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Article

Fulfilling the potentials of residential solar energy in Egypt

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Abstract: Energy plays a very important role in Egypt's economic development, but the country has a gap between its produced energy and the demand of its growing population. Utilization of solar power systems in Egypt could help the country to close this gap and fulfil its national and international obligations. However, since 1980, the focus in Egypt has been on large-scale industrial solar projects. Limited attention is given to smaller systems for typical residential buildings. The aim of this research, therefore, is to highlight the potential of small residential solar systems (SRSS) in Egypt. With the huge number of residential buildings accommodating more than 115 million Egyptians, SRSS could be the unearthed gem of a sustainable source of energy in Egypt. The geographical location of Egypt and climate were used to generate solar data using the Global Solar Atlas application. The amounts of monthly and annual solar irradiations were calculated and analysed to decide the best orientation of the system (facing east, west, north, and south), identify the optimum tilt angle of the system, and determine the size of the solar panels. A case study was used to illustrate the procedures of designing SRSS for a typical residential building in Egypt. The results showed that a 26 kWp SRSS oriented facing the east with an optimum tilt angle between 15° and 30° could produce an annual total output of electricity more than the annual demand of the occupants of the studied residential building. Such a system would fit easily on the roof of the building. It was concluded that the installation of SRSS in Egypt could help the country meet the demand of its ever-increasing population if properly regulated, financed, and managed. It is recommended that Egypt develop and implement policies to make installations of SRSS an attractive choice among homeowners and investors by introducing encouraging incentives and creating a competitive market with affordable SRSS.

Keywords: sustainability; solar power; energy efficiency; residential buildings

1. Introduction

Energy used in everyday human activities is huge, and its environmental impact is substantial. In the last three decades, researchers have paid great attention to the impact of different human activities and processes on the environment. Thus, concepts such as sustainable development, greener human activities, green processes, green technologies, and protection of natural resources have emerged. However, the global demand for energy is increasing due to the continuous growth of the world's population, which could approach ten billion by 2050. Moreover, it is projected that the population in cities and urban areas will be more than two-thirds of the world population in the next two decades, leading to further demand for infrastructure for service [1–2].

In 2021, Tadros et al. [3] reported that developing countries in Asia and Africa will witness the fastest growth in urbanization, with seven of the ten countries with the fastest projected urbanization rates between 2018 and 2050 being in Africa. Energy plays a very important role in the economic development of developing countries, but many of them have gaps between their produced energy and the demand of their growing populations. One of those countries is Egypt.

Egypt is the third-most populous country in Africa, after Nigeria and Ethiopia. With a current population of about 115 million, it is the 14th most populous country in the world. **Figure 1** presents the growth of its population in the past, present, and future prediction by the UN Population Division.

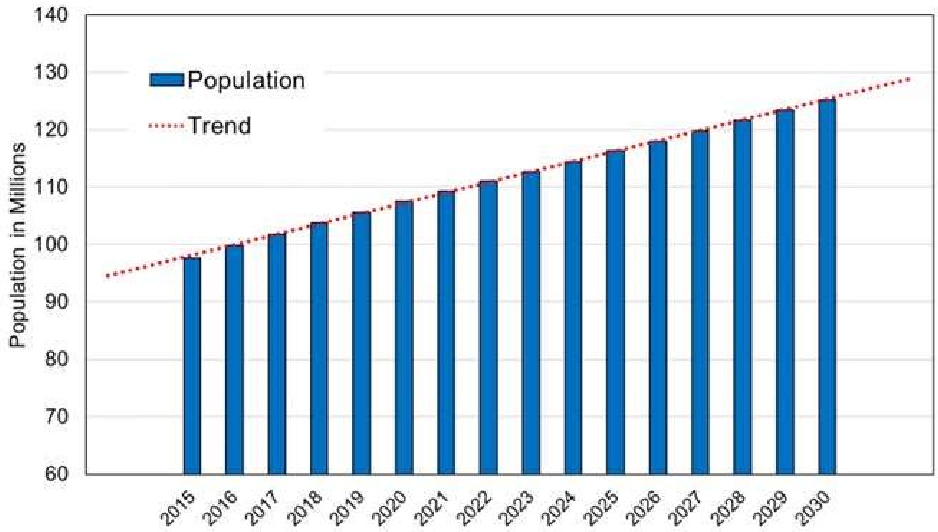

Figure 1. Projection of Egypt population, 2015 to 2030 (UN Population Division).

The total population in Egypt is predicted to continuously increase between 2024 and 2030 by more than 10%, from 115 to 125 million [4]. The trend indicates ten consecutive years of population growth, with no sign of fading. In response to this ever-increasing population, Egypt is witnessing a rapid rate of construction to accommodate its expanding population and the demand for affordable housing with basic infrastructure services. Construction of buildings requires enormous resources, including materials and energy, among other resources that are vital for the proper operation of any building. In addition, Egypt is one of those developing countries progressing in their development and trying to achieve its ambitions of becoming a recognised industrial state. Therefore, energy plays a very important role in Egypt's economic development. However, the country has limited energy resources, with the current per capita installed power being less than 0.50 MW/c, as shown in **Table 1** [5]. According to the IEA [6], Egypt will need some 19 GW of new capacity by 2030 to meet the forecast electricity demand. Attempting to increase the production of energy by traditional sources is a real challenge. Several international organisations suggested that Egypt should aim to exploit renewable energy (RE) sources [6,7].

Recently, Egypt recognized that sustainable development requires sustainable resources and deemed the current energy situation not sustainable. The Egyptian Supreme Council for Energy adopted an ambitious plan aiming to generate 20% of Egypt's electricity needs from RE resources by 2027 [8,9]. However, the focus is on large-scale industrial projects, such as concentrated solar power (CSP), which are employed in Egypt for industrial productions of electricity [10]. Other large industrial solar systems include generation of electricity from ground-mounted large-scale systems, which include photovoltaic panels—also known as modules or solar collectors—mounted on fixed or movable tilted structures aligned in a matrix of rows and columns. Unfortunately, the utilization of solar systems in residential buildings is very limited and only exists in the form of solar collectors used for individual domestic water heaters. Furthermore, most of these water heater units have been installed in state-owned new developments in new cities and some hotels in remote tourist resorts.

Table 1. Egypt's installed electric power indicators (2012–2032), adapted from Comsan et al. [5].

Year	2012	2017	2022	2027	2032
Population (million)	91.2	101.8	110.9	119.8	128.7
Per capita installed power (MW/c)	0.32	0.37	0.43	0.48	0.54
Total (GW)	29.0	37.8	47.1	57.7	70.0
Installed power annual growth rate (%)	6.5	6.1	4.9	4.5	4.3

This research, therefore, aims to highlight the huge potential for solar energy applications in residential buildings. With the huge number of residential buildings accommodating more than a hundred million Egyptians, small residential solar systems (SRSS) could provide an invaluable source of clean energy in Egypt. The implementation of SRSS could trigger the development of cost-effective alternative renewable energy in Egypt, which could help in closing the gap between the huge demand and its limited energy from conventional resources.

This paper is structured to report the outcome of this research. Section 2 provides a background on solar energy and the three generations of photovoltaic (PV) technology. Section 3 discusses the current energy resources in Egypt, including solar energy, and highlights the need for implementing more RE to supplement the limited conventional resources. Then, the small residential solar system (SRSS) is introduced in Section 4, showing the possibilities of interconnecting the system to the power grid. Section 5 includes discussion on quantifying the potentials of SRSS in Egypt and then uses a case study to illustrate the initial design of a SRSS. The main taking-away outcomes are then concluded in Section 6, which is followed by some recommendations in Section 7. Finally, the limitations of this research and suggested further work are given in Section 8.

2. Solar power systems

Producing the energy needed for any activity or process from a sustainable renewable source could reduce its negative impact on the environment. RE produced onsite could be converted to electricity before using in any application. Alternatively, it could be integrated directly into the process or operation. Integrating renewable energy within any process could enhance its own sustainability credentials. For example, Badr [11] suggested that the environmental benefits of integrating renewable energy in desalination could enhance its sustainability and reduce its impact on the environment, such as a photovoltaic (PV)-powered desalination unit [12,13]. Several sources of renewable energy could be utilised including wind, biomass, and geothermal, but solar power is the most obvious candidate. Solar energy can be utilised for sustained energy supply. It could help in reducing the impact on the environment [14,15].

Photovoltaic (PV) is a promising process that can convert solar irradiation to electricity [16]. Integrating PV systems within new building structures, known as Building Integrated Photovoltaics (BIPV), requires installing fully functional PV modules within the building enclosure, preferably during the construction process. Compared to non-integrated systems, BIPV offers advantages such as reducing utilised land. It could also be used as a valuable marketing feature for planned developments [17–20]. However, most of the PV systems installed worldwide are from first-generation PV technologies. Li et al. [21] provided an insight into the development of PV technology from the first generation to the current third generation. The latter focuses more on utilizing new materials in developing more efficient PV panels with lightweight structure and reduced material consumption [22]. There is evidence in the literature that the progress in the development of such systems is promising and that the new generation of PV systems is more efficient, economical, and has a better environmental impact. For example, Li et al. [17] investigated the economic and environmental performance of new types of BIPV in three countries in Europe and proved that they are economically feasible systems. They concluded that the outcome of their study can serve as valuable guidelines for the design of BIPV projects. In all cases, and regardless of the PV technology generation, all PV systems require exposure to significant sun irradiation, which in turn depends on the geographical location and optimum orientation of the system.

3. Energy resources and solar power in Egypt

Figure 2 shows the share of different primary energy sources in the production of electricity in Egypt. The figure illustrates the change of the pattern over the years in the past, present, and projected in the future until 2050 [6].

The share of different primary energy sources in electricity generation changes with time. In 2008, gas was the main source, representing about 85% of the total electricity production. This was followed by 12.5% for hydropower and 1.5% for wind power [23].

The DLR (German Aerospace Center) forecasted the electricity consumption for Egypt up until 2050, considering the expected population increase and the expected economic growth. DLR indicated that meeting the demand would not be possible by relying on conventional energy sources and suggested that the country should aim to exploit renewable energy sources. It also suggested that solar energy should be among the prime sources of renewable energy and that Egypt shall target a share of more than 50% by the year 2050 [7].

Renewable energy (RE) resources in Egypt include wind, solar, and biomass. Since the 1970s and 1980s, Egypt has dedicated effort to exploit RE potentials. A renewable energy strategy was formulated and included in the national energy planning. In 1986, the New and Renewable Energy Authority (NREA) was established to progress efforts to develop and introduce RE technologies in Egypt.

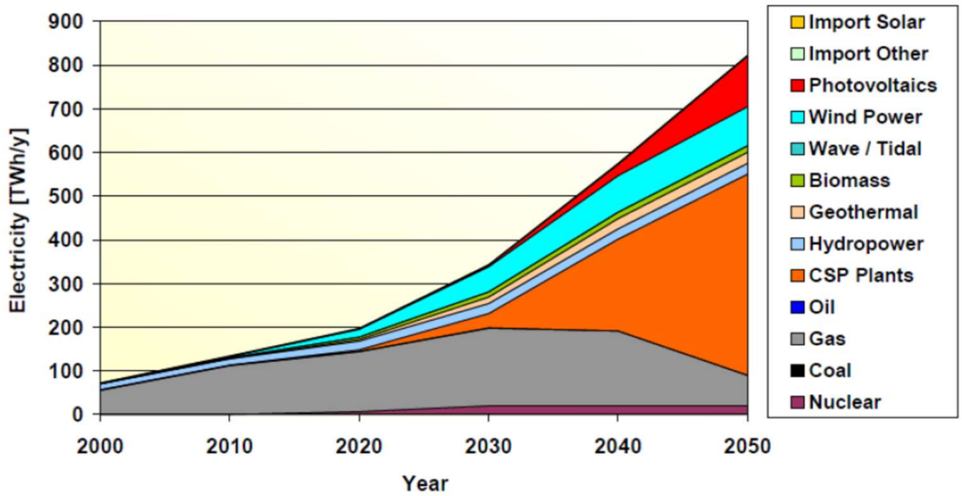

Figure 2. Electricity production by primary energy sources in Egypt [6].

Egypt's strategic plan, aiming to generate one-fifth of the country's electricity needs from RE resources by 2027, was announced by the Egyptian SCoE in 2007 [5,9]. To achieve this target, the Ministry of Electricity and Energy (MoEE) updated its electricity generation plans, as shown in **Table 2**. The share of electricity generation from RE sources was significant but focused more on wind energy up to 2027. The plan opened the door for private sector involvement in the process and encouraged investors to participate and invest in developing the country's RE resources. However, most of the effort from the state and the private sector focused on large industrial applications [5,8].

Table 2. MoEE Generation Plans 2007–2027 (GWe).

Year	Pre 2007	2007–12	2012–17	2017–22	2022–27	Total	Total (%)
Thermal	18.936	6.550	11.900	10.450	13.000	60.836	79.4
Hydro	2.783	0.064	0.032	-	-	2.879	3.8
Wind	0.225	1.600	2.980	2.500	0.500	7.805	10.2
Solar-thermal	-	0.140	-	-	-	0.140	0.2
Nuclear	-	-	1.000	2.000	2.000	5.000	6.5
Total	21.944	8.354	15.912	14.950	15.500	76.660	100

In general, the private industrial applications of solar power are thermal systems for water heating. According to Mobarak [23], there are three solar thermal systems utilized in Egypt. Two of them are flat-plate solar collectors, including solar water heating systems and integrated solar water heating systems. The third is a parabolic collector solar system. Most of these systems are imported, although solar hot water systems have been manufactured in Egypt since the early eighties [23,24]. Also, concentrated solar power (CSP) projects are large-scale industrial projects that are employed in Egypt for industrial productions of electricity [10]. Other large industrial solar systems include generation of electricity from ground-mounted large-scale systems, which include photovoltaic panels mounted on fixed or movable tilted structures.

Currently, the utilization of solar systems in residential buildings is very limited and only exists in the form of solar collectors used for individual domestic water heaters. A typical system comprises a 150-liter tank, a 2 m^2 solar collector, and a 3-kW electric backup heating element. Most of these water heater units have been installed in state-owned new developments in new cities in the desert. Some hotels use several units of the same system, particularly in remote tourist resorts.

4. Small residential solar system (SRSS)

A small residential solar system is like an industrial ground-mounted system but with a much smaller matrix of photovoltaic panels mounted on a tilted roof of a building or a tilted structure on top of a residential building. Its installation is easy and does not require additional areas for installation. As an additional advantage, a small residential solar system also acts as an additional layer of insulation on the roof of the building. Installation of small residential solar systems on tilted structures offers the best options because the systems could be installed facing the preferred direction and optimum tilt angle. Advanced technologies offer more flexible motorized systems to allow for changing the tilt angle and move the panels to face the sun path during the day to maximize the exposure to the radiation. They can also be installed on sloped roofs and vertical surfaces facing preferred directions. Technological improvements in materials and design resulted in the availability of the panels in several colours and forms, including solar tiles, bifacial solar panels, and transparent solar modules [15,16,19].

The electricity generated by the system could be used directly by the occupants of the building for their everyday needs. It is advisable in this case to consider electricity storage facilities to cater for the times when the generated electricity is less than the consumption, such as at night or on cloudy days. Alternatively, it could be connected directly to a low-voltage grid through an inverter, in which case electricity storage is not needed. Three possibilities are illustrated in **Figure 3** [15].

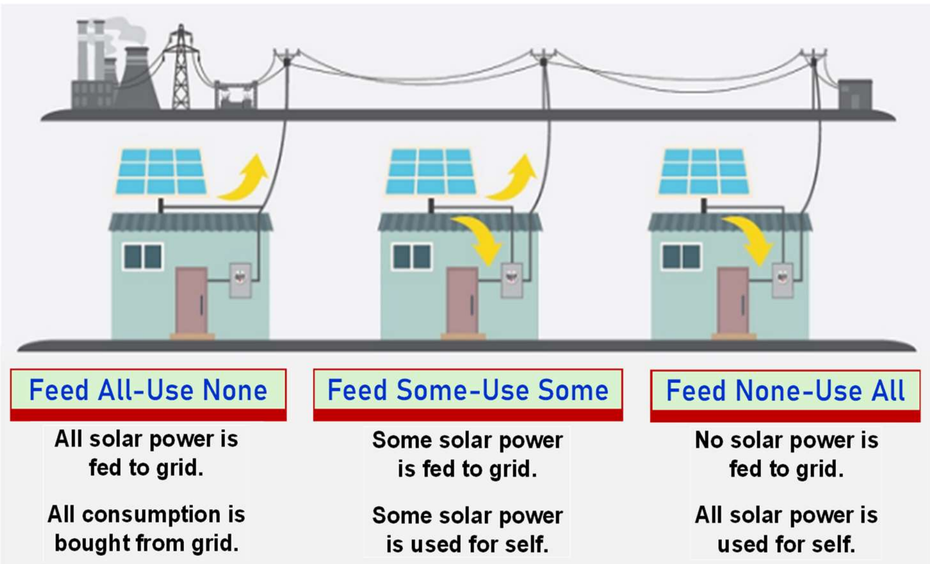

Figure 3. Interaction of solar system with the power grid, adapted from [ESMAP 2021]. License: Creative Commons Attribution CC BY 3.0 IGO

5. Discussion

The amount of solar energy produced from a PV system, regardless of its technology generation, is proportional to the amount of sun irradiation received by the system. The exposure to enough sun irradiation, in turn, depends on the geographical location (particularly longitude and latitude) and the season or the time of the year. Therefore, this section starts with highlighting the advantage of Egypt's geographical location. Then the discussion on quantifying the potentials of SRSS in Egypt is provided. This is followed by a case study on a typical Egyptian residential building to illustrate the initial design of an SRSS, including deciding on the orientation of the system, its optimum tilt angle, and sizing the SRSS system.

5.1. Egypt's geographical location

Egypt has a strategic location in Africa and the Middle East. Most of the country is in northeastern Africa and is extended into Southwest Asia via its Sinai Peninsula. Historically, it was connecting the main old three continents: Africa, Europe, and Asia. The latitude and longitude of the centre of Egypt are 26°15′ N and 30°20′ E. Egypt has an area of just over one million square kilometres, 6% of which is urbanised and populated. The rest is mostly flat, open, sunny deserts [25].

5.2. Quantifying the potentials of SRSS in Egypt

The geographical location determines the climate of a country, city, district, or property. Due to its unique location and climate, Egypt is considered one of the Sun Belt countries, which has great solar potential, as can be seen in **Figure 4**. The amount of annual and daily global solar irradiation should be considered and analysed to decide on the feasibility of using solar power as an alternative sustainable source of energy in a specific location, city, or country.

In addition to the solar system's capacity, type, and technology, the amount of solar energy produced in a full cycle of one day depends on many other factors. However, there are three factors that are most important. The first is the orientation of the system (facing east, west, north, and south). The second is the tilt angle of the system. The third is the number of sunshine hours daily and annually. Clearly, the latter cannot be altered, although it should be considered in the initial stage of the decision-making. The correct choice of the orientation and the tilt angle are, however, crucial in getting the maximum possible power output.

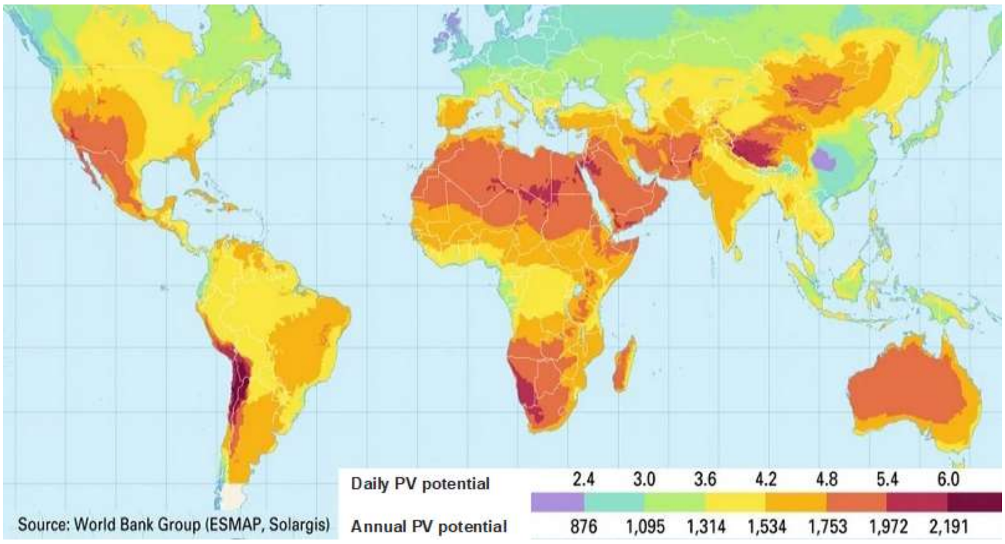

Figure 4. Daily and annual PV power potential in the world (kWh/m^2) [ESMAP, Solargis].

In 1991, a solar atlas for Egypt was issued, confirming the massive potential for solar energy production. It highlighted that the sunshine is in abundance with plenty of sunshine, and the annual direct normal irradiation (DNI) density ranges from 1700 to 3000 kWh/m^2, as can be seen in **Figure 5**. These solar credentials resulted in the technical projection of a potential solar-thermal electricity generation of more than 70 petawatt-hours (PWh) [14].

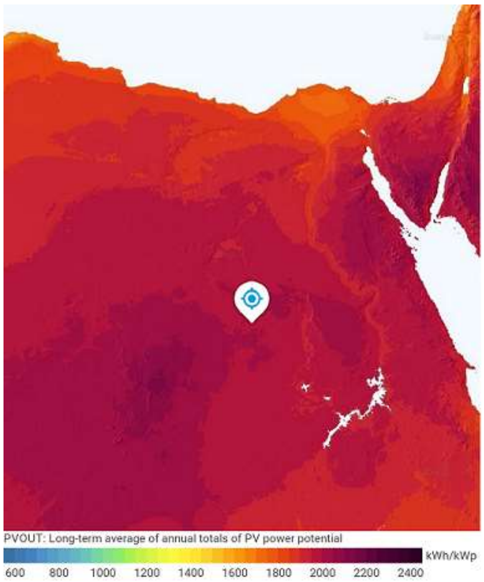

Figure 5. Distribution of annual solar DNI in Egypt (kWh/m2) [ESMAP, Solargis].

The number of sunshine hours per day is more in summer than winter and varies according to the location and geography of a place. The potential of producing solar power using a specific solar system is greater for locations exposed to longer hours of sunshine, as the longer the exposure to sunshine, the more the power output.

Egypt enjoys long hours of daylight around the year, as can be seen in **Figure 6**, with an average of more than 12 h and a maximum of 14 h in June. Sunshine is around for most of the daylight hours. The average hours of sunshine are 9.4 h per day, with a maximum of 11.9 h recorded in June. Except for January and December, all days in Egypt have more than 8 h of sunshine. The annual value is a massive total of more than 3440 h of sunshine per year out of possible 4200 h of daylight. As such, the daily and total hours of sunshine in Egypt indicate great potential for generating photovoltaic electricity from solar radiation.

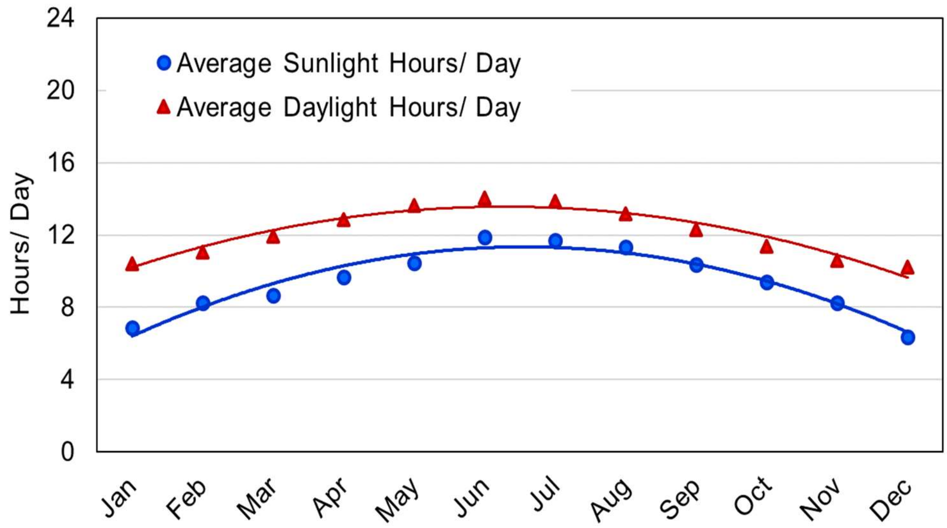

Figure 6. Sunshine hours per day in Egypt.

5.3. Case study: Typical Egyptian residential building

The assessment of the potential of an SRSS installed on the roof of a residential building in Egypt requires information about its location, the number of occupants, their monthly or yearly electricity consumption, and the size of the roof, particularly the area available for installation, which should be free from other facilities.

The mode of residential buildings in Egypt is a 4- or 5-story building. This is the maximum practical height to avoid the need to install an elevator. Such buildings would have a floor area of about 120 to 150 m^2 with a total residential area of about 600 m^2 and have a capacity to accommodate 30 people on average. A typical building of these specifications is considered for illustrating the potential of an SRSS system and deciding on key design aspects, including 1) the best orientation of the SRSS, 2) the optimum tilt angle, and 3) the required size of the system.

5.3.1. Orientation of the SRSS

Proper design of an SRSS requires deciding on the best direction of the panels, at which they are exposed to the maximum irradiation. Using data from the site, irradiation data, and information about the system, the potential of generated power could be calculated per m^2 of the panel or per a prefabricated commercial system, which could be manufactured of a specific size. It could be calculated for a specific period but is usually calculated per day, per month, or annually. To decide on the best direction, the initial calculation was based on the longitude and latitude of Egypt, assuming that the panels are mounted vertically on the face of the building. The results for systems facing North, East, West, and South are shown in **Figure 7**.

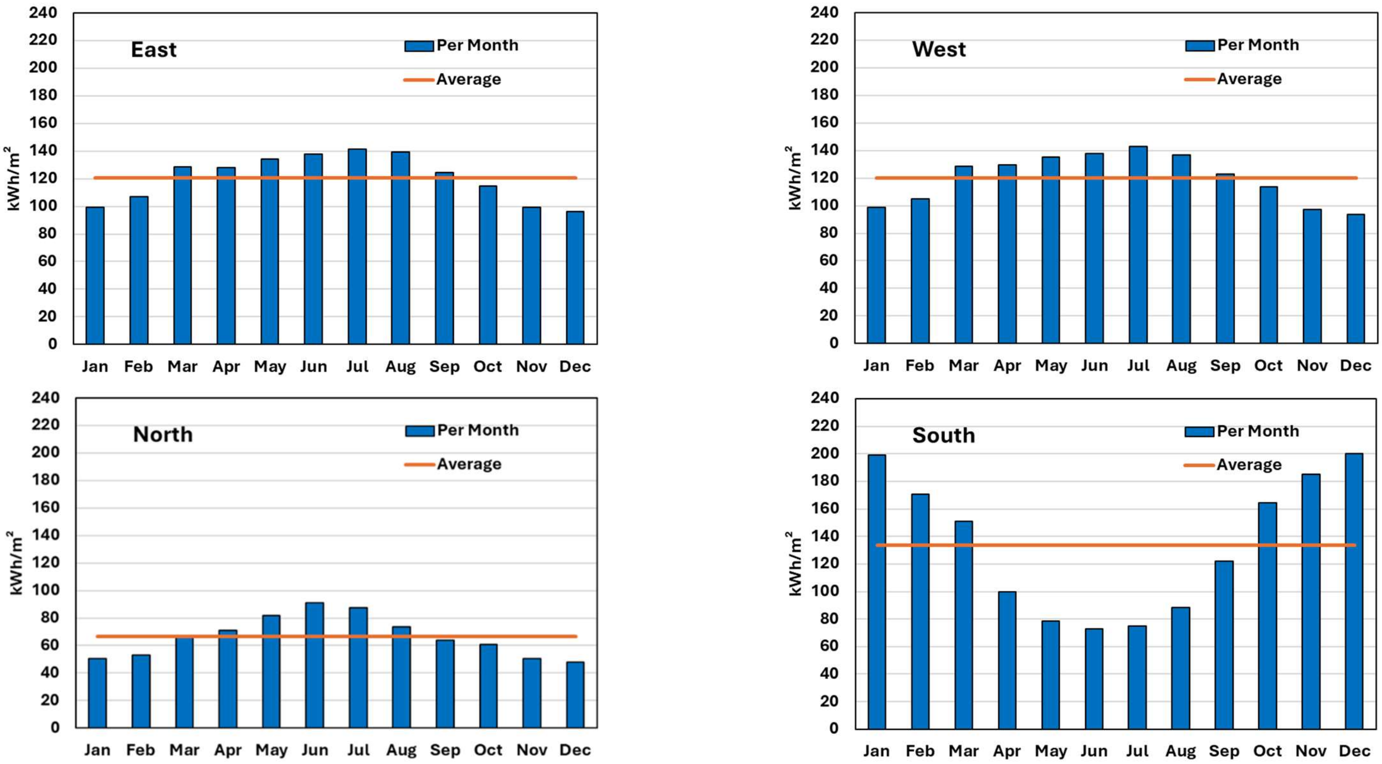

Figure 7. Solar radiation on SRSS facing East, West, North and South.

Comparing the results of solar energy potential for the North, East, West, and South indicated that the south side has the highest average irradiation, at 133 kWh/m^2 per month and a total annual average of about 1600 kWh/m^2. This would have been expected, as facing the Equator offers more exposure to sunlight. However, the south-facing system might not be the best solution because the received irradiation is the lowest during the peak consumption in hot summer months in Egypt, when air-conditioning systems are operating for long hours in the summer.

The higher irradiation in winter compared to that in summer for the south-facing side (facing equator) could be explained using solar motion geometry. The most important factor affecting solar exposure in any location on earth at a specific time is the position of the sun in the sky, which is a function of both the time and the geographic location. The sun appears to move along a circular path across the sky. This sun path depends on the geographic latitude, hemisphere side, and season. For a location in the northern hemisphere, as in the case of Egypt, the winter sun rises in the southeast and sets in the southwest. Therefore, during the day, the sun is always on the south side, hence the higher irradiation in winter on the south-facing side [26–29].

The next highest potential was obtained from the east side, which recorded an average monthly irradiation of 121 kWh/m^2 and a total annual average of more than 1450 kWh/m^2. Comparing the options, it is suggested that the SRSS should be installed facing east and south if the area permits. However, the East would be a priority. It could be noticed also that the West results could be considered as good as the East. As such, the panels could also be installed in the west direction if there were restrictions on site to install in the east and/or south directions.

5.3.2. Optimum tilt angle

Once the best orientation is decided, which for our case is a system facing east direction, the optimum tilt angle should be identified. Using the irradiation data for the east-facing system, the potential solar power at different tilt angles is calculated. For the sake of simplicity, a 1 kWp system is assumed.

The results of the photovoltaic electricity (in kWh) delivered by a 1 kWp system are shown in **Figure 8** for different tilt angles. For example, at 15°, the average output is 144 kWh per month. The corresponding values for each tilt angle are presented in **Figure 9**. It could be suggested that the best tilt would be an inclination between 0° and 15° for this site. It could be argued that such a small inclination would require a large area for installation. Tilt angles close to the vertical will require less area but would have inferior power generation potential. Practically, the results showed that an inclination up to 30° would still produce decent photovoltaic electricity.

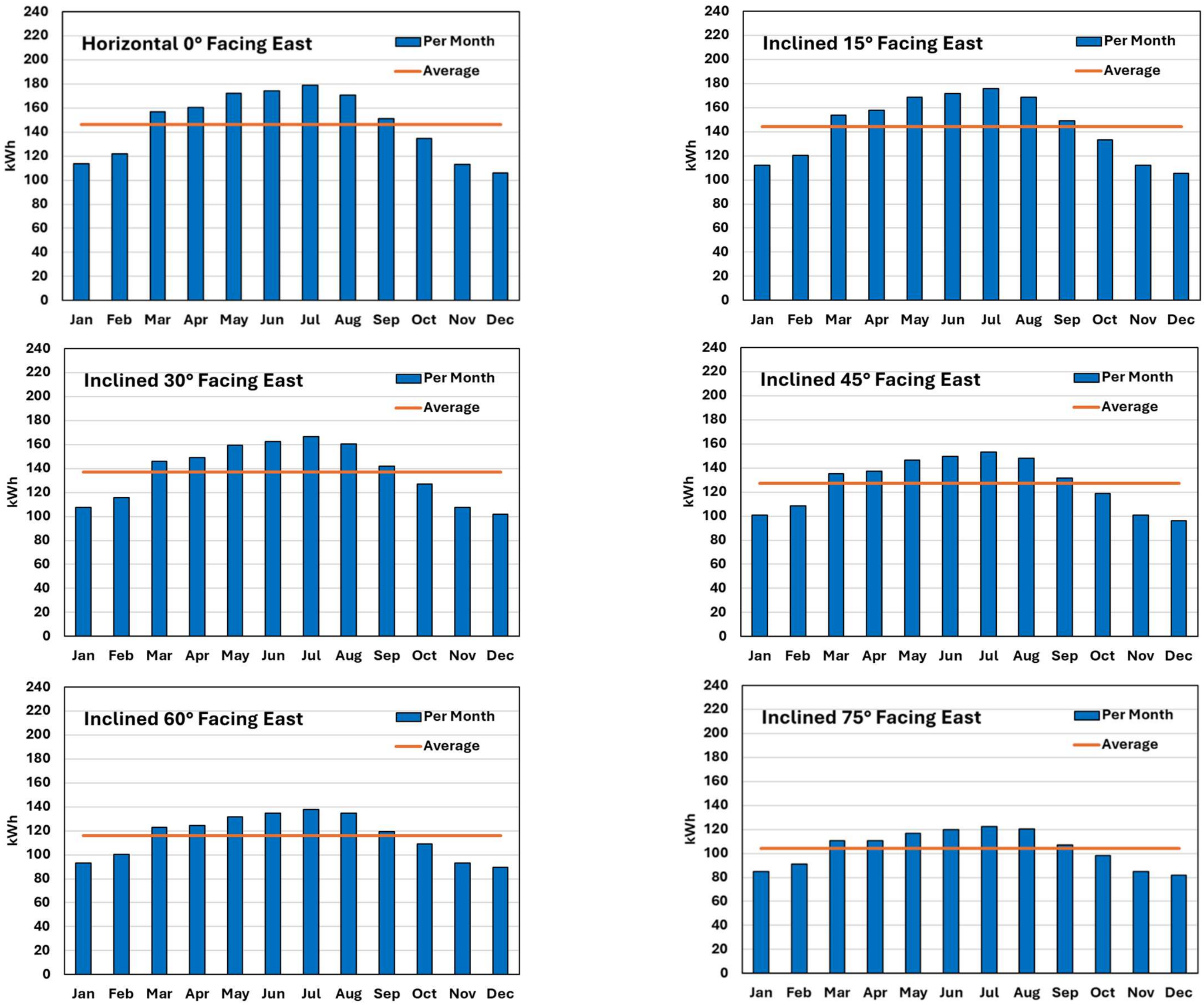

Figure 8. Photovoltaic electricity delivered by 1kWp PV SRSS.

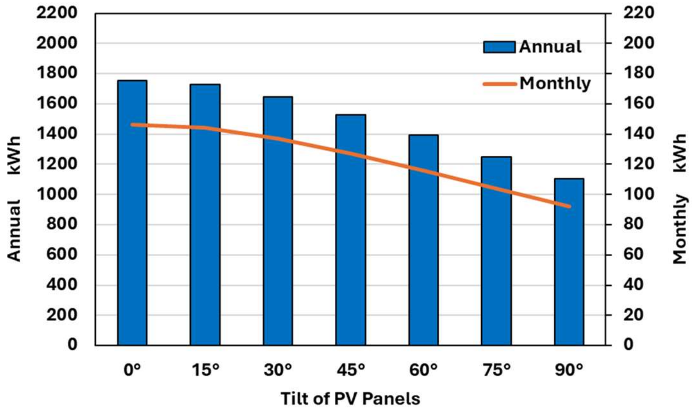

Figure 9. Effect of tilt angle on PV electricity delivered by 1kWp SRSS.

5.3.3. Size of SRSS

The final stage of the design is to decide the size of the SRSS. Taking into consideration the average per-capita electricity consumption in Egypt, the size of the SRSS could be decided. This is currently at 1500 kWh of electricity per year. Thus, for the building under consideration, of about 30 occupants, a total of 45,000 kWh of electricity is needed per year.

Our proposed SRSS is oriented facing the east with an optimum tilt of 15°. Thus, the expected output from a 1 kWp system is 144 kWh per month, on average. The annual total output of this system would be 1730 kWh, meaning a system with 26 kWp will be needed. Such a system would fit easily on the roof of that building, with ample space remaining for air circulation of the SRSS panels and other facilities to be installed on the roof, if needed.

6. Conclusions

This paper highlighted the huge potential for solar energy applications in Egypt, with a focus on small system applications in residential buildings.

This research contributes to promoting the utilization of solar power and the application of small residential solar systems (SRSS) to generate cleaner energy in Egypt. The system not only has a great potential to enable Egypt to close the gap between its produced energy and people's demand but also could help Egypt meet its national and international obligations in reducing emissions.

A case study was used to illustrate the initial design of an SRSS for a typical residential building in Egypt. It provided easy and straight-forward procedures for determining the main parameters of a SRSS, including the capacity of the system, its orientation, and the optimum tilt angle of the solar panels. It also showed that a properly designed SRSS could produce enough electricity to surpass the consumption of the residents of a typical residential building in Egypt.

The implication of implementing the outcome of this research could be significant in helping the country to realise its solar power potentials. If properly regulated, financed, and managed, the utilisation of SRSS in residential buildings in Egypt could provide the country with a sustainable and affordable renewable source of energy.

7. Recommendations

Considering the great potential of utilising SRSS in Egypt, it is recommended that installations of residential solar systems should be made an attractive alternative for homeowners and investors. This could be achieved by implementing the following recommendations.

- Introduce a financial structure that is mainly subsidized to provide the population with easy and adequate access to financial support for solar energy.
- Create a competitive market by encouraging investors from the private sector to invest in designing and manufacturing affordable SRSS of different sizes to accommodate the needs of old buildings and new developments.
- Implement and improve the existing policies to require all new residential and commercial buildings of certain sizes to install certain number of solar units proportional to the size of the building and the number of occupants.

8. Limitations and further research

The focus of this research was on highlighting the importance of small residential solar system (SRSS) for Egypt to realize its great solar potential. Mainly, to close the gap between its produced energy and the demand of its growing population. However, due to the lack of reliable data and vital information on social and economic aspects, it was not possible to conduct a complete life cycle assessment of the proposed system. This could be addressed in future research, once the required information is made available.

Furthermore, the economical affordability of the system could be investigated, including viable proposals for financial funding for installing the system based on targeted profit for investors and property developers.

In addition, further research could also include optimizing the design of SRSS for specific geographical governorates in Egypt.

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Conflict of interest: The author declares no conflict of interest.

Nomenclature

kW	kilowatt (thousand watt)	kWh	kilowatt-hour
PV	photovoltaic	kWp	kilowatt-peak of a PV system
MW	megawatt (million watt)	MW/c	per capita installed power
GW	gigawatt (billion watt)	GWe	gigawatt-electric (billion watt)
PW	petawatt, (1015 watts)	BIPV	building integrated photovoltaic(s)
RE	renewable energy	SRSS	small residential solar system(s)

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