for the number of housing units as discussed in Section 3.1. A 56.6% of total apartment roof area is calculated as usable:

$$\text{Area of balustrade shadow for apartments} : 1.732 \times 3.5\left(\sqrt{\frac{A}{1.5}}\right). \quad (2)$$

Similarly, for a balustrade height of 0.5 m, in the case of traditional houses, the shadow can be calculated as follows:

$$\text{Area of balustrade shadow for apartments} : 0.86 \times 3.5 \times \left(\sqrt{\frac{A}{1.5}}\right). \quad (3)$$

A reduction of 43% and 75% from the total roof area was observed for apartment and villa housings, respectively. Similarly, a reduction of 22% of usable area in traditional housing was observed.

Satellite dish antennas and water tanks are two essential features of building rooftops while a significant proportion of buildings roofs also contain AC units. A typical satellite dish antenna measures around 1 m in diameter (0.8 m^2) making a shadow of about 0.9 m^2; and a typical water tank of 2 × 1.5 × 1 m dimension casts a shadow of about 5 m^2. Hence, an area of 17 m^2 should be deducted from the apartment, 6 m^2 for both villa and traditional houses' roof areas. Table 6 enlists the new calculated total usable areas. Balustrade correction for forecasted and others type of housing units is assumed to be 47% (the average of all other housing type reductions due to balustrade shadow). Similarly, 10 m^2 and 6 m^2 of shadow are assumed for each forecasted and other types of housing units.

Air-conditioning systems are a part of every housing unit in Saudi Arabia. Estimating the use of Split AC units is very difficult due to the dynamics of household choices, hence, a meticulous estimate is necessary for each type of housing unit. In addition, six, three, one and two AC units for each apartment, villa, traditional and forecasted houses, respectively, are assumed with an effective usable area reduction of 1%.

One additional construction on the roof is the *staircase room*. As per the architectural design, this room is in the middle of the building. The room has its own roof which little affects the total roof area, but the shadow created by its 9 ft high walls of about 4 m in length each, cast a shadow area of about 20 m^2, which is a significant value. A consistent building orientation would help us in more precisely calculating this value. Assuming a shadow on all three sides of the staircase room, we calculate the total usable area in villas to be 13,174,728.91 m^2, a 48.5% reduction of area. Similarly, an area reduction of 17% is seen in apartment roofs.

Although apartment PV installation cannot cater to all of the power demand of the building in such a small roof area, a few PV panels can support at least 10% of the building's household electricity requirements [27] including services like external lightings, water pumps, etc. (Figure 4).

Figure 4. Satellite image of residential area with apartment buildings, Al-Khobar city, Eastern Region.

Inter-row gap is set to avoid PV panels casting a shadow on the hind rows. Each panel takes a footprint area of 1.5 m^2 and another 1.25 m^2 as inter-row gap. In order to calculate the exact number of rows, precise dimension, orientation and building type is needed. Nonetheless, a good estimate of the dimensions can predict the possible number of rows (not the number of panels) that can fit on the housing type. A typical apartment is sized at 20 m × 12 m (240 m^2), whereas a villa or traditional house size vary largely. If the building is well oriented, maximum roof area can be utilized; otherwise, only 75% of the roof area is usable. For our calculation, let us consider that most of the houses are not oriented, assuming a 75% of the total usable area. This assumption can also be taken for villa and traditional housing units due to lack of data. Hence, the final cumulative usable roof area for the residential buildings in Saudi Arabia can be listed as in Table 6. PV panel inclination angle adjustments according to the country's geographical location can reduce the usable area to another 5%.

Table 6. Net usable roof area by administrative area and housing unit type.

Region	Apartments (m^2)	Villas (m^2)	Traditional Houses (m^2)	Others (m^2)	Demand Forecast 2014 (m^2)	Sum (m^2)
Al-Riyadh	2,538,551	3,406,883	7,886,086	8,033,555	31,585,125	50,911,650
Makkah Al- Mukarramah	4,202,194	1,148,610	23,709,617	2,849,107	35,958,450	63,665,784
Al-Madinah Al-Monawarah	923,413	297,707	5,852,562	915,428	7,891,422	14,957,120
Al-Qaseem	256,611	676,383	3,072,759	1,326,918	4,956,435	10,032,494
Eastern Region	1,679,008	1,843,358	6,125,983	1,529,217	16,161,866	25,660,423
Aseer	517,194	666,319	7,766,209	1,201,581	8,076,074	17,710,182
Tabouk	360,815	172,050	2,274,882	396,615	3,780,497	6,624,043
Hail	78,166	277,840	2,624,658	373,076	1,992,293	5,267,866
Northern Borders	57,310	163,728	510,504	176,031	1,117,628	1,967,890
Jazan	156,525	226,584	7,937,148	587,588	4,868,969	13,620,289
Najran	138,900	140,127	1,973,258	551,973	2,099,196	4,764,553
Al-Baha	136,107	101,816	1,721,747	254,562	1,681,301	3,759,426
Al-Jouf	120,755	265,589	912,233	336,096	1,311,998	2,825,916
Sum	11,165,550	9,386,994	72,367,645	18,531,747	121,481,250	221,767,636

4. PV Potential of Residential Buildings

Saudi Arabia's annual electricity consumption (2014) was 272 TWh, of which 136 TWh was consumed by the residential sector [15,29]. Calculating the potential of residential sector in clean energy production is both wise and important as Saudi Arabia is playing its role in reducing CO_2 emission and developing more environmentally friendly policies.

Distributing the total usable area from among nationwide regions with respect to each city, we get a final usable roof area for each city.

The net area in Table 6 is divided by the cosine of panel inclination angle to calculate the net PV module area. Assuming a modest market module efficiency of 15%, which is equivalent to specific capacity of 150 W/m^2, the building capacity of residential sector (38 TW) can be calculated as shown in Table 7.

Table 7. Buildings installable capacity in kW.

Region	Apartments (kW)	Villas (kW)	Traditional Houses (kW)	Others (kW)	Demand Forecast 2014 (kW)	Sum (kW)
Al-Riyadh	416,779	559,342	1,294,737	1,318,948	5,185,643	8,775,450
Makkah Al- Mukarramah	679,778	185,808	3,835,445	460,893	5,816,908	10,978,833
Al-Madinah Al-Monawarah	152,815	49,267	968,538	151,494	1,305,948	2,628,063
Al-Qaseem	42,466	111,934	508,510	219,591	820,239	1,702,740
Eastern Region	277,858	305,057	1,013,787	253,070	2,674,621	4,524,392
Aseer	82,553	106,355	1,239,614	191,792	1,289,074	2,909,388
Tabouk	60,735	28,961	382,927	66,762	636,365	1,175,750
Hail	13,044	46,364	437,981	62,256	332,457	892,101
Northern Borders	9735	27,811	86,716	29,901	189,844	344,007
Jazan	24,686	35,735	1,251,777	92,669	767,891	2,172,758
Najran	22,171	22,367	314,964	88,104	335,066	782,672
Al-Baha	21,591	16,151	273,127	40,382	266,711	617,964
Al-Jouf	20,512	45,114	154,955	57,090	222,860	500,531
Sum						**38,004,648**

The power produced by the PV panels is not only dependent upon its efficiency and input annual irradiation per surface area, but also other factors like dust, shadows, clouds and malfunction. Hence, the annual power generation of any region can be calculated, including losses, as [25]:

$$W_g = A \cdot I_R \cdot \eta \cdot PR \cdot (1 - L), \quad (4)$$

where

W_g is Annual electric generation of the geographic location (W),
A is Area of module surface (m^2),
I_R is Irradiation of the geographic location (W/m^2),
η is PV panel efficiency (%),
PR is performance ratio (%),
L is losses (%).

The annual irradiation data for major cities is provided in Table 9. The performance ratio (PR) 0.84 is considered for pleasant climatic conditions, however, considering the harsh weather of Saudi Arabia signified by high temperatures, a figure of 0.75 is used in the study [30,31]. In Saudi Arabia, dust can be a factor affecting the performance of PV systems. An uncleaned PV panel for six months produces 50% less power; hence, regular cleaning on a monthly frequency is assumed and recommended [32]. A monthly 10% power reduction can be assumed based on literature with another 5% for shadows for few hours of a day [25]. The PV modules' specifications and losses considered for calculations are given in Table 8.

Table 8. Photovoltaic module and losses specifications.

No.	Item	Specification
1	PV Module	
	Type	Standard (crystalline silicon)
	Efficiency	15%
	Temperature Coefficient of Power	−0.47%/°C
	Cover	Glass
2	Array Type	Facing south with fixed tilt
3	Azimuth angle	180°
4	Losses	
	Soiling	10%
	Temperature	5–18%
	Inverter	4–15%
	Mismatch	2%
	Cable	2%
	Connections	1%
	Light-Induced Degradation	1.5%
	Nameplate Rating	1%
	Age	0%
	Availability	1%
	Shading & weak radiation	3–10%
	Total	**~35%**

A cumulative power generation capacity of residential buildings in these 13 regions of Saudi Arabia is therefore calculated to be 51 TWh per year (Table 9). The estimated power generation from different region is listed in Table 9. Figure 5 provides the net PV utilizable area, potential for PV capacity and subsequent power generation capacity from the studied 13 regions on a national thematic map.

Table 9. Potential electricity generation per region and building type.

Region	Solar Radiation (kWh/m^2)	Apartments (kW)	Villas (kW)	Traditional Houses (kW)	Others (kW)	Demand Forecast 2014 (kW)	Sum (kW)
Al-Riyadh	2193	549,540,445	737,515,221	1,707,164,131	1,739,087,926	6,837,484,715	11,570,792,438
Makkah Al- Mukarramah	2194	896,724,557	245,106,912	5,059,498,872	607,983,404	7,673,330,920	14,482,644,665
Al-Madinah Al-Monawarah	2326	213,713,299	68,900,855	1,354,508,039	211,865,263	1,826,378,693	3,675,366,147
Al-Qaseem	2337	59,670,522	157,281,358	714,517,821	308,552,203	1,152,534,623	2,392,556,526
Eastern Region	2043	341,308,407	374,717,441	1,245,288,585	310,858,922	3,285,380,851	5,557,554,206
Aseer	2459	122,051,908	157,243,714	1,832,737,094	283,559,465	1,905,861,714	4,301,453,895
Tabouk	2306	84,208,611	40,153,795	530,922,087	92,563,774	882,309,218	1,630,157,484
Hail	2438	19,120,051	67,961,964	642,013,070	91,257,477	487,331,357	1,307,683,919
Northern Borders	2061	12,063,203	34,463,166	107,456,173	37,052,829	235,249,926	426,285,298
Jazan	2213	32,846,015	47,547,557	1,665,572,138	123,302,501	1,021,729,607	2,890,997,818
Najran	2521	33,605,291	33,902,150	477,407,553	133,543,652	507,876,833	1,186,335,478
Al-Baha	2472	32,090,766	24,005,770	405,946,640	60,019,613	396,410,444	918,473,233
Al-Jouf	2165	26,700,368	58,724,890	201,705,578	74,314,827	290,098,380	651,544,044
Sum	-	**2,423,643,441**	**2,047,524,793**	**15,944,737,782**	**4,073,961,857**	**26,501,977,280**	**50,991,845,153**

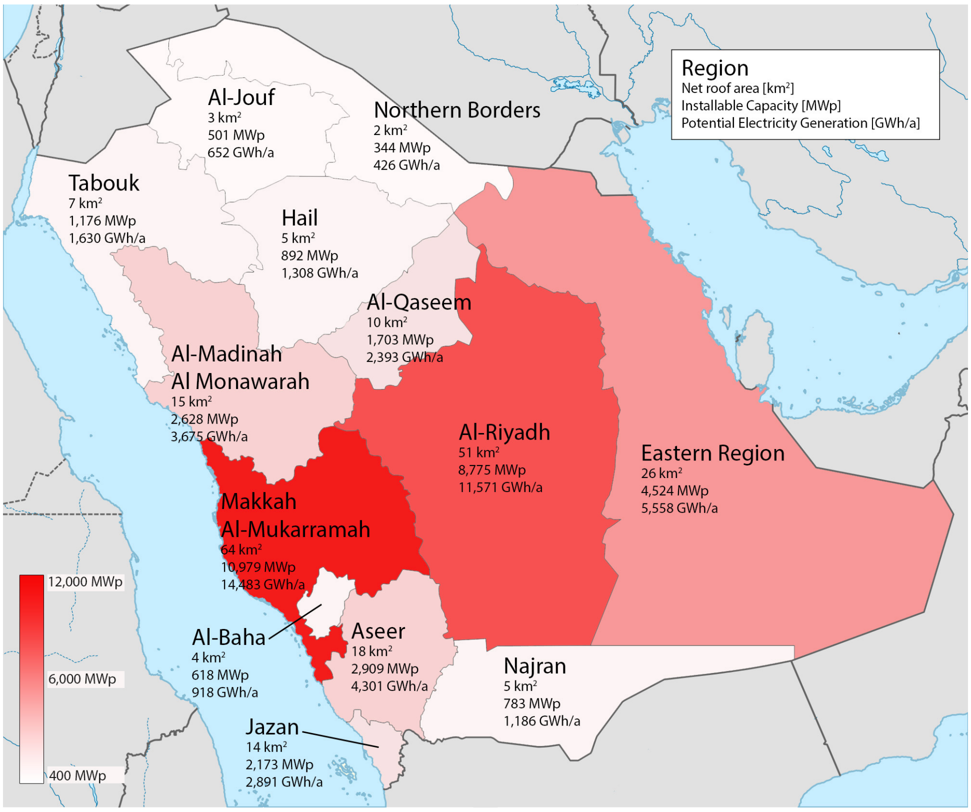


Figure 5. Thematic map of net roof area, installable Photovoltaic capacity, and electricity generation potential by region.

5. Case Study: KFUPM

The King Fahd University of Petroleum and Minerals (KFUPM) is one of the largest universities in the Kingdom of Saudi Arabia situated in the city of Dhahran in its Eastern Province. It is situated on 26°18′29″ North, and 50°9′1″ East, with a mean elevation of 62 m above sea level. Dhahran has annual solar radiation level of 2100 kWh/m^2. The KFUPM campus has been selected as the study area, as, due to its diverse building range including academic buildings, administration blocks, faculty and staff residences, student housing, community centers, schools, shopping centers, sport centers, medical clinic, restaurants, warehouses, workshops and multipurpose buildings, it resembles a town. Its residential buildings range from student housing and studio flats to as big as five bedroom villas.

In terms of construction, all KFUPM buildings have flat rooftops. The total roof area of buildings has been determined using ArcGIS 10.2 software. The roof area available for application of PV varies by type of buildings, depending upon their construction, architectural features and utilization. In the absence of balustrades, the utilization of the roof area for PV application is noted to be affected by HVAC systems (as buildings have central air handling units), satellite dish antennas and water tanks. Further taking into account the shadow avoidance and maintenance spacing between successive rows of PV panels inclined at 24°, the utilizable rooftop area has been calculated to be varying between 24% and 40% for the three main types of residential buildings: student housing, staff housing and faculty villas. From the total roof area of 248,452 m^2 after taking into account the obstructions, the net utilizable area has been calculated to be 73,293 m^2. The overall utilizable area for all residential buildings has thus been calculated to be 30%.

The power generation from the rooftop PV systems on the residential buildings, based upon the above calculated utilizable area, has been calculated using PVsyst software. PVsyst is a specialized photovoltaic system design and simulation software extensively used by the PV industry. In this study, a grid-connected PV system is designed with the help of mandatory input parameters including the site coordinates (26.28° N and 50.21° E), local weather data, orientation (south) and inclination (24°), system sizing and detailed losses. Optional input perimeters including the far and near shading definitions, and module layout have also been considered. The PV modules selected from the software library are 250 Wp mono crystalline with dimensions 1.65 m by 1 m and 60 cells. The capacity of the PV system is specified according to the available roof area taking into account the selected modules. Other components including inverters are also selected from the software library. The software then proposes a system configuration and allows for conducting simulation, generating a set of outputs. Findings of the PV modeling reveal a performance ratio in the range of 75–84% as shown in Figure 6. The power output from PV systems and the involved losses for a block of residential buildings with PV utilizable area of 31,236 m^2 have been presented in Figure 7. The total rooftop area for the three types of residential units in KFUPM with respective installable capacity of PV and power output have been shown in Figure 8. The overall performance of the PV systems for the entire residential buildings in KFUPM have been provided in Table 10.

Table 10. Overview of the PV systems on residential buildings.

Parameter	Value
Total roof area (m^2)	248,452
Roof area utilizable for PV (%)	30
Total area of PV panels (m^2)	73,293
Energy produced (MWh)	15,604
Reduction in Emissions (Metric tons CO_2e)	12,764

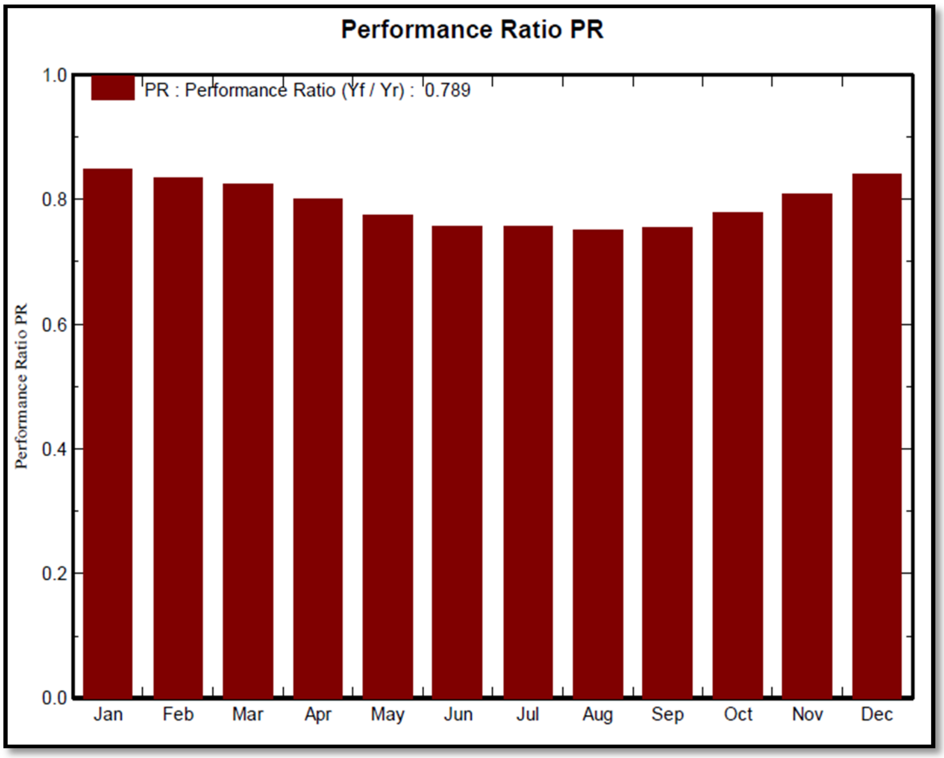


Figure 6. Typical performance ratio of PV panels.

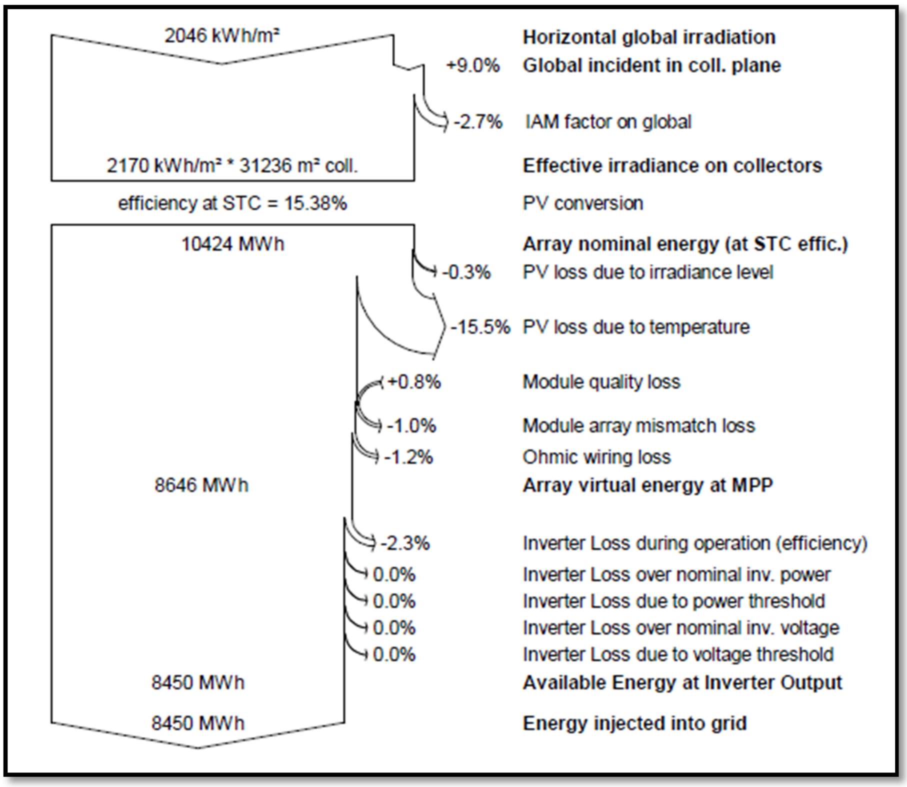


Figure 7. Power generation and losses diagram for a block of residential buildings.

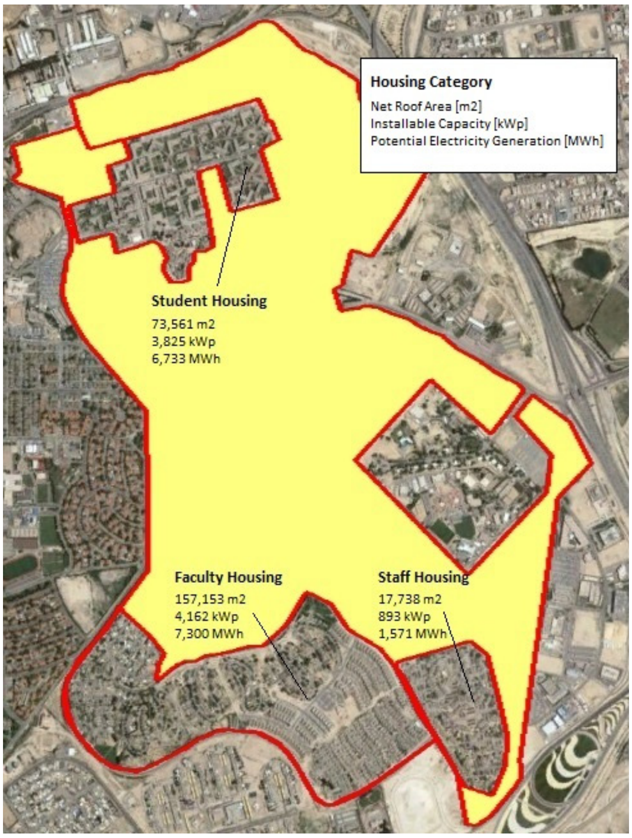


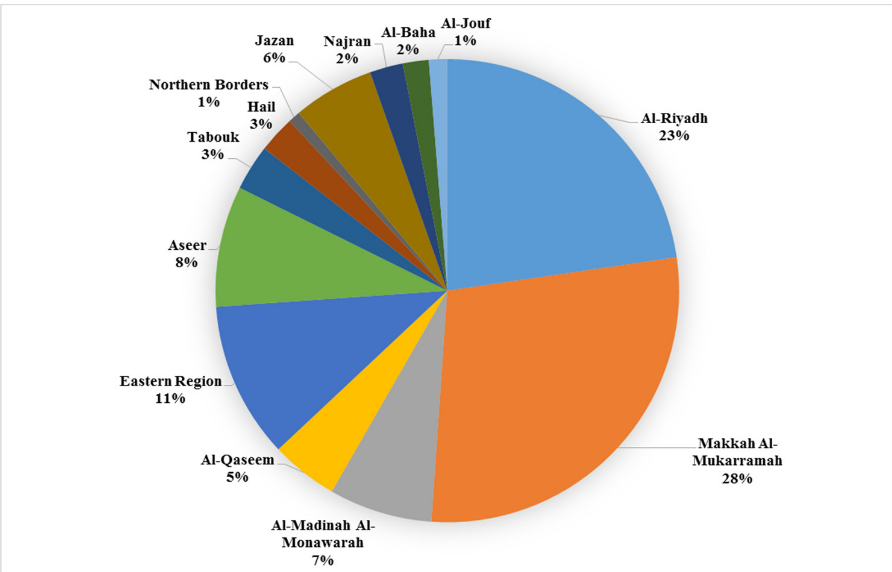
Figure 8. Estimation of rooftop area and PV output from the three types of residences in KFUPM.

It can be seen that PV systems installed on the residential building rooftops in KFUPM can annually produce 15,604 MWh of electricity, resulting in 12,764 Metric tons CO_2e of savings.

6. Results and Discussion

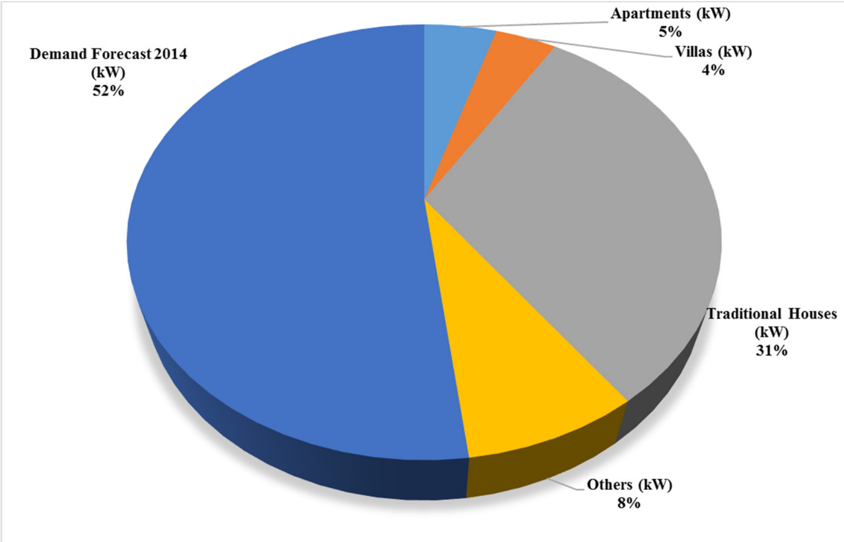
Residential buildings make up a substantial proportion of the total building stock in KSA. Between 1990 and 2010, for example, more than 90% of the total new building licenses have been in the residential sector [11]. Solar energy is the most promising form of renewable energy the country can tap to help address the sustainability challenges its building and energy sectors are facing. Solar PV is being deemed as an important technology to help meet the 9.5 GW renewable energy targets the country has set. The work estimates the rooftop PV power generation potential in the residential sector of KSA covering the 13 main administrative regions. While making the available rooftop area estimation, the typology of buildings and their respective construction features influencing the utilizability of PV have been taken into account. The total PV power generation capacity from residential buildings at the national level has been calculated to be 51 TWh. Figure 9a illustrates the percentage of contribution that a region can make in total residential power generation capacity of the Kingdom. It can be seen that 62% of the total capacity is from three regions only: Al-Riyadh (23%), Makkah Al-Mukarramah (28%) and the Eastern Region (11%). Traditional housing units contribute about 65% of power generation among all of the regions and constitute on average 55% in the top three regions (without considering Demand Forecast), as shown in Figure 9b. Makkah Al-Mukarramah has the highest capacity of power generation, partly due to the highest number of traditional houses (74%) as well as apartments (13%) among all of the regions, as reflected in Figure 9c.

The residential PV power generation capacity of Saudi Arabia can contribute to 30% of total residential electricity demand (2014 census). The top five regions alone can cater to more than 23.4% of total residential electricity demand. Rooftop features affecting the application of PV such as water tank, satellite dishes and split AC units can be re-arranged in the shaded region on the roof to maximize the availability of space. Balustrade walls with a typical height of 6–7 feet also impact the application of PV on roofs; and a decrease in their height can increase the penetration of sunlight. This can be managed without compromising on privacy since modified array arrangement would serve the purpose.

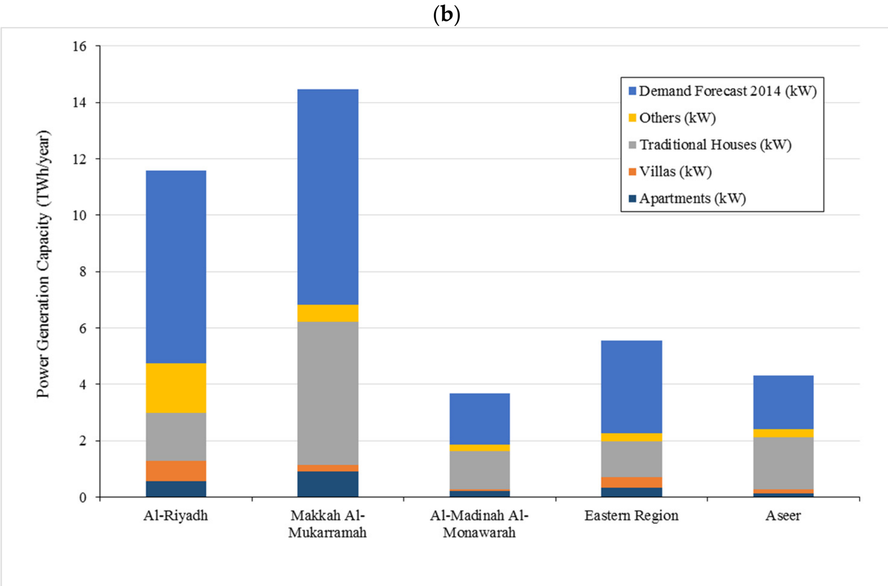


(a)

Figure 9. *Cont.*



(**b**)



(**c**)

Figure 9. Power generation capability (**a**) in all the regions; (**b**) by building type; and (**c**) by building type in top cities.

The present work realizes that there are issues with availability of precise and updated data on building sector. Information like building orientation, city planning, permits for new constructions and types of HVAC systems can help make more precise estimates, especially in calculating the balustrade shadows. It is therefore important that updated information be recorded, and made available online, with the local municipality on the type of approved constructions and modifications.

The findings of the case study on KFUPM in terms of estimation of PV utilizable area and subsequent power generation are in close proximity with the estimates at the national level. The PV utilizable area in KFUPM and at the national level is 30% and 31.8%, respectively. The PV power generation at the national level estimated with the help of standard equations 230 kW/m^2 or kWh/m^2, while the PVsyst based modeling reveals a figure of 212.9 kW/m^2 for KFUPM housing. This value is about 10% of average solar irradiation (1800–2200 kW/m^2) received by the country. It also suggests that the average PV module efficiency is about 10% in the hot climate of Saudi Arabia as investigated by Benghanem et al [33].

The buildings related application has made a major contribution to the fast growth of PV technology in recent years. The leading countries in the world with PV installed capacity such as Germany, USA, Japan, Italy and Spain have all seen a significant contribution coming from the building sector. Germany, for example, has 15% of its total PV power generation contributed by the domestic sector [34]. The application of PV in buildings is attracting new avenues and ventures across the world. Tesla has stepped into the solar energy business by offering solar PV tiles for buildings making the application aesthetically pleasing [35]. The strong penetration of PV in buildings has been propelled by supportive policies and initiatives such as net metering, feed-in-tariff, and renewable obligation certificate. The effectiveness of these policies is well established and Saudi Arabia can emulate these trends to promote the application of PV in the building sector. Currently, there is a lack of awareness and initiative in the building industry about sustainability in general and renewable energy in particular. Building industry professionals are skeptical about the technical and economic viability of renewable technologies [5]. To promote PV application in buildings, it is therefore important to raise awareness amongst the building industry professionals as well as consumers besides formulating a detailed policy framework.

Meeting the rapidly growing peak power demand is one of the most important energy challenges the country faces, and application of PV in buildings can be a helpful option in this aspect. Utility tariffs, which traditionally have been heavily subsidized, are in a process of being rationalized. In 2016, electricity tariffs have been increased for the first time in 15 years, by as much as 45% [36]. Further tariff hikes are being widely forecasted as under the recently announced National Transformation Plan (NTO) by 2020, electricity and water tariff subsidies are to be cut by 200 Billion Saudi Riyals (54 Billion US$) [37]. The increasing trend in electricity tariff is going to positively affect the economic viability of PV.

7. Conclusions

Saudi Arabia needs to utilize the building sector for PV application to help achieve its 9.5 GW renewable energy targets. The study examines the residential sector of Saudi Arabia for rooftop PV power generation. The total building rooftop area for four main categories of housing units—villa, apartment, traditional house, and others—covering 13 major regions in the country has been calculated to be about 695 million square meter. The net rooftop area for PV utilization taking into account obstacles like balustrade walls, stair cases, water tanks, satellite dish antenna and air conditioning units has been found to be equivalent to 221 million square meters, accounting for 31.8% of the total roof area. It is found that rooftop PV systems in domestic buildings can provide 51 TWh of output per year, meeting 30% of the total residential electricity demand. Traditional houses exhibit the highest potential compared to other housing unit types. Riyadh, Makkah Al-Mukarramah and the Eastern region can produce more than 60% of the total estimated power generation. The findings of the case study at the KFUPM residential buildings undertaken with the help of ArcGIS 10.2 and PVsyst software corroborate the area and power generation estimates at the national level. The common obstructions can be rearranged in the shaded part of rooftops to maximize the space for PV installations. A decrease in the balustrade height can increase the sunny area on the roof. Housing authorities and municipalities should maintain comprehensive and up to date datasets. There is a need for appropriate policies and incentives in place to promote the take-up of PV in residential buildings, while lessons can be learnt from similar initiatives in developed countries.

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