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A Comparative Assessment for the Potential Energy Production from PV Installation on Residential Buildings

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Abstract: This paper targets the future energy sustainability and aims to estimate the potential energy production from installing photovoltaic (PV) systems on the rooftop of apartment's residential buildings, which represent the largest building sector. Analysis of the residential building typologies was carried out to select the most used residential building types in terms of building roof area, number of floors, and the number of apartments on each floor. A computer simulation tool has been used to calculate the electricity production for each building type, for three different tilt angles to estimate the electricity production. Tilt angle, spacing between the arrays, the building shape, shading from PV arrays, and other roof elements were analyzed for optimum and maximum electricity production. The electricity production for each household has been compared to typical household electricity consumption and its future consumption in 2030. The results show that installing PV systems on residential buildings can speed the transition to renewable energy and energy sustainability. The electricity production for building types with 2–4 residential units can surplus their estimated future consumption. Building types with 4–8 residential units can produce their electricity consumption in 2030. Building types of 12–24 residential units can produce more than half of their 2030 future consumption.

Keywords: photovoltaic; energy demand; renewable energy; residential buildings; PV*SOL

1. Introduction

Energy is considered one of the most important issues in both developed and developing countries [1]. Today, a large share of electricity is produced worldwide by renewable energy technologies [2]. Solar photovoltaic (PV) is one of the fastest-growing and most promising of these technologies and has many advantages [2]: (1) The solar PV is considered the most feasible renewable energy that can be successfully applied as distributed systems and building-integrated components in residential environments [3]. (2) The system performance can easily be modeled from the solar radiation depending on the orientation and tilting of solar PV [4]. (3) Solar PV technologies represent a safe, pollution-free, and environmentally friendly source of energy [5]. Several factors affect the PV performance other than the orientation and tilting of solar PV such as wind speed, ambient temperature, relative humidity, and dust deposition [6–8].

Studies for the life cycle assessment of PV systems and other traditional and emerging technologies show that the PV systems environmental impact, with greenhouse gas emission of around 0.043 kg CO_2 eq/kWh, is considered one of the most environmentally friendly systems when compared with traditional energy sources, and with newly available technologies such as hybrid solar plants, which combine solar power with another source of energy [9–11]. For example, even a solar hybrid gas turbine plant produces more emissions, 0.236 kg CO_2 eq/kWh, than PV power plant, mainly because of the fuel used [12].

Globally, the growth of installed photovoltaic (PV) capacity reflects a strong commitment by scientists, researchers, industry, and governments to decarbonizing the economy for sustainable development [13]. For example, de-carbonizing of the building stocks by 2050 is one of Europe's most important long-term targets that accounts for approximately 36% of the European Union's CO_2 emissions [13]. Photovoltaic technology plays an important role in the transition of buildings to becoming low-carbon ones [14]. The typology of urban areas has a profound impact on sunlight access and building energy efficiency and consumption levels [15–18]. Buildings in the European Union are now being designed and built to stricter building codes and standards to reduce their energy consumption and greenhouse gas emissions [19]. In 2019, Gaglia et al. mentioned that the residential buildings contribute to the higher percentage of energy usage in the building sector [20]. Residential buildings can use grid connected PV system, in this regard Sharma, Arvind, et al. (2020) introduced minimizing the energy cost of sustainable energy systems [21]. The promotion of rooftop PV systems can significantly reduce electricity bills [22].

In the Middle East, which is one of the regions with plenty of sunshine, PV potential is one of the highest in the world. In Palestine, solar energy is promising due to the high solar irradiation potential, and sunshine availability, which is about 3000 h per year [23,24]. On the other hand, Palestine imports almost all of its electricity needs [25]. In 2016, the energy supply in Palestine was (471Ktoe) were 91% of this supply was imported, and 9% were from local renewable and non-renewable energy sources [26]. Building energy consumption was about 60% of this imported energy, which is the highest consumption segment of final energy among the other Middle East and North African countries, and the share of electricity in Palestinian household expenditures is around 9% due to the very high price of electricity [27]. Additionally, Palestine suffers from electricity shortage and continuously blackout in the cold and hot seasons due to the very high demand for heating and cooling, the limited amount of imported electricity, and the weak infrastructure of the public electricity distribution companies.

Electricity has the largest part of the Palestinian energy mix, at around 34%. In 2016, the average annual electricity consumption per household was 3672 KWh, and the monthly average was 306 kWh. As the main fuel used for heating, 39.4% of Palestinian households used electricity [26]. For cooling, Palestinian households used almost only electric energy to operate fans and air conditioning units [26]. Due to the growing urbanization and the rapid growth in population, the demand forecast for electricity consumption for a household in 2030 will reach 6536 kWh per year, with an average monthly consumption of 545 kWh [27]. Due to the increased urbanization, expensive energy, and the lack of natural resources in Palestine, there is an urgent need to find mitigation strategies for future electricity consumption in residential buildings [28].

Most households in Palestine have access to electricity: 93% for rural and 99% for urban households, which make grid-connected PV systems a feasible solution for residential buildings. In West Bank the residential buildings have almost 24 h access to power; however, in Gaza strip this access is limited to around 16 h [26]. Additionally, the supply is not always sufficient to cover the needs of the West Bank and Gaza Strip, which are growing rapidly (5–7%/year) especially for the Gaza Strip. The percentage of household units having solar water heating has decreased from 75% in 2001 to 57% in 2015. It is worth mentioning that one-third of these solar heating systems are out of order, which creates a high demand for electricity for heating especially in the cold season [29].

In Palestine, the government, private sectors, and NGOs are now supporting the investment in renewable energy by installing Solar PV on public buildings especially school buildings and investing in solar energy fields [30]. Other buildings sectors like residential buildings (the largest building sector) are still not getting the proper attention, despite the very high electricity consumption of this sector. This study will focus on selected typologies of existing and new residential buildings to integrate

PV systems, which can lead to a reduction in the final network's electricity demand and provide an investment in the renewable energy sector for the wide range of private residential buildings.

The apartment buildings in Palestine represent the majority of residential households, 61.5%, 53% in the West Bank, and 65.6% in Gaza Strip as can be seen in Figure 1. The typical apartments of three and four bedrooms represent the majority of household units in Palestine (35% and 30% of the apartments), followed by two bedrooms (16%), and more than five bedrooms (15%) [26]. In Palestine 85% of household's units are owned by the residents, which makes the investment in the PV systems in residential buildings directly affect the ownership of the building [26].

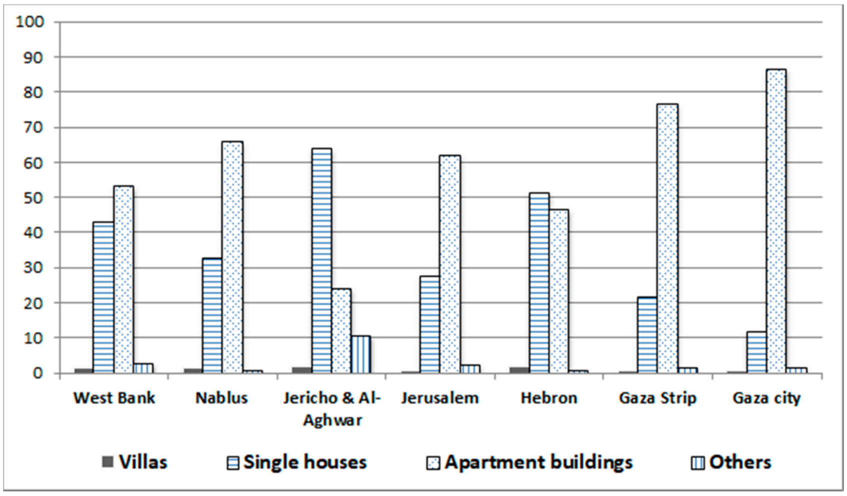


Figure 1. Percentage of apartment buildings compared to other forms of residential buildings in Palestine. Data derived from Palestinian Central Bureau of Statistics (2017).

Residential buildings are usually found in Palestinian cities in clusters and neighborhoods [31]. Those buildings contain multiple forms of separate or semi-connected residential apartments that are combined by a staircase [32]. Such buildings belong to international prototypes and can be found in other countries but with different shapes and sizes. The design of the building often follows the planning and organizational laws of the lands into Patterns A, B, and C. These laws are provided by the Ministry of Local Government to determine the proportion of the building and the number of floors [33]. Such laws are supposed to control the density of the buildings according to the planning goals for each region. The following is a brief explanation of the most used patterns for residential buildings in Palestinian cities [34]:

– Building type A: residential buildings for single families consisting of a maximum of two floors intended for single-family use. These buildings are usually located on sorted land plots with an area of 500–800 m^2, and the construction percentage is 30% of the land area so that the average roof area in this pattern is 200 m^2 including the stair's roof. This pattern could contain buildings in the form of two common units with a staircase and the roof area reaches 300 m^2.
– Building type B: residential buildings for multiple-family apartment buildings. Such buildings consist of 5–7 floors; each floor includes two to four apartments [35]. These buildings are located on sorted land plots with an area of 800–1500 m^2 and a construction rate of 50% of the land area is permitted. Thus, the average roof area of this pattern is from 300 to 600 m^2 including the stair's roof.
– Building type C: residential buildings for extended families. Those buildings consist of 4 floors. Each floor consists of one apartment or two. The average area of the sorted land lots is 400–600 m^2—and the permitted area of the building is around 49%, which led to an average built area 180 up to 250 m^2, including the stair's roof.

For all the mentioned types of buildings, there are some common architectural and structural characteristics:

- Most of these buildings tend in their design to regular forms of square or rectangular shapes. The floors are usually distributed as parking in the basement or ground, and residential apartments on the upper floors.
- Each floor consists of one or four apartments, and the building contains one or more vertical access units (staircase) in addition to the elevator and skylights, which are often in B and C patterns [36].
- The roof is concrete slab, normally flat, and has a parapet of 80 cm height.
- The staircase roof is used for water tanks and solar water heating units.
- The residential buildings envelope is not thermally insulated. The glass used for the window is single/double glazing with an aluminum frame. The walls use the typical components of stone, concrete, hollow concrete block, and plaster.

Due to the difficult political conditions, the shortage of natural resources, the population density and the financial crisis in Palestine, the energy sector is dependent on nearby countries and highly vulnerable compared to other Middle Eastern countries. Moreover, Palestine depends on neighboring countries for 100% of its non-renewable energy imports and for 87% of its electricity imports. Solar Energy potential in Palestine can open new perspectives for energy sector in order to prompt practices for sustainable development. Although the problems for energy sector in Palestine are well known, evaluating the solar energy production from PV installation on residential buildings typologies in this climatic and economic contest has not been done before. This research will contribute to the evaluation studies needed for decision making and scientific communities in terms of new results, evaluating the parameters affecting energy production from installing PV on residential buildings and a proposed approach to achieve energy sustainability.

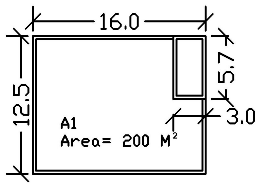
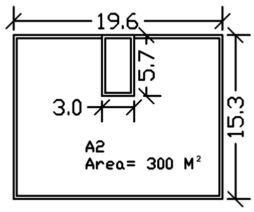
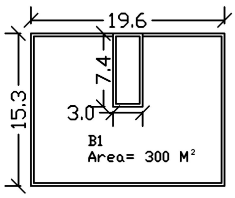
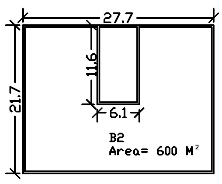
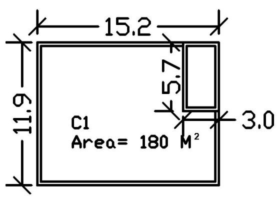
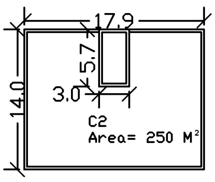
2. Materials and Methods

A new developed approach is used which brings together a combination of energy consumption in residential buildings; surveying the most used residential typologies; and renewable energy production for different scenarios using a computer simulation tool (PV*SOL).

2.1. Selecting Residential Building Types

The targeted residential buildings have been selected based on the most used types and shapes in the Palestinian cities. The numbers of household units for each building type and the available roof areas for installing PV systems have been selected in reference to the most popular apartment types in the Palestinian cities. According to the local government building legislation in West Bank and Gaza Strip, the residential buildings have been categorized into three main categories: A (maximum two floors, with one or two apartments at each floor); B (four-seven floors, with two or four apartments at each floor); and C (maximum four floors, with one or two apartments at each floor) [32]. The common area of each type was collected based on the local law of land lots in the Palestinian Land Authority [37]. Three to four bedrooms apartment has been selected as it represents the majority of household units in the Palestinian cities [26]. One and three apartments per floor for type B were excluded because these types are not widely spread in the Palestinian cities; these types are not likely to have three bedrooms for each apartment, which is not common in the Palestinian cities. Table 1 below provides a summary of the selected residential building types and related information to install PV systems on the rooftop of these buildings. The roof area available for PV installation has been calculated by subtracting the shaded area (calculated by the PV *SOL premium 2020) and the area used for water tanks from the total roof area.

Table 1. The most common types of residential buildings in Palestinian cities, classified according to the organizational regions of the Ministry of Local Government.

Building Type	Building Shape	Total Roof Area (m^2)	Number of Floors	Number of Apartment/Floor	Roof Area/Apartment (m^2)	Stairs Roof Area-Used for Water Tanks and Solar Water Heating (m^2)	Building Orientation	The shaded Area (m^2)	Area available for PV Installation (m^2)
A1		200	2	1	200	17	South-North East-West	14 12	169 171
A2		300	2	2	150	17	South-North East-West	21 24	262 259
B1		300	5–7 (6)	2	30–21.5 (25)	22	South-North East-West	25 30	253 248
B2		600	5–7 (6)	4	30–21.5 (25)	70	South-North East-West	29 35	501 495
C1		180	4	1	45	17	South-North East-West	14 12	149 151
C2		250	4	2	31.25	17	South-North East-West	21 24	212 209

The study used the selected building types in four cities in Palestine, which represent the different governorates in the West Bank (North, Central, and South) and Gaza Strip, as can be seen in Figure 2. Nablus (Latitude 32°13′ N, Longitude 35°16′ E, Altitude of 560 m and annual global irradiation of 1979 kWh/m^2) in the Northern part of the West Bank; Jerusalem (Latitude 31.7683° N, Longitude 35.2137° E, Altitude of 757 m above sea level and annual global irradiation of 2035 kWh/m^2) in the central part of the West Bank; Hebron (Latitude 31.5326° N, Longitude 35.0998° E, Altitude of 930 m above sea level and annual global irradiation of 2054 kWh/m^2) in the Southern part of the West Bank; Gaza (Latitude 31.5017° N, Longitude 34.4668° E, Altitude of 45 m above sea level and annual global irradiation of 1977 kWh/m^2) [38].

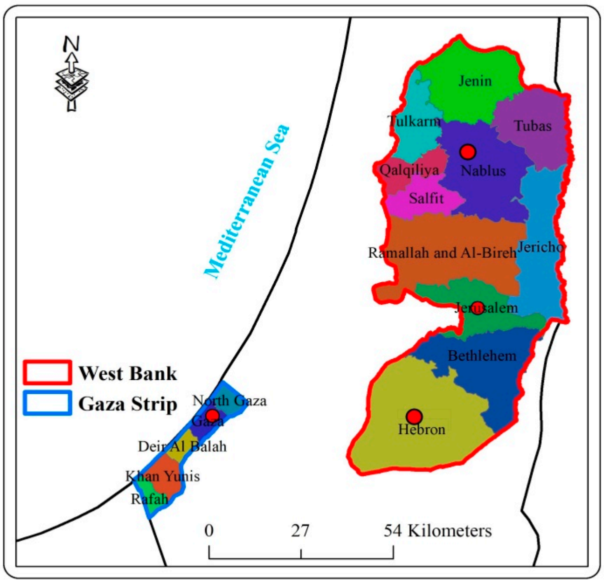


Figure 2. The map shows the different parts of Palestine (West Bank and Gaza Strip) and the selected cities.

2.2. Estimating Electricity Consumption

The average monthly and yearly electricity consumption for the selected household has been identified using surveys for the households done by the Palestinian Central Bureau of Statistics [26]. It has been done by identifying the number of appliances per household and then approximating daily consumption by usage. For the residential building sector, the main usages of electricity are air-conditioned, heating, water heating, fridge, and lighting. The average annual electricity consumption per typical household (three bedrooms and household members of 5.2) was 3672 kWh, and the monthly average was 306 kWh (442 kWh for the central region, 294 kWh for the south region, 272 kWh for the north region, and 265 kWh for Gaza strip). The future demand for electricity consumption for a typical household in 2030, which will reach 6536 kWh per year, with an average monthly consumption of 545 kWh, was identified based on a study by the World Bank [27].

2.3. Solar PV Simulation

To calculate the potential electricity production from installing PV systems on the roof of the selected building types and orientation a simulation was done by the software PV*SOL premium 2020 (R8). PV*SOL is specially designed for simulation and analysis of solar PV by Valentine Software [39]. The software is produced and improved in Germany with 3D visualization and detailed shading analysis for the PV systems, which is considered one of the leading countries in the solar PV industry and technology. PV*SOL provides solar radiation data for nearly all the cities in the world and supplies an up to date database and electrical characteristics for most commercial PV module devices. From the several commercial PV modules available in Palestine today, JAM72S10-410/MR (high power rating 410 W and high efficiency 20.43%) is used based on information from several companies operating in the local market that this module is highly efficient and provides higher energy production per given area.

The simulations were made for Grid-connected PV Systems for different cities (Jerusalem, Hebron, Nablus, and Gaza city) and buildings for two orientations (South-North and East-West). In designing array modules two significant aspects have to be considered for maximizing the solar power production and minimizing the shading losses: the optimum tilt angle for the specific location and the distance between the arrays.

Three tilt angles were chosen for the simulation: (1) 27°: Since the Optimum tilt angle for the most cities in Palestine is about 27° [40], which is in line with the result from the study by Jacobson et al. [6], but it required a relatively long distance between the arrays to minimize the shading losses; (2) 1°: since it is required less distance between the arrays to minimize the shading losses. It is also preferred to choose the tilt angle more than 15° to minimize the soiling effect [41]. (3) 7°: To maximize the power production from the limited area of the roof by increasing the number of the modules as much as possible. For all cases, the array spacing has been calculated for PV systems orientated to the south by the following equations

$$d_1 = h/\tan(SA) \tag{1}$$

$$\tan(SA) = \tan(\gamma)/\cos(\alpha) \tag{2}$$

$$h = b\sin(\beta) \tag{3}$$

where d_1 is the array spacing, b is the height of the solar panel, SA is the Shading Angle between the sun and the array, h is the height of the tilted solar panel, γ is the solar elevation angle, and α is the solar azimuth angle as it can be seen in Figure 3. Usually, the solar elevation and azimuth angle at 10:00 am or 2:00 pm on the winter solstice (21 December) are utilized for estimating the array spacing [42]. These times have been chosen to make sure there is no self-shading between these two hours during the worst case for the solar PV array orientated to the south on the winter solstice. The PV*SOL premium 2020 used another method of solar elevation and azimuth angle at noon to calculate the array spacing.

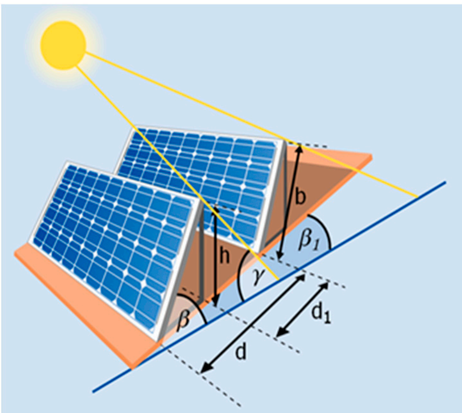


Figure 3. Solar angles tilt angles and distance between arrays (derived from PV*SOL software).

For example, $\gamma = 35°$ and $\alpha = 0°$ at noon for Hebron city at the winter solstice (21 December).

Substitute in Equation (2): tan (SA) = tan (35°)/cos (0°) = 0.70

Then substitute in Equation (3): h = 2.015*sin (27°) = 0.916 m ($\beta = 27°$)

Finally substitute in Equation (1): d_1 = 0.916/0.70 = 1.3 m (Spacing = 1.3 m)

But if 10 am is utilized for estimating the array spacing where $\gamma = 30.3°$ and $\alpha = 26°$ then $d_1 = 1.4$ m (spacing = 1.4 m).

In this manuscript, the spacing between arrays was changed in order to give the maximum power output in each array system. For example, for building type A1 with North-South building orientation at a tilt angle equal 27° the spacing was 1.4 m. Because, in this case, if the spacing was 1.3 m, then the number of modules will be the same and the power produced will decrease due to the increase of the self-shading effect. Another example for Building type A2 with North-South orientation at tilt angle

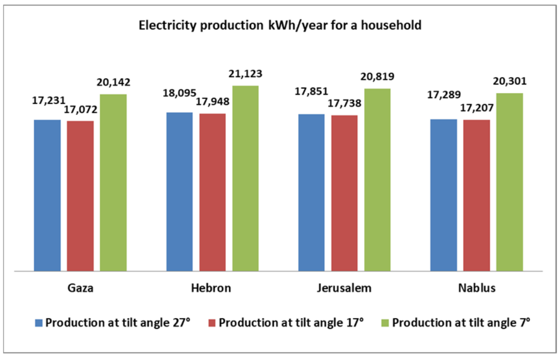
27° the spacing was 1.3 m. Because, in this case, if the spacing was 1.4 m, this would result in the loss of an array of modules and thus reduce the power produced.

3. Results

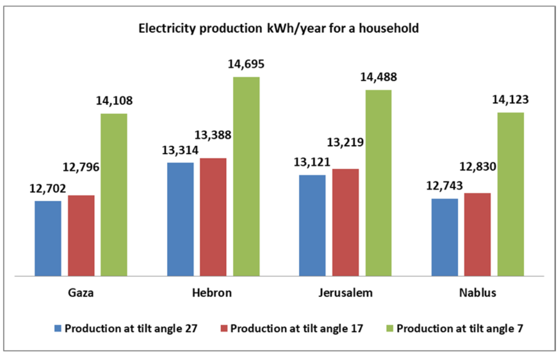
The results for potential electricity production from installing PV panels on residential buildings in Palestine to reduce the energy demand on the public electricity network have been summarized for the selected building types and orientations.

3.1. Residential Building Type A

For building orientation South-North, the annual electricity production from installing PV systems on the rooftop of building type A1 (two residential units) in four different cities at three different tilt angles are in the ranges 34,144 kWh–36,189 kWh for the system installed power of 22.14 kW with a tilt angle of 27°; 34,144 kWh–35,896 kWh for the same installed power with a tilt angle of 17°; and 40,284 kWh–42,245 kWh for the system installed power of 27.06 kW with a tilt angle of 7°; where these ranges vary depending on the selected cities. There is a slight difference between the selected cities in terms of electricity production due to differences of solar radiations, where Hebron has the highest production of 42,245 kWh at tilt angle 7°, while Gaza city has the lowest production of 40,284 kWh at the same angle. The annual electricity production for each household unit (the electricity production for the whole building then divided by the number of household units) is in the ranges 21,123 kWh–20,142 kWh for the system with tilt angle 7°; 18,095 kWh–17,231 kWh for the system with tilt angle 17°, and 17,984 kWh–17,072 kWh for the system with tilt angle 27°, where these ranges vary depends on the selected cities as can be seen in Figure 4. If we compare the electricity production with future consumption in 2030 and the consumption of 2016 for each household, this production represents 2.19 to 3.29 times the 2030 electricity consumption and represents 3.34 to 6.33 times the electricity consumption in 2016. These ranges vary depending on the tilt angle and the selected city, as can be seen in Table 2.



(**a**)



(**b**)

Figure 4. For South-North orientation: (**a**) the annual electricity production for each household for building type A1 and (**b**) the annual electricity production for each household for building type A2.

For building type A2 (four residential units) the annual electricity production is higher than A1 due to the fact that the roof is larger. However, the annual electricity production for each household unit is less than A1, because the share of the roof is less than the share in building type A1. This production for each household unit is in the ranges 14,108 kWh–14,695 kWh for the system installed power of 39.36 kW with a tilt angle of 7°; 12,769 kWh–13,388 kWh for the system installed power of 33.62 kW with a tilt angle of 17°; and 12,702 kWh–13,314 kWh for the same installed power with a tilt angle of 27°; where these ranges vary depends on the selected cities as can be seen in Figure 4. This production represents 1.62 to 2.29 times the future electricity consumption for households in 2030 and represents 2.47 to 4.44 times the electricity consumption of 2016 depending on the selected city and the tilt angle.

Table 2. Total Electricity production and production for households for different building types, orientation, cities, and tilt angles.

City			Nablus				Jerusalem				Hebron				Gaza			
Building Type	**Orientation**	**Tilt Angle**	**Total Production (kWh/year)**	**Production by Household (kWh/year)**	**Production to Consumption 2016 (%)**	**Production to Consumption 2030 (%)**	**Total Production (kWh/year)**	**Production by Household (kWh/year)**	**Production to Consumption 2016 (%)**	**Production to Consumption 2030 (%)**	**Total Production (kWh/year)**	**Production by Household (kWh/year)**	**Production to Consumption 2016 (%)**	**Production to Consumption 2030 (%)**	**Total Production (kWh/year)**	**Production by Household (kWh/year)**	**Production to Consumption 2016 (%)**	**Production to Consumption 2030 (%)**
A1	S-N	27°	34,577	17,289	530	279	35,702	17,851	337	220	36,189	18,095	513	282	34,462	17,231	542	279
		17°	34,414	17,207	527	277	35,475	17,738	334	219	35,896	17,948	509	280	34,144	17,072	537	276
		7°	40,602	20,301	622	327	41,638	20,819	393	257	42,245	21,123	599	329	40,284	20,142	633	326
	E-W	27°	32,379	16,190	496	261	33,433	16,717	315	206	33,854	16,927	480	264	32,364	16,182	509	262
		17°	32,130	16,065	492	259	33,134	16,567	312	205	33,543	16,772	475	261	32,033	16,017	504	259
		7°	38,532	19,266	590	311	39,632	19,816	374	245	40,159	20,080	569	313	38,388	19,194	604	311
A2	S-N	27°	50,971	12,743	390	205	52,484	13,121	247	162	53,257	13,314	377	207	50,808	12,702	399	206
		17°	51,321	12,830	393	207	52,874	13,219	249	163	53,551	13,388	379	209	51,184	12,796	402	207
		7°	56,493	14,123	433	228	57,952	14,488	273	179	58,781	14,695	417	229	56,433	14,108	444	228
	E-W	27°	47,587	11,897	364	192	49,073	12,268	231	151	49,709	12,427	352	194	47,481	11,870	373	192
		17°	47,519	11,880	364	191	49,908	12,477	235	154	49,558	12,390	351	193	47,255	11,814	372	191
		7°	57,628	14,407	441	232	59,047	14,762	278	182	59,881	14,970	424	233	57,357	14,339	451	232
B1	S-N	27°	47,498	3958	121	64	48,813	4068	77	50	49,610	4134	117	64	47,471	3956	124	64
		17°	47,670	3973	122	64	49,182	4099	77	51	49,792	4149	118	65	47,635	3970	125	64
		7°	54,440	4537	139	73	55,738	4645	88	57	56,510	4709	133	73	54,394	4533	143	73
	E-W	27°	44,700	3725	114	60	46,047	3837	72	47	46,621	3885	110	61	44,597	3716	117	60
		17°	44,653	3721	114	60	45,919	3827	72	47	46,496	3875	110	60	44,403	3700	116	60
		7°	58,251	5825	178	94	59,631	5963	112	74	60,473	6047	171	94	57,820	5782	182	94
B2	S-N	27°	95,497	3979	122	64	98,222	4093	77	51	99,671	4153	118	65	95,145	3964	125	64
		17°	96,897	4037	124	65	99,760	4157	78	51	100,947	4206	119	66	96,542	4023	126	65
		7°	115,949	4831	148	78	118,569	4940	93	61	120,641	5027	142	78	115,215	4801	151	78
	E-W	27°	93,181	3883	119	63	95,608	3984	75	49	97,355	4056	115	63	92,756	3865	122	63
		17°	94,816	3951	121	64	97,635	4068	77	50	98,933	4122	117	64	94,372	3932	124	64
		7°	114,846	4785	147	77	117,711	4905	92	61	119,369	4974	141	77	114,415	4767	150	77

Table 2. *Cont.*

City			Nablus				Jerusalem				Hebron				Gaza			
Building Type	Orientation	Tilt Angle	Total Production (kWh/year)	Production by Household (kWh/year)	Production to Consumption 2016 (%)	Production to Consumption 2030 (%)	Total Production (kWh/year)	Production by Household (kWh/year)	Production to Consumption 2016 (%)	Production to Consumption 2030 (%)	Total Production (kWh/year)	Production by Household (kWh/year)	Production to Consumption 2016 (%)	Production to Consumption 2030 (%)	Total Production (kWh/year)	Production by Household (kWh/year)	Production to Consumption 2016 (%)	Production to Consumption 2030 (%)
C1	S-N	27°	30,375	7594	233	122	31,217	7804	147	96	31,715	7929	225	124	30,373	7593	239	123
		17°	30,694	7674	235	124	31,584	7896	149	97	31,943	7986	226	124	30,608	7652	241	124
		7°	31,794	7824	240	126	32,543	8009	151	99	32,916	8102	230	126	31,232	7684	242	124
	E-W	27°	30,819	7705	236	124	31,631	7908	149	98	32,191	8048	228	125	30,738	7685	242	124
		17°	31,252	7813	239	126	32,203	8051	152	99	32,626	8157	231	127	31,139	7785	245	126
		7°	36,881	9220	282	149	37,890	9473	179	117	38,418	9605	272	150	36,699	9175	289	148
C2	S-N	27°	41,452	5182	159	84	42,561	5320	100	66	43,047	5381	153	84	41,337	5167	162	84
		17°	43,412	5427	166	87	44,713	5589	105	69	45,319	5665	161	88	43,254	5407	170	87
		7°	45,879	5735	176	92	46,602	5825	110	72	47,240	5905	167	92	45,317	5665	178	92
	E-W	27°	41,022	5128	157	83	42,226	5278	100	65	42,925	5366	152	84	40,804	5101	160	83
		17°	42,224	5278	162	85	43,464	5433	102	67	44,028	5504	156	86	42,000	5250	165	85
		7°	47,121	5890	180	95	48,297	6037	114	75	48,955	6119	173	95	46,929	5866	184	95

If we change the building orientation to East-West for types A1 and A2 by rotating the building 90° counterclockwise the total electricity production will decrease except for A2 at a tilt angle of 7° the production will increase. The reduction or increase can be justified by the lower/higher power installed due to the new PV arrangement on the rotated same building shape. Consequently, the electricity production share for each residential unit will decrease in the range of 948 to 1176 kWh/year for building type A1, and in the range of -284 to 998 kWh for building type A2 depending on the tilt angles and selected city as can be seen in Figure 5 and Table 2.

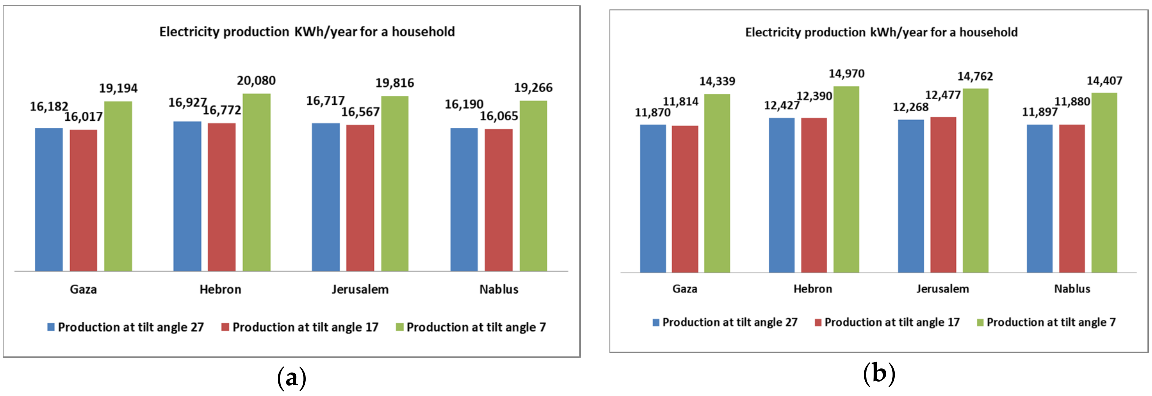


Figure 5. For East-West orientation: (**a**) the annual electricity production for each household unit A1 and (**b**) the annual electricity production for each household unit A2.

3.2. Residential Building Type B

For building orientation South-North, the annual electricity production for building type B1 (12 residential units) in four different cities at three different tilt angles are in the ranges: 47,471 kWh–49,610 kWh for the system installed power of 32 kW with a tilt angle of 27°; 47,635 kWh–49,792 kWh for the same installed power with a tilt angle of 17°; and 54,394 kWh–56,510 kWh for the system installed power of 39.36 kW with tilt angle 7°; again these ranges vary depending on the selected cities. The annual electricity production for each household unit is in the ranges 3956 kWh–4134 kWh for the system with tilt angle 27°; 3970 kWh–4149 kWh for the system with tilt angle 17°; and 4533 kWh–4709 kWh for the system with tilt angle 7°; where these ranges vary depending on the selected cities as it can be seen in Figure 6. If we compare the electricity production with future consumption in 2030 and the consumption of 2016 for each household, the production represents 0.5 to 0.73 times the 2030 electricity consumption and represents 0.77 to 1.43 times the electricity consumption in 2016. These ranges vary depending on the selected city and the tilt angles as can be seen in Table 2.

For building type B2 (24 residential units) the annual electricity production is higher than B1 due to the fact that the roof is larger. However, the annual electricity production for each household unit is close to the building type B1, because the share of the roof is almost the same. This production for each household is in the range 3964 kWh–4153 kWh for the system installed power of 63.14 kW with a tilt angle of 27°; 4023 kWh–4206 kWh for the same installed power with a tilt angle of 17°; and 4801 kWh–5027 kWh for the system installed power of 81.6 kW with a tilt angle of 7°; where these ranges vary depends on the selected cities as can be seen in Figure 6. This production represents 0.51 to 0.78 times the 2030 electricity consumption for households and represents 0.77 to 1.51 times the electricity consumption of 2016 depending on the selected city and the tilt angle.

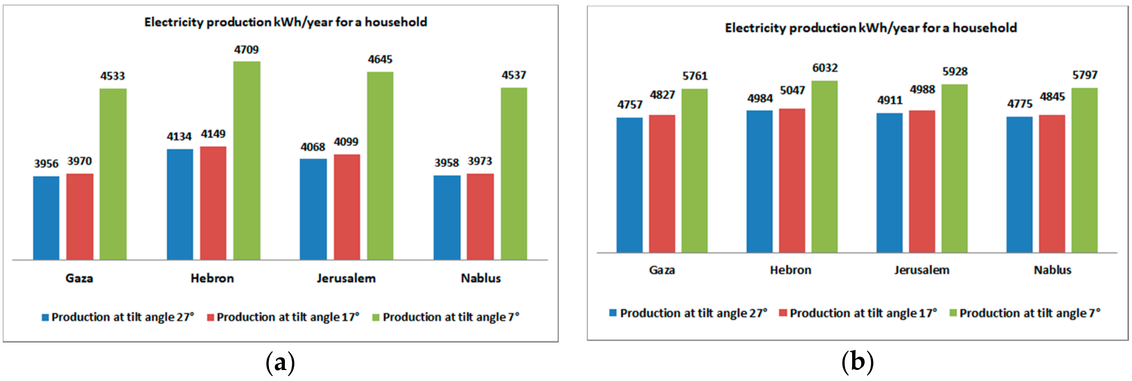


Figure 6. For South-North orientation: (**a**) the annual electricity production for each household unit B1 and (**b**) the annual electricity production for each household unit B2.

As in the case of building types A1 and A2, if we change the building orientation to East-West for building types B1 and B2 the total electricity production will decrease except for B1 at a tilt angle of 7° the production will increase. Consequently, the electricity production share for each residential unit will decrease in the range of −330 to 274 kWh/year for building type B1 and in the range of 34 to 99 kWh/year for building type B2 depending on the tilt angles and selected city as it can be seen in Figure 7 and Table 2.

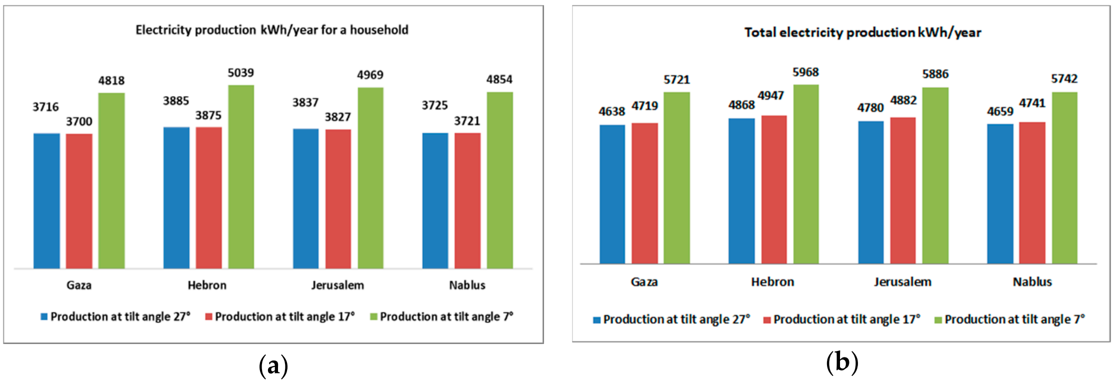


Figure 7. For East-West orientation: (**a**) the annual electricity production for each household unit B1 and (**b**) the annual electricity production for each household unit B2.

3.3. Residential Building Type C

For building orientation South-North, the annual electricity production for building type C1 (four residential units) in four different cities at three different tilt angles are in the ranges 30,373 kWh–31,715 kWh for the system installed power of 20.5 kW with a tilt angle of 27°; 30,608 kWh–31,943 kWh for the same installed power with a tilt angle of 17°; and 31,232 kWh–32,916 kWh for the system installed power of 25 kW with a tilt angle of 7°; again these ranges vary depending on the selected cities. The annual electricity production for each household unit are in the ranges 7593 kWh–7929 kWh for the system with tilt angle 27°; 7652 kWh–7986 kWh for the system with tilt angle 17°; and 7708 kWh–8229 kWh for the system with tilt angle 7°; where these ranges vary depending on the selected cities as can be seen in Figure 8. If we compare the electricity production with future consumption in 2030 and the consumption of 2016 for each household, the production represents 0.96 to 1.26 times the 2030 electricity consumption and represents 1.47 to 2.42 times the electricity consumption in 2016. These ranges vary depending on the selected city and the tilt angles as can be seen in Table 2.

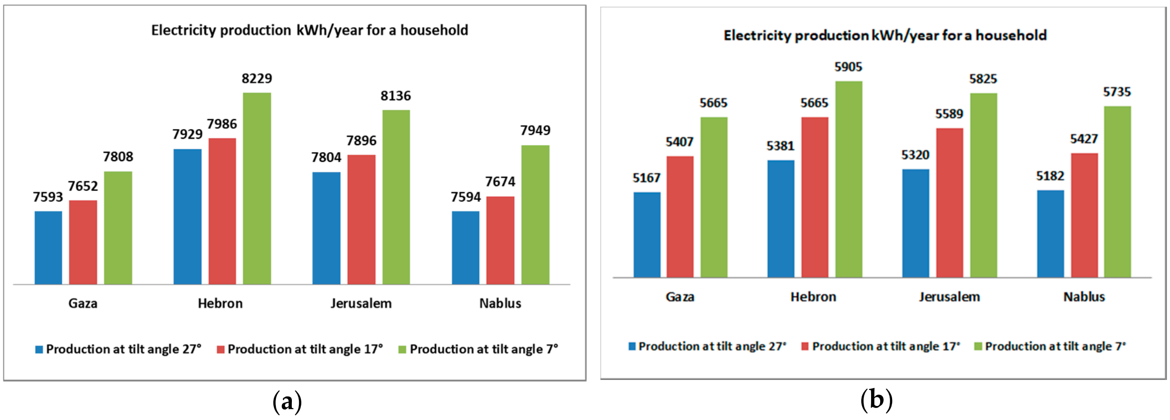


Figure 8. For South-North orientation: (**a**) the annual electricity production for each household unit C1 and (**b**) the annual electricity production for each household unit C2.

For building type C2 (eight residential units) the total annual electricity production is higher than C1 due to the fact that the roof is larger. However, the annual electricity production for each household unit is less than C1, because the household unit share of the roof area is less than the share in building type C1. This production for each household is in the range 5167 kWh–5381 kWh for the system installed power of 29.52 kW with a tilt angle of 27°; 5407 kWh–5665 kWh for the same installed power with a tilt angle of 17°; and 5665 kWh–5905 kWh for the system installed power of 35.7 kW with tilt angle 7°; where these ranges vary depends on the selected cities as can be seen in Figure 8. This production represents 0.66 to 0.92 times the 2030 electricity consumption for households and represents 1.0 to 1.78 times the electricity consumption of 2016 depending on the selected city and the tilt angle.

If we change the building orientation to East-West for building type C1 the total electricity production will increase, because the spacing between the arrays is higher which will increase the efficiency. Consequently, the electricity production share for each residential unit will increase in the range of 92 to 1376 kWh/year. For building type C2 the total electricity production will decrease, except for the PV system at a tilt angle of 7° the production will increase. The electricity production for each household will change in the range of 14 to -214 kWh/year depending on the tilt angles and selected city as it can be seen in Figure 9 and Table 2.

From the results above, it could be concluded that electricity production from the PV solar panel is totally dependent on the building type. The energy production for building type A and B is more for North-South orientation while building type C has more energy production for East-West orientation. The tilt angles 27 and 17 give almost similar results for the different building types and they give the best specific yearly yield (kWh production for each installed kW) since PV array production totally depends on the tilt angle (for maximum solar energy capture) and the space between the arrays (self-shading effect). Because the tilt angle 27 is the optimum tilt angle for achieving the highest energy for most cities in Palestine, it requires a further distance between the arrays, which has a negative shading effect by reducing the resulting energy. On the other hand, the angle 17 does not give the highest energy output, but it requires less distance between the arrays. Therefore, if there is enough spacing between the arrays and enough area on the building roof then the best tilt angle for maximum PV production is about 27° for the same kW power installed. However, if there is limited space between the arrays, then the maximum production is at the tilt angle 17°, for the same kW power installed. For Example A1: South-North (Hebron city) the total production at 27° and space is 1.4 m is equal 36,189 kWh, while at 17°, and space is 1.2 m the total production is 35,896 kWh. For A2: South-North (Hebron city) the total production at 27° and space is 1.3 m is equal 53,257 kWh, while at 17°, and space is 1.2 m the total production is 53,551 kWh. While the tilt angle 7 gives the best yearly kWh production for each m2 of the roof area since it has the maximum installed kW.

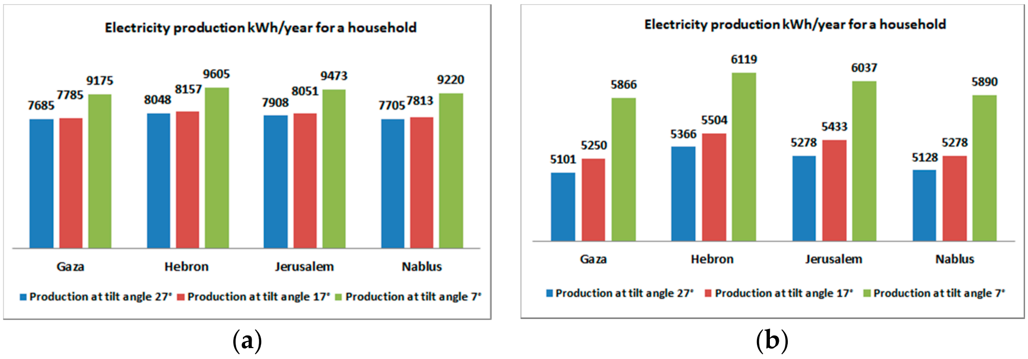


Figure 9. For East-West orientation: (**a**) the annual electricity production for each household unit C1 and (**b**) the annual electricity production for each household unit C2.

For building types, A1 and A2, where the share of roof area for each apartment unit is high (150–200 m^2), installing PV systems at the optimum tilt angle of 27° will provide the building with the electricity with low investment (low installed power). The production for A1 apartments is around 3 to 5 times its electricity consumption in 2016 and around 2 to 3 times the consumption in 2030, depending on the selected city, and the production for A2 apartments is 2.5 to 4 times its electricity consumption in 2016 and 1.5 to 2 times the electricity consumption in 2030 depending on the orientation and the selected city.

For building type C1 where the share of the roof area for each apartment unit is (45 m^2), installing a PV system at the tilt angle of 17° will give the space to increase the distance between PV arrays and increase the total production. The production for C1 apartments is around 1.5 to 2.45 itis electricity consumption in 2016 and around 0.97 to 1.27 times electricity consumption in 2030. For building type C2 where the share of the roof area for each apartment unit is low (31 m^2), installing a PV system at the tilt angle of 7° will give the best production to cover its electricity consumption. The production for each apartment is around 1.1 to 1.84 its electricity consumption in 2016 and around 0.72 to 0.95 times electricity consumption in 2030 depending on the orientation and the selected city.

For building types, B1 and B2, where the share of the roof area for each apartment unit is low (25 m^2), installing a PV system at the lower tilt angle of 7° will give the space to install more power and increase the total electricity production. The production for B1 and B2 apartments is around 0.75 to 1.78 times its electricity consumption in 2016 and around 0.6 to 0.75 times the consumption in 2030, depending on the orientation and the selected city.

The evaluation of the payback period and the economic benefits of installing PV systems, perform the analysis for all building types and all Palestinian cities taking into consideration different possibilities for tilt angles can be considered as limitations for this study. Moreover, it is recommended to examine the expected effect of installing these PV systems on the urban energy demands in the Palestinian cities since some building types can produce a surplus of their electricity consumption.

4. Conclusions

Although the problems for the energy sector in Palestine are well known, evaluating the solar energy production for the targeted residential buildings typologies in this climatic and economic contest has not been done before. The results from this research can support the efforts toward future energy sustainability and the use of solar energy in residential buildings.

The research used a new developed approach which brings together a combination of energy consumption in residential buildings, surveying the most used residential typologies and renewable energy production for different scenarios using computer simulation tools. This research will contribute to the evaluation studies needed for decision making and scientific communities in terms of new results, evaluating the parameters affecting energy production from installing PV on residential buildings and a proposed approach to achieve energy sustainability.

The sunshine availability (around 3000 h/year) and the high solar radiation intensity, which can reach up to 2050 kWh/m^2 in this region, make the PV system one of the best options for residential building owner's to invest in renewable energy. A 1 kW system in Palestine installed at the rooftop at optimum tilt and orientation angles generates up to 1635 kWh/year in Hebron, 1613 kWh/year in Jerusalem, 1562 kWh/year in Nablus, and 1557 kWh in Gaza city. These results are in line with the results from another study in a neighboring country which gives around 1560 KWh annual production [43]. The annual kWh production per m2 for the Palestinian cities could reach 250 kWh/m^2 per year. There is a small difference in power production by PV solar panels for the Palestinian cities. Hebron has the highest power production where Gaza city has the lowest. PV installation on the rooftop of residential buildings can provide electricity production compared to the buildings consumption in ranges between 0.5 to 6 times depending on the selected city, building type and shape, tilt angle, spacing between arrays, building orientation and installed power. These results can be adapted in similar climatic conditions and similar building types, especially in the east Mediterranean region.

Residential buildings in urban areas in Palestinian cities have the potential to provide electricity production to mitigate the current and future increasing electricity demand in Palestine. Building types A1 with two residential units and A2 with four residential units can give an electricity production that surpasses their average current and 2030 future electricity consumption. While building types B1 with 12 residential units and B2 with 24 residential units can produce more than half their current and future electricity consumption. Building type C1 with four residential units can produce its future electricity consumption, and around double the electricity consumption in 2016. Building types C2 with 8 residential units can produce more than half its future electricity consumption for households in 2030 and represents its electricity consumption of 2016.

Changing building orientation for the same roof area will result in different distribution on solar PV arrays and can result in decreasing or increasing the electricity production depending on the building dimensions (the building length on the S-N or E-W) and spacing between the PV arrays. The tilt angle can play an important role in determining the quantity of the PV installation based on the available roof area, the number of floors, and the number of residential units.

The highest specific yearly yield from PV systems (kWh generated by 1kWp) occurs at the optimum tilt angle (27°), however, the installed power and the total building electricity production is the lowest, due to the large distance between PV arrays. This can be the best option for building type (A) as there is enough area for electricity production (roof area/number of household units). The lower tilt angle of around 7° is the best option for low rooftop availability (roof area/number of household units) for installing PV systems, as it gives the highest installed power and the highest electricity production, this is because the distance between PV arrays is small which will allow for more PV power installation. This can be the best option for building types (B) and (C). If there is enough spacing between the arrays and enough area on the building roof, then the best tilt angle for maximum PV production is about 27° for the same kW power installed. If there is limited space between the arrays, then the maximum production is about 17°, for the same kW power installed.

The tilt angles 27° and 17° give almost similar results for the different building types and they give the best specific yearly yield (kWh production for each installed kW). While the tilt angle 7° gives the best yearly kWh production for each m^2 of the roof area. The specific yearly yield could reach 1650 kWh/kW at tilt angle 27° and the kWh production per m^2 could also reach 250 kWh/m^2/year for tilt angle 7°.

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