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Potential Electricity Production by Installing Photovoltaic Systems on the Rooftops of Residential Buildings in Jordan: An Approach to Climate Change Mitigation

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Abstract: Countries with limited natural resources and high energy prices, such as Jordan, face significant challenges concerning energy consumption and energy efficiency, particularly in the context of climate change. Residential buildings are the most energy-consuming sector in Jordan. Photovoltaic (PV) systems on the rooftops of residential buildings can solve the problem of increasing electricity demands and address the need for more sustainable energy systems. This study calculated the potential electricity production from PV systems installed on the available rooftops of residential buildings and compared this production with current and future electricity consumption for residential households. A simulation tool using PV*SOL 2021 was used to estimate electricity production and a comparative method was used to compare electricity production and consumption. The results indicated that electricity production from PV systems installed on single houses and villas can cover, depending on the tilt angle and location of the properties, three to eight times their estimated future and current electricity use. PV installation on apartment buildings can cover 0.65 to 1.3 times their future and current electricity use. The surplus electricity produced can be used to mitigate urban energy demands and achieve energy sustainability.

Keywords: PV panels; sustainability; residential buildings; electricity consumption; system sizing; climate change; Jordan

1. Introduction

Energy has been crucial to the demographic, social and economic development of human society [1–5]. However, climate change is now one of the world's most pressing environmental issues [6–9]. As outdoor temperatures rise, building energy demands will also increase [10–12]. Climate change is causing more frequent heatwaves in the Middle East, which will lead to a substantial increase in energy consumption, particularly electricity consumption [13–15]. Installing PV systems on the rooftops of residential buildings can provide a mitigation strategy for the increase in future energy consumption and may play a crucial role in the development of clean and sustainable energy sources [11]. Jordan's population is expected to rise to 12.9 million by 2030. This will result in a rise in energy demand for the residential building sector [16]. Currently, to meet its energy demands, 94% of Jordan's oil and gas are imported from abroad [17], making fuel prices vulnerable to change; Jordan's demand for energy is increasing at a rate of 3% annually. Therefore, one of the most significant challenges Jordan faces is the issue of energy. Jordan's debts represent 97% of its national income [18] and the largest part of this debt is due to the increase in its energy bill, which is mostly due to the regional circumstances surrounding Jordan in recent years [18]. Thus, it has become necessary for Jordan to find renewable energy sources as an alternative to the costly energy imported from abroad. The best of these alternatives is solar energy, which is considered the most successful in terms of investment. This is due to the high irradiation rate in Jordan, with days of solar energy use exceeding 310 sunny days [17].

The building sector plays a vital role owing to its significant environmental and societal impact [19]. Worldwide, buildings sector account for approximately 40% of total final energy consumption and around 1/3 of greenhouse gas (GHG) emissions, regardless of the obtained energy efficiency benefits; energy consumption in buildings is expected to increase further [20,21]. Buildings account for 16–50% of global energy use [4,22–24], while the residential building sector accounts for 43% of the total electrical energy consumption in Jordan, making this sector the largest consumer of electricity [25]. Residential energy consumption is expected to account for 67% of the total energy demand by 2030, whereas non-residential energy consumption will constitute 33% [26]. The cost of energy in Jordan has a 20% share of the total GDP [27]. Installing PV on the rooftops of apartment buildings can provide household owners with a range from approximately 50% to over 100% of the electricity needed to operate the residential unit; this range depends on the available rooftop which depends on apartment building type, particularly the number of floors and number of units on each floor [11].

PV technology is essential to achieve a significant increase for the use of renewable solar energy sources for achieving the sustainable development goals [28,29], because Jordan has a massive solar energy potential as it is located within the world's solar belt, with average solar radiation ranging between 5 and 7 (kWh/m^2). In addition, global power production from solar photovoltaic (PV) panels exceeded 627 GW in 2019 but was less than 23 GW in 2009 [29]. Rooftop mounted PV systems have become a key source of renewable energy in numerous countries; the growth of residential rooftop PV systems and battery storage systems, and their installation in buildings and dwellings, has been rapid in recent years—a trend that is expected to continue [12,30]. Additionally, PV rooftop systems can significantly reduce greenhouse gas (GHG) emissions from the residential electrical sector, as renewable energy sources are producing less emissions [31]. Thus, the expansion of rooftop PV technology has become an essential component of the energy policies and strategies of several countries [30]. Recently, there has been a wide-scale installation of rooftop PV systems due to their technical, economic, and socio-environmental advantages [32]. With rapid reductions in the cost of PV modules [33] and rises in their efficiency [34], rooftop PV systems connected to the grid may be a crucial component of Jordan's transition towards energy sustainability [32]. Rooftop-mounted solar PV technology is an effective approach for creating social, economic and environmental benefits, and it has the potential to contribute to local energy sustainability and security [35–37].

This study estimates the amount of electrical energy produced by installing solar panels on the rooftops of residential buildings to cover their energy needs. The residential sector is the largest consumer of electrical energy in Jordan, constituting approximately 46% of the total electricity consumption in the country. The industrial sector is in second place, accounting for 22%, followed by water plumbing at 15%, commercial building at 14% and street lighting at 2% [17,38–41].

2. Materials and Methods

To compare the estimated electricity production from the installation of PV systems on the available rooftops of residential buildings with current and future electricity consumption, the following methods were used.

2.1. Selecting the Most Used Residential Building Typologies

In 2008, the department of statistics in Jordan [42] provided figures concerning each household type (see Figure 1 below). In urban areas in the middle region of Jordan, apartment buildings represented the majority of buildings (79%), followed by single houses (18%) and villas (3%). In urban areas in the northern and southern regions, single houses represented the majority of buildings (51%), followed by apartment buildings (47%); villas represented the smallest number of buildings (0.6% in the north and 1.2% in the south). In rural areas, the majority of buildings were single houses (73% in the middle region and 78% in the northern and southern regions). The second most common building type was apartment buildings (representing 24% of buildings in the middle region, 22% in the northern region, and 6% in the southern region). Villas represented a small portion of buildings (2% in the middle region, 0.5% in the northern region and 0.65% in the southern region). In 2015, the percentage of houses, apartments and villas in urban areas was 55%, 42% and 2.4% and in rural areas was 88.9%, 9.9% and 1.2%, respectively (see Figure 2) [43].

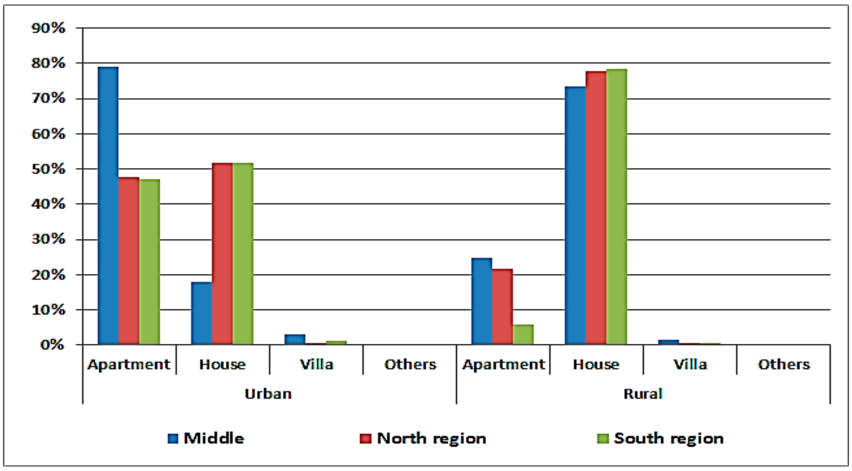


Figure 1. The percentages for each building type in different regions in Jordan in 2008.

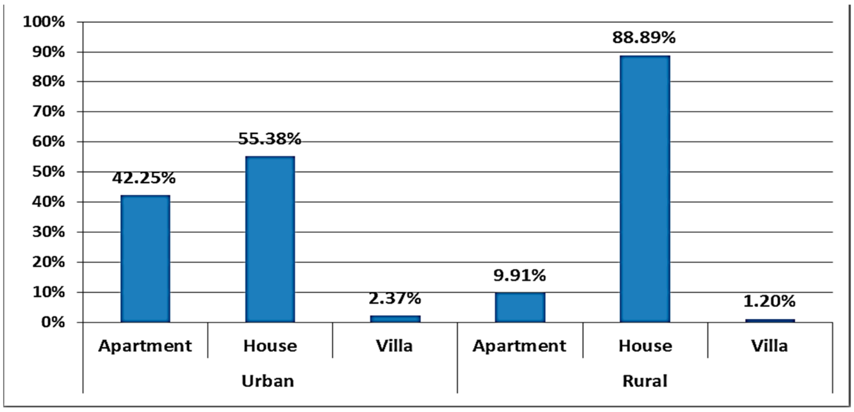


Figure 2. The percentage of households for urban and rural areas in Jordan in 2015.

Based on these survey results, the following building typologies were selected as they represent the most used building types in Jordan.

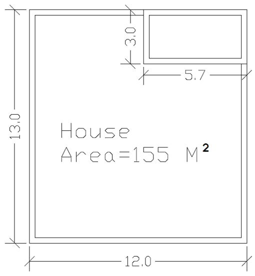
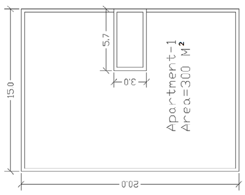
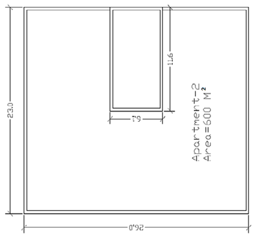
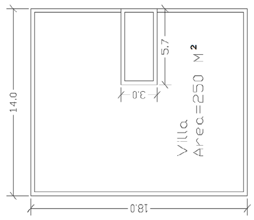
Single house: contains one household over one to two floors with an average roof area of 155 m^2.

Apartment buildings: there are two types each with five floors. Type 1 has two apartments per floor, ten units per apartment building and an average rooftop area of approximately 300 m^2. Type 2 has four apartments per floor and 20 units per apartment building and an average rooftop area of approximately 600 m^2.

Villa house: typically, one household with an average rooftop area of 250 m^2.

To evaluate the potential electricity production from the installation of PV systems on the rooftops of residential buildings and to make a comparative assessment of their electricity production and consumption, these four types of residential buildings were selected. The number of floors in the building, the number of apartments on each floor, and the available roof areas were determined as shown in Table 1. None of the selected buildings were thermally insulated; thermal insulation is not typical for residential buildings in Jordan [9]. The average number of family members for a typical household in Jordan [44] was used for all selected buildings.

Table 1. Descriptions of the targeted buildings for rooftop PV installation.

Building Type	Single House	Apartment Building-1	Apartment Building-2	Villa
Shape				
Roof area (m^2)	155	300	600	250
Shaded areas and stairs (m^2)	29	47	100	37
Area for PV installation (m^2)	126	253	500	213
Number of floors	1–2	5	5	2
Number of household units	1	10	20	1

2.2. Estimation of Electricity Consumption in Residential Buildings

For the second approach and to establish a comparison between the production and consumption of electricity, the monthly average electricity consumption for each household for each building type was identified according to the average electrical through Energy Use Intensity (EUI); annual figures were obtained of 31.6 and 22.5 kWh/m^2 for residential apartments and for houses, respectively [44]. According to the Energy and Minerals Regulatory Commission [45], the majority of households in single houses (58%) consume an average of approximately 300 kWh of electricity and 35% of apartment households consume an average of approximately 600 kWh of electricity. Only 1% of villa households consume over 900 kWh of electricity.

Based on the above data provided by the electric company regarding household electricity consumption, the researchers found that single houses had an average electricity consumption of 3600 kWh/year, apartment units had an average consumption of 5400 kWh/year and villas had an average consumption of 9600 kWh/year. Driven by climate change and other factors such as rapid population and economic growth in Jordan and better quality of life associated with residential buildings, residential electricity consumption is expected to increase by 30% by 2030 [46]. Based on the suggested increase, electricity consumption will be 6204 kWh/month, 7020 kWh/month and 12,480 kWh/month for houses, apartment units and villas, respectively.

2.3. Estimation of Electricity Production from PV Systems

To calculate the total rooftop area available for PV installation, the shaded areas by the building parapets and the satire cases—which are normally used for solar water heating panels and water tanks—were excluded from the total rooftop area. The typical rooftop of the selected building types is a flat roof and the available area for the PV installation after excluding shaded areas and other uses for the roof is in the range of 80–85% of the total roof area as seen in Table 1. Then, the best arrangement for PV panels on the rooftop was determined using a computer simulation tool. PV*SOL premium simulation tool was employed to calculate the potential electricity production from the installation of PV systems on the available rooftops of each selected building type, as shown in Table 1. JAM72S10-410/MR (high output rating 410 W and efficiency 20.43 percent) is utilized among the commercialized PV modules marketed in Jordan nowadays, depending on the information from numerous local businesses that this module is extremely effective and gives more energy output per given area. Table 2 shows the Specifications of JAM72S10-410/MR Module. To obtain maximum electricity production for each building type, the following factors were analyzed: tilt angle for PV panels, the distance between arrays, and shading effect. Tilt angles were fixed at 7°, 17° and 28°. The outcomes indicated the potential PV electricity production and its ability to meet energy demands.

Table 2. Specifications of the used PV panels (JAM72S10-410/MR Module).

Basic Data		Electrical Data		Dimensions	
Company	JA Solar Holdings Co., Ltd.	Cell Type	144	Width in mm	966
Name	JAM72S10-410/MR	Cell Count	3	Height in mm	2015
Version	2	Number of Bypass Diodes	1	Surface Area in m^2	2.01
		Loss Voltage per bypass diode in V	41.88	Depth in mm	35
		MPP Voltage in V	9.79	Frame Width in mm	40
		MPP Current in A	50.12	Weight in kg	22.7
		Open Circuit Voltage in V	10.45		
		Short-Circuit Current in A	410		
		Nominal Output in W	78.28		
		Fill Factor in %	20.43		
		Efficiency in %	144		

To maximize solar power output while reducing shading losses, two important factors must be addressed while constructing array modules: the optimal tilt angle for the given site and the spacing between the arrays. The tilt angle 28° was chosen because it's the Optimal tilt angle for most cities in Jordan [47] yet minimizing shade losses needed a relatively lengthy separation between the arrays; the tilt angle 17° was chosen because minimizing shading losses requires a shorter distance between the arrays, and also preferable to pick a tilt angle greater than 15° to reduce soiling [48]. Finally, the tilt angle 7° was chosen to increase the number of modules as much as possible to optimize power output for the roof's restricted area.

The array separation for PV systems oriented to the south has been computed using the following formulae in all scenarios:

$$d1 = h/\tan(SA) \tag{1}$$

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

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

d1 is the arrays separation, b is the length of the photovoltaic panels and SA is the Sun-Array Shading Angle. h is the inclined photovoltaic panel's height, γ is the angle of sun elevation and α is the solar azimuth angle as shown in Figure 3. Array separation is typically estimated using the sun elevation and azimuth angle at 10:00 a.m. or 2:00 p.m. on the winter solstice [49]. PV*SOL calculated array spacing using a different approach based on solar elevation and azimuth angle at noon.

Four cities in Jordan were selected to perform the calculation. The selected cities represented the most important location with the highest population density and covered different climatic and geographical areas in Jordan in terms of solar radiation intensity and climate data. The selected cities were Amman (latitude 31.96316° N and longitude 35.93036° E), Irbid (latitude 32.55145° N and longitude 35.85148° E), Ma'an (latitude 30.19496° N and longitude 35.73424° E), and Aqaba (latitude 29.52667° N and longitude 35.00778° E) (see Figure 4 below). Those four cities represent three different climatic zones, according to Koppen classification, Amman and Irbid has a BSk and BSh climate, respectively with hot and dry summer and cold winter, Ma'an has a warm Sahara climate and Aqaba has a BWh climate which is hot Sahara climate.

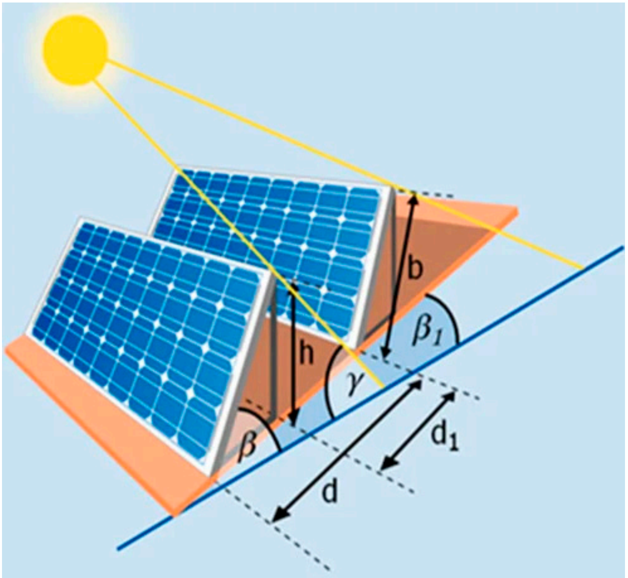


Figure 3. Solar angles, tilt angles and distance between arrays (as calculated by the PV*SOL program).

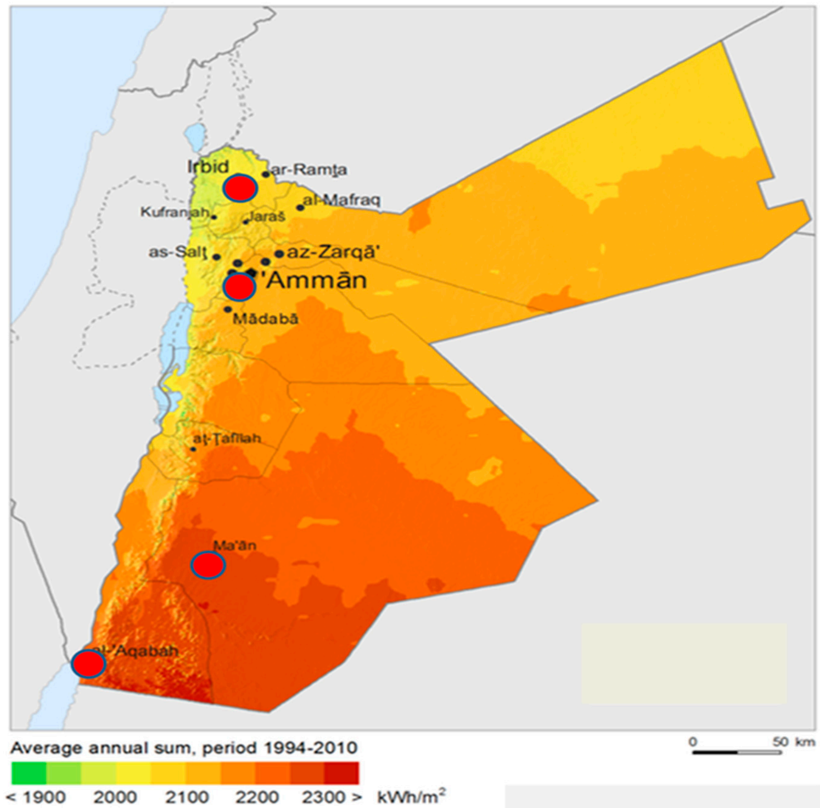
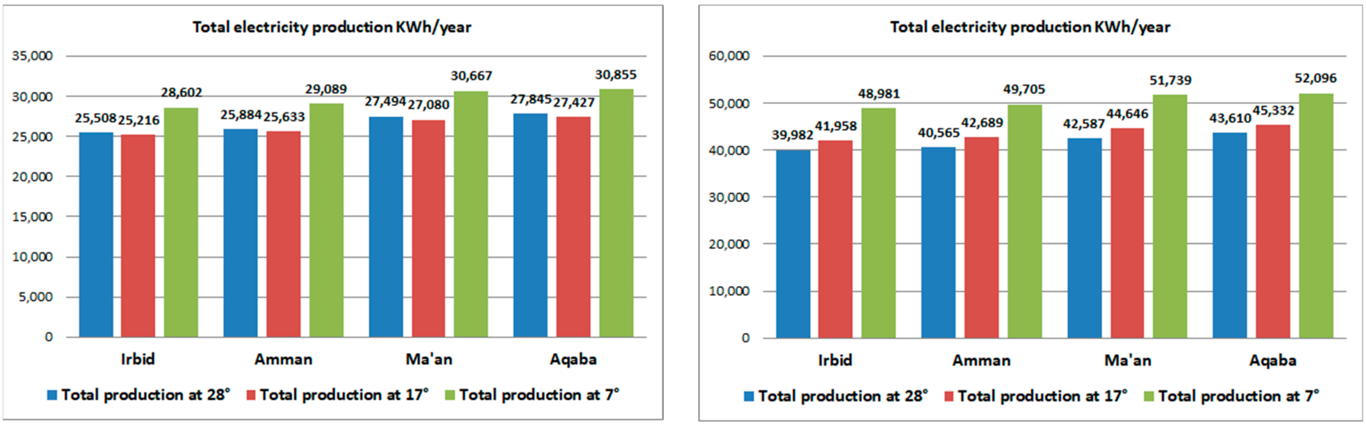


Figure 4. The selected cities and the solar radiation intensity (global horizontal irradiation) for different regions in Jordan (solarGIS 2021 Geomodel solar).

Finally, the total energy production was calculated for each building type and for each household (apartment), as the rooftop of apartment buildings is shared, and then compared with the average current electricity consumption and the average future consumption for 2030.

3. Results and Discussion

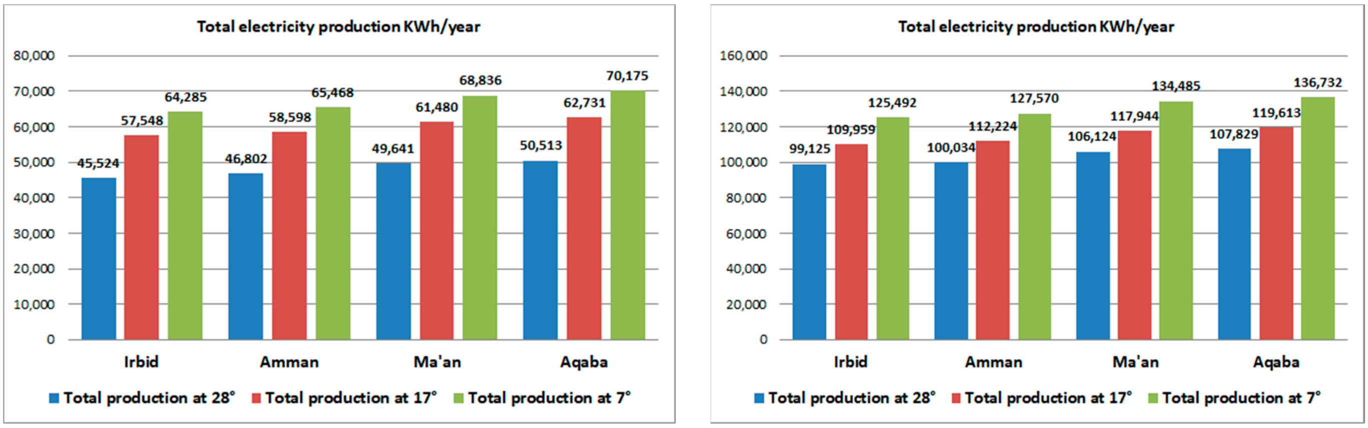
The electricity production from the installation of PV systems on the rooftops of different types of buildings was calculated. The total electricity production was dependent on the available roof area, building type, selected city, and tilt angle. The highest energy production was for apartment building A2 as it had the largest roof area. For all building types and cities, the highest electricity production was achieved with PV panels at a tilt angle of 7° as this enabled the installation of more PV panels because the distance between panels was smaller. The second highest was achieved with PV panels at a tilt angle of 17°, which was followed by PV panels at the optimum angle of 28°. The highest energy production for each kW of installed power was achieved by PV panels at a tilt angle of 28° (see Figures 5 and 6). Regarding the selected cities, the PV system with 1 KWp installed on a rooftop with an optimum distance between the raw and optimum tilt angle of 28° produced the highest value in the city of Aqaba (approximately 1750 kWh per year), followed by the cities of Ma'an (approximately 1720 kWh per year), Amman (approximately 1650 kWh per year) and Irbid (approximately 1620 kWh per year).



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

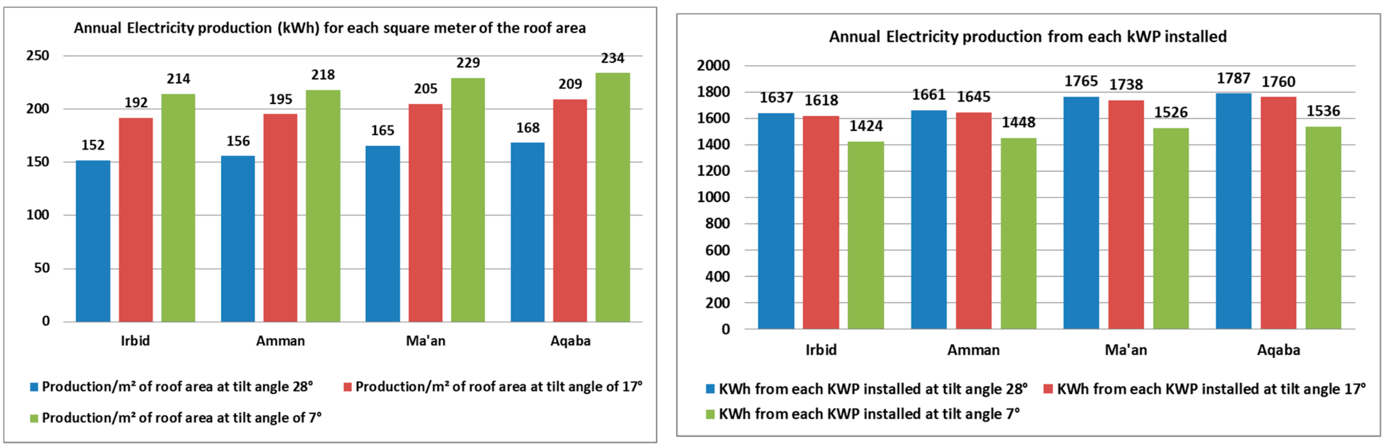
Figure 5. Total electricity production from the installation of PV systems on the rooftops of (**a**) single houses and (**b**) villas.

When installing the PV systems to cover the rooftops of the buildings (except shaded areas and the stair's roof), the total electricity production for all locations and building types was higher with PV panels at lower tilt angles rather than the optimum angle. The total electricity production for the square meter of the roof area at the optimum tilt angle of 28° was 152 kWh, 156 kWh, 165 kWh and 168 kWh for Irbid, Amman, Ma'an and Aqaba, respectively. At a tilt angle of 17°, electricity production was 192 kWh, 195 kWh, 205 kWh and 209 kWh for Irbid, Amman, Ma'an and Aqaba, respectively. At a tilt angle of 7°, electricity production was 214 kWh, 218 kWh, 229 kWh and 234 kWh for Irbid, Amman, Ma'an and Aqaba, respectively. This is mainly because at lower angles, there was less space between panels and, in this case, the installed power and consequently the electricity production was higher. The difference in the total annual production from the installed PV power at each square meter of the rooftop between the optimum tilt angle of 28° and a lower tilt angle of 7° was up to 62 kWh for Irbid and Amman, and 64 kWh and 66 kWh for Ma'an and Aqaba, respectively (see Figure 7a). The annual electricity production from each kW of power installed was the highest at the optimum angle of 28°, reaching up to 1637 kWh, 1661 kWh, 1765 kWh and 1787 kWh for Irbid, Amman, Ma'an and Aqaba, respectively. Production at a lower tilt angle of 17° reached up to 1618 kWh, 1645 kWh, 1738 kWh and 1760 kWh for Irbid, Amman, Ma'an and Aqaba, respectively. Production at the lowest tilt angle of 7° reached up to 1424 kWh, 1448 kWh, 1526 kWh and 1536 kWh for Irbid, Amman, Ma'an and Aqaba, respectively. The difference in the annual electricity production from 1 kWp installed between the optimum tilt angle of 28° and a lower tilt angle of 7° reached up to 213 kWh for Irbid and Amman, and 239 kWh and 251 kWh for Ma'an and Aqaba, respectively (see Figure 7b).



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

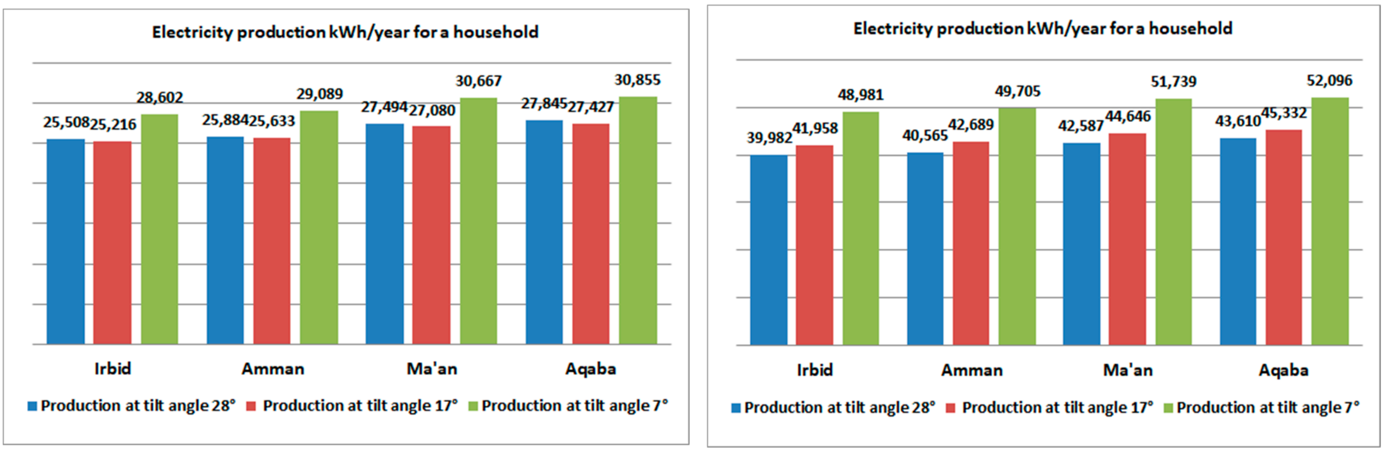
Figure 6. Total electricity production from the installation of PV systems on the rooftops of apartment buildings type (**a**) A1 and (**b**) A2.



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

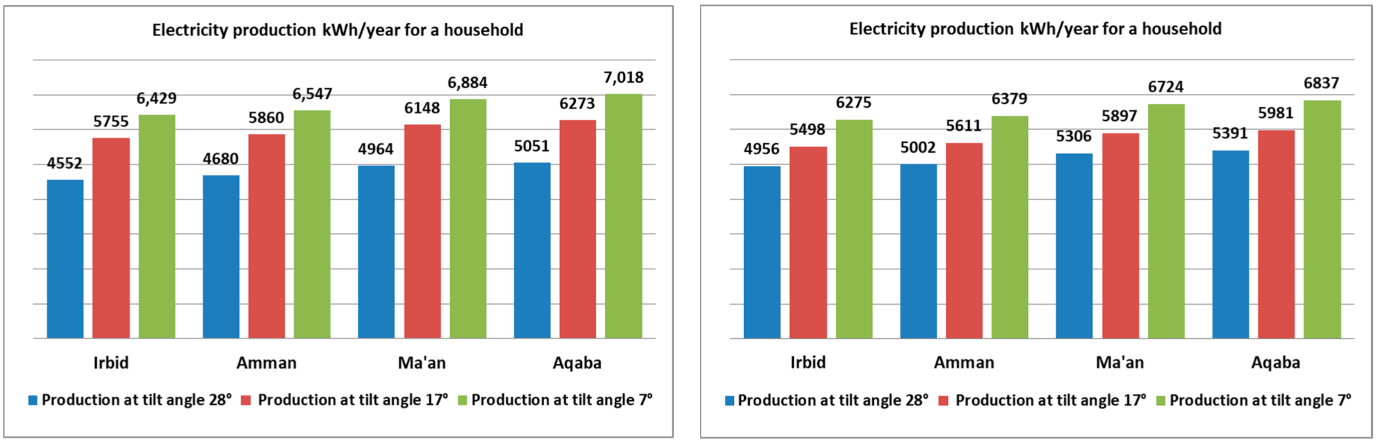
Figure 7. (**a**) Total annual electricity production in kWh for each square metre of the roof area and (**b**) the annual electricity production from each kWp installed.

The electricity production for each household was dependent on the number of households in each type of building. Villas had the highest electricity production per household with electricity production ranging between 39,982 and 52,096 kWh per year. This was followed by single houses where electricity production ranged between 25,216 and 30,855 kWh per year (see Figure 8). This was because the roof area was owned by only one household. For apartment buildings, the electricity production per household ranged between 4552 and 7018 kWh per year (see Figure 9). This is because the production from the installed PV power on the rooftop area was divided by a larger number of households.



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

Figure 8. Electricity production for each household from the installation of PV systems on the rooftops of (**a**) single houses and (**b**) villas.



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

Figure 9. Electricity production for each household from the installation of PV systems on the rooftops of apartment buildings type (**a**) A1 and (**b**) A2.

When the rooftop area available for installing PV systems for each household is high, such as in the case of Villas and single houses, the important factor to be considered is the optimum electricity production. The PV panels can be installed at the optimum tilt angle (28°). In this case, the building (one household) will produce the maximum potential compared with the investment in the systems, especially, when considering the efficiency and the payback period of the system. Even if the total production is less than the PV system at the tilt angle 7°, the PV system installed at the optimum tilt angle will produce more than four times its future electricity consumption. When the rooftop area available for each apartment is low, such as in the case of apartment buildings, the important factor becomes the total electricity production. In this case, the installation of PV systems at a tilt angle of 7° becomes more attractive even if the efficiency is lower and the payback period is longer. The installation of PV panels at the tilt angle of 17° shows no significant difference from installing the system at the tilt angle of 28° in terms of total electricity production. For this reason, the installation at tilt angles between 28° and 7° needs further analysis in future studies.

Regarding the comparison between future energy consumption and the energy production from PV systems, for single houses in different cities with panels at different tilt angles, the energy produced could cover seven to more than eight times their current energy consumption and more than four to five times their energy consumption by 2030 (see Figure 10). For villas in different cities with panels at different tilt angles, the energy produced could cover four to more than five times their current energy consumption and three to more than four times their energy consumption by 2030 (see Figure 11). Thus, the surplus energy for the two building types could be used to cover other buildings or other urban energy uses.

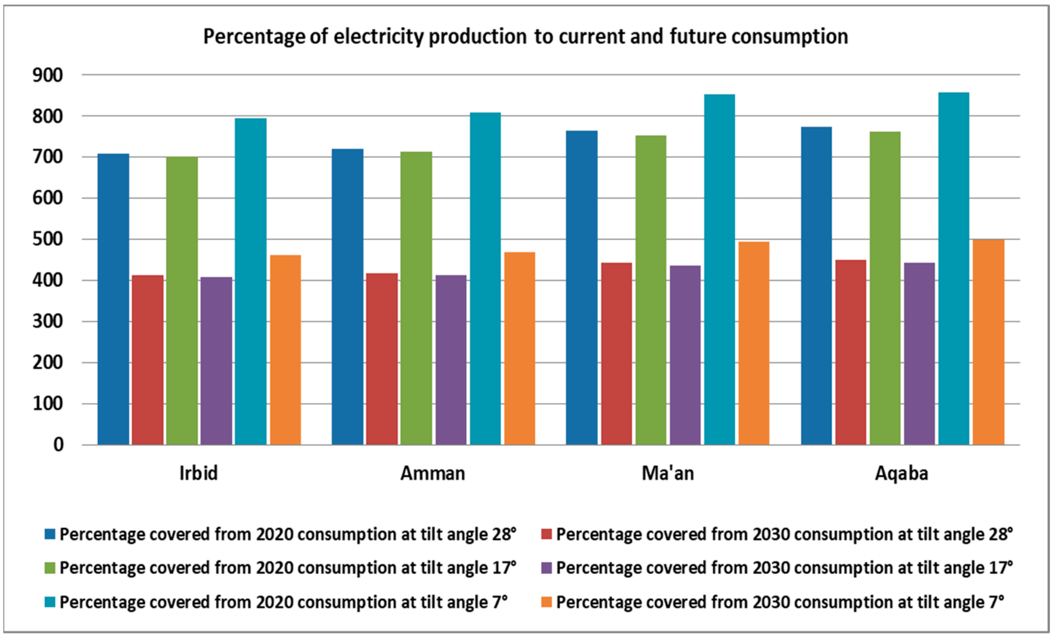


Figure 10. A comparison between electricity production from the installation of PV systems on the rooftops of single houses in relation to its current and future energy consumption.

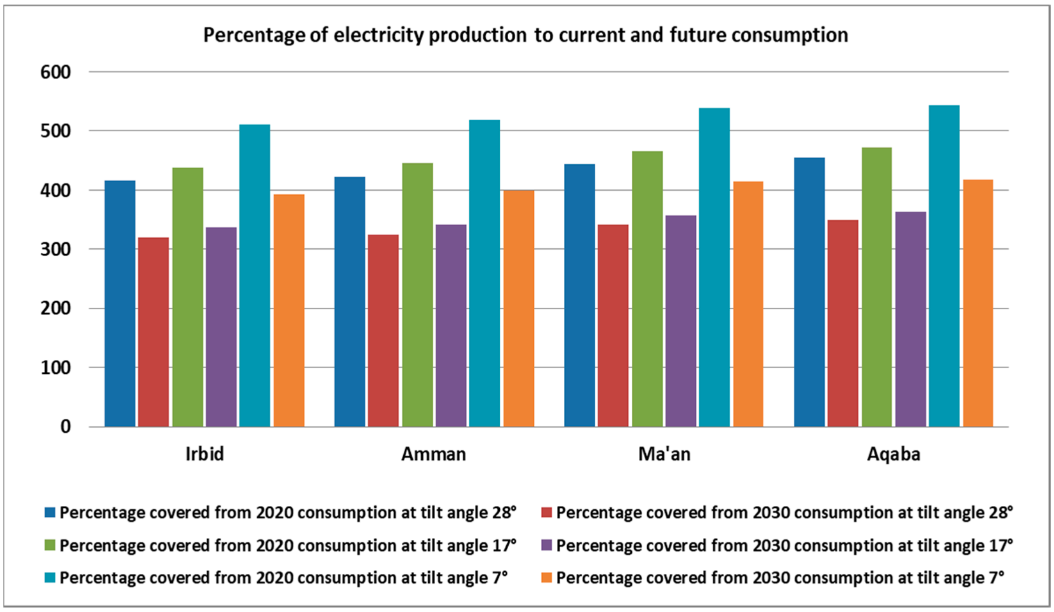


Figure 11. A comparison between electricity production from the installation of PV systems on the rooftops of villas in relation to its current and future energy consumption.

For apartment buildings type A1, the comparison between electricity consumption and production showed that energy production from PV systems could cover 0.84 to 1.3 times their current energy consumption and 0.65 to one time their energy consumption for 2030.

For apartment buildings type A2, the energy production could cover 0.92 to 1.26 of their current energy consumption and 0.7 to 0.97 times their energy consumption for 2030, as shown in Figures 12 and 13.

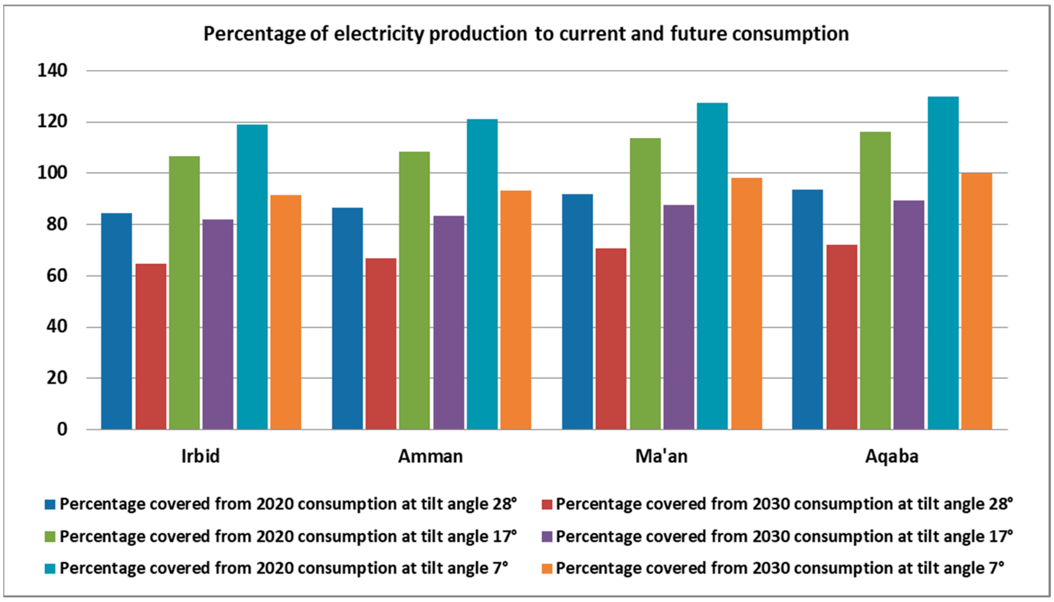


Figure 12. A comparison between electricity production from installing PV systems on the rooftops of apartment buildings type A1 in relation to its current and future energy consumption.

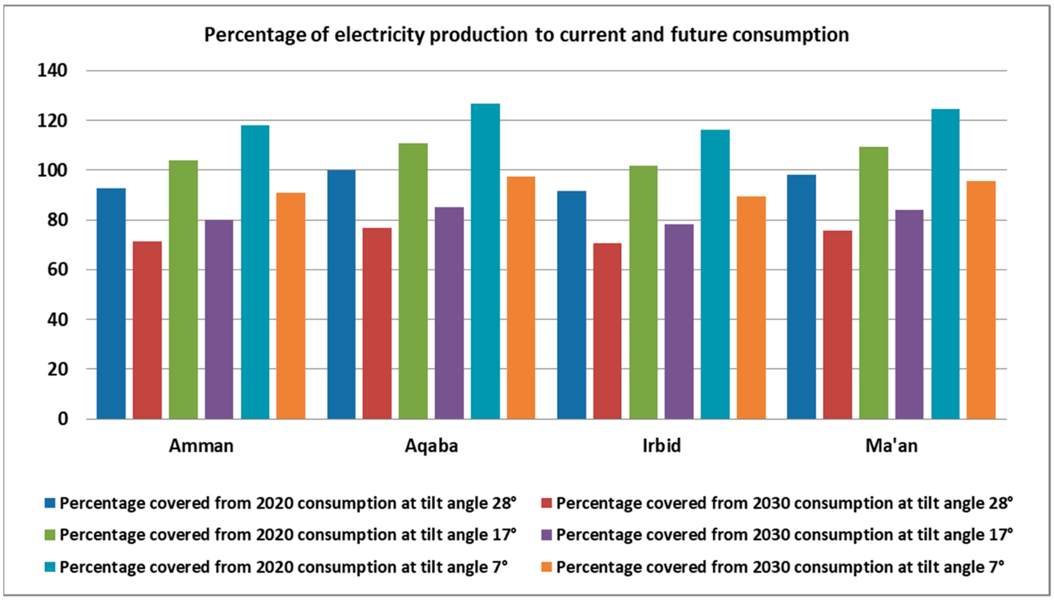


Figure 13. A comparison between electricity production from installing PV systems on the rooftops of apartment buildings type A2 in relation to its current and future energy consumption.

4. Conclusions

Despite the importance of integrating renewable energy sources to mitigate the effects of climate change and growing electricity demands, an evaluation of electricity production after installing PV systems on the rooftops of residential buildings in Jordan has not been conducted before. Jordan has high solar irradiation intensity, reaching 2281 kWh/m^2 in some regions, making solar PV investment an excellent option. Installing 1 kWp of PV systems at the optimum angle of 28° can give up to 1750 kWh per year for the city of Aqaba, followed by approximately 1620 kWh per year for Ma'an, Amman and Irbid. The annual kWh productions per each available square meter on the rooftops of residential buildings range between 152 kWh and 234 kWh, depending on the selected city and the tilt angle.

The electricity produced from installed PV systems on the rooftops of residential buildings varies depending on building type, geographic location and tilt angle. Single houses and villas with larger roof areas, compared with the number of households in the building, yield higher electricity production compared with consumption. Villas have the highest electricity production per household, ranging between 39,982 and 52,096 kWh per year, followed by single houses, with electricity production ranging between 25,216 and 30,855 kWh per year. The variation depends on the tilt angle and geographical location. These residential building types can not only cover their current and future electricity consumption but also provide an energy surplus. Single houses in different cities with panels at different tilt angles can provide seven to more than eight times their current energy consumption and four to more than five times their future energy consumption. Villas with PV panels can provide four to more than five times their current energy consumption and three to more than four times their future energy consumption. Apartment buildings produce more energy but less electricity for each household as the available roof area for each household is low compared with single houses and villas. Apartment buildings have an electricity production per household ranging between 4552 and 7018 kWh per year. PV panels can cover 0.84 to 126 times their current energy consumption and 0.65 to 1 time their future energy consumption.

The ideal tilt angle of 28° produces the highest yearly output from PV systems (kWh produced by 1 kWp). As there is a sufficient area for power generation (roof area/number of dwelling units), this may be the best option for single houses and villas because the spacing among PV arrays is limited, enables for further Photovoltaic installation, a smaller tilt angle of approximately 7° is the easiest alternative for smaller rooftop availability because it achieves the highest electricity production. For apartment buildings 1 and 2, this may be the best solution. For various building types, tilt angles of 28° and 17° produce comparable outcomes and provide highest annual output (kWh production for each installed kW). The best annual kWh output for each m^2 of roof area is at a tilt angle of 7°. At a tilt angle of 28°, the annual yield might reach 1790 kWh/kW, whereas at a tilt angle of 7°, the kWh generation per m^2 can reach 235 kWh/m^2/year.

When taking into consideration other factors affecting the electricity production from installing PV systems, such as overall efficiency, the cost and payback period for the investment, the maintenance and the cleaning, the single house and villas are the most attractive types as they have the highest roof area compared with the number of households and consumption. In this case, the installation can be at the optimum tilt angle (highest efficiency) and the payback period for the cost of the system, maintenance and cleaning is the most feasible. Other important building types with large number of households and high electricity consumption such as apartment buildings, the installation of PV systems can focus on the total electricity production—even with lower efficiency—to cover the majority of their consumption. In this case, the investment cost in the PV system is higher and the payback is longer.

The results from this research show that the investment in the installation of PV systems on the rooftop has high feasibility, with some differences between building types- and can provide a surplus in the production compared with the consumption for some building types and can produce the majority of the consumption for other building types. These results can be used to address the rise in energy and mitigate the effects of climate change in the Middle East. Residential buildings can cover much of their needs and some urban electricity demands, which will lead to more energy sustainability in the future.

Finally, the study has limitations and assumptions that can be addressed in future studies, including the efficiency for the conversion systems and the maintenance and cleaning of the PV system were predefined by the software based on the selected PV type and the selected modules. The study also does not include the effects of cost analysis incorporated with the life cycle cost LCC and LCA and life cycle analysis.

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