Performance Analysis of a 22.8 kW PV Solar System of the HCT Eco-house in Oman

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Abstract: This paper investigates the performance of a 22.8kW PV solar system for the eco-house in the Higher College of Technology in Oman. The house is located in Muscat at 23.579° N, 58.432°E**.** Data measurements from October 2017 to September 2018 were used to analyze different ambient temperature conditions, wind, daytime, and solar irradiation. The soiling and dust effects were also considered. The solar system is grid-connected, and the total annual net energy out of the imported and exported energy is calculated and found equal to 1540kWh, which shows a positive net-zero house compared to the traditional Omani house. The average monthly generated solar energy varied between 1800kWh and 4500kWh at the optimum weather and clean solar panels case. The annual average efficiency of the solar system was found equal to 5.44%.

Keywords: PV system, Eco-house, Net metering, Net-zero energy building, Weather

1. Introduction

Besides the global economic challenges and the recent national announcement in Oman about the new electricity and water tariff, the expected increase in the electricity cost is around 28% in non-residential and 5% in residential sectors; Therefore, need for an innovative, practical, economical solution becomes a must to cater electricity demand of the users. Solar systems represent a vital solution for most of the energy applications in Oman and most of the Arab Gulf Region. Solar energy is one of the necessary and strategic solutions for supplying electric power in Oman to achieve the set target of 20% contribution of renewable energy by 2030. In Oman, solar energy is abundant, and the highest amount of solar energy is received in desert areas. Figure 1 shows the solar intensity in Oman. It shows that Oman is located high solar intensity range, and the average measured daily received amount of energy is more than 5 kWh/m^2/day [1-3].

Study [4] claimed that the potential of solar energy in Oman has the ability to generate 20,000 tons/day at wet steam of pressure 40 bars, at 50°C.

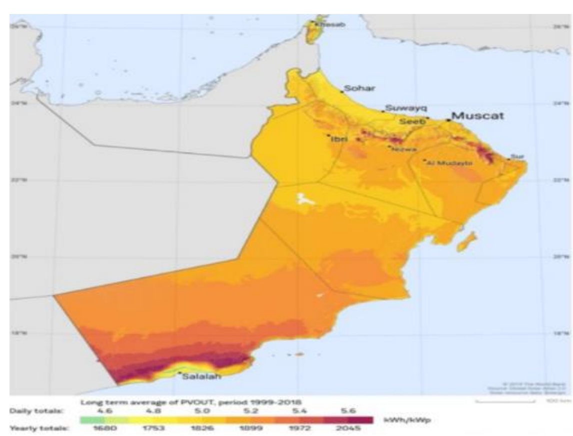

Fig. 1 Map of Oman–solar intensity[5]

The study which was carried by [6] indicate that possibilities of reducing the CO_2 production by 38% if hybrid solar- diesel system is used in compare with the conventional gas powered system. Up to 2025, OPWP plans to procure around 2,200MW of renewable energy using solar, wind, and waste-to-energy or hybrid systems [7]. In 2015, a 370kW solar power plant started to operate in Al Mazyunah, Dhofar Governorate. Around 1817 solar panels were installed in 8000 square meters and planned to produce around 60% electricity. A 500 MW solar system is located in Ibri -Al Dahirah Region, which is the first utility-scale renewable energy facility in the Sultanate of Oman [8].

The social investment of some companies plays a good role in the adoption of the solar system in many schools with a total of 0.3MWh yearly. The other solution which can be targeted to decrease the electricity bills is to increase the efficiency of the building through energy conservation and the using smart technologies. Eco-houses present a practical implementation of these features. Eco-house combines architectural, mechanical, environmental science, and electrical elements to conserve water, reduce and recycle waste materials, control pollution resulting in global warming, and reduce carbon emission. Most of the old Omani traditional houses built in the thirteenth and fourteenth century were eco-houses building that makes a livable home that is energy-efficient, eco-friendly, and boasts marketable architectural design [9]. Figure 2 shows an example of one traditional Omani eco-house.

Fig. 2. An old traditional Omani eco-house

In 2011, the research council in Oman sponsored the eco-house design competition to raise awareness and possibilities of building eco-friendly design buildings in Oman. Five eco-houses were constructed in Oman by the end of 2014. The central theme of these eco-houses was increasing the energy conservation of the residential building while keeping the Omani tradition and culture intact. The HCT eco-house is the official entry of the Higher College of Technology, and it scored first place in the eco-house design competition in Oman in 2014.

2. HCT Eco-house Description

An eco-friendly, low-impact home built using materials and technology decreases carbon emissions and lowers energy requirements. Figure 3 shows a south view of the house, including a pergola and solar panels installed on the house's rooftop. This paper targets the performance analysis of the installed 22.8KW Solar system. However, more discussion of the other energy conservation features will be presented.

Fig.3. Photo of the eco-house in HCT

The house is a two-storied building powered by 76 solar panels and has one of the best architectural designs in keeping the Omani tradition and culture. The solar panels are placed on the top-roofs, which act as a shade to the house during the daytime. The house has three bedrooms with attached bathrooms, kitchens, and a sitting room. The house is designed to maintain a temperature between 25°C- 27°C and relative humidity in the range of 50%- 70%. Grey-water recycling is used for irrigation purposes. The floor planning is well-executed to maximize natural sunlight and air ventilation entry. The light equipment combines green technology and uses a light-emitting diode (LED) which is more energy-efficient and has more long-lasting life than other appliances. The house uses a VRF (variable refrigerant flow) air conditioning system to control the amount of refrigerant flowing at various indoor units connected to a single outdoor unit [10].

The HCT greenhouse has many other features that make it beautiful and elegant. The roof is shaded with solar panels, the primary energy source of the house. It also acts as a shelter during the daytime and provides electricity to the appliances inside the house. As the house faces the North-South direction, the amount of sun will be sufficient to enter the home. The windows are made up of double-layered glasses known as double-glazed windows, which lessen the heat transfer to the house, reduce noise transmission, and create a soundless atmosphere. The walls are made up of Insulated concrete form

(ICF), which is fire-resistant, environmentally friendly, withstand strong wind and other weather conditions in Oman, as shown in Fig. 4.

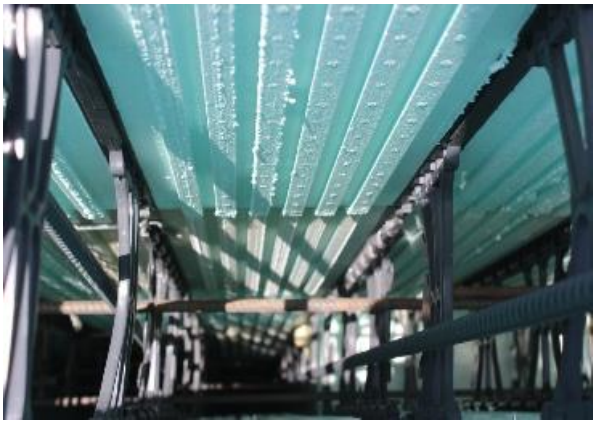

Fig. 4. Insulated concrete form for walls

The insulated concrete walls lower the heat transfer rate and thus decrease the use of the air-conditioners, and fans, etc. The house is surrounded by a sufficient amount of indoor and outdoor plants, which gives an advantage of a nature-friendly home. Also, the house is equipped with a wastewater treatment plant and rainwater harvesting system. The house also has a solar-powered water heater placed horizontally above the solar collectors installed on a rooftop. The hot water naturally rises due to the hot water storage tank due to the thermosiphon principle without any water pump. Table 1 summarizes the U values of some materials in the HCT eco-house [11].

Table 1: U values of Materials

S/No	Materials	U values
1	Insulated Concrete Forms (ICF) wall system	0.233W/m^2.K
2	Hollow-cores labs	0.339W/m^2.K
3	Shading coefficient of 0.28	Overall U value of 1.88 W/m^2. K
4	Certified wooden doors	3.62 W/m^2.k

Having a building in Oman as one of the hot countries, these features significantly increase the thermal factor and provide a standard atmosphere inside the home. The previous reference shows that HCT eco-house energy demand is 61.24% less than the traditional Omani house.

3. Data Acquistion System Description

The data for the eco-house was taken for one year, from October 2017 to September 2018. The readings were taken once every 20s for higher reliability. A high-reliability data acquisition system (DAS) shown in figure 5 is used to store the data and accumulate valuable estimation information for characterization and energy management inside the eco-house. DAS also measures all house living spaces temperature and relative humidity by utilizing thermocouple instruments.

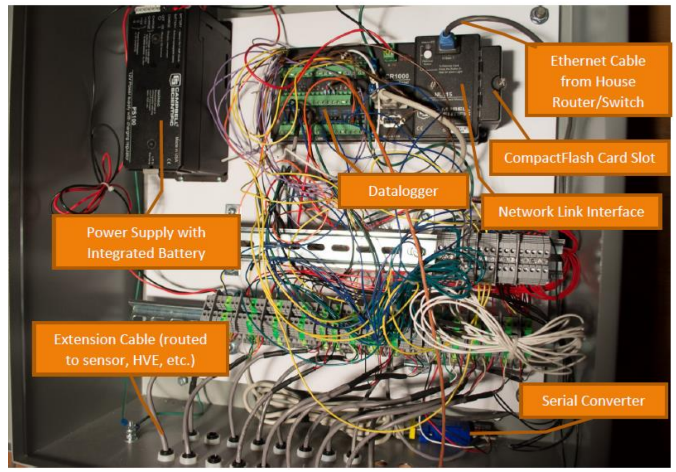

Fig. 5. Image of Data Acquisition System in HCT

The DAS measure and record the voltage, current, and temperature of all appliances inside the house. The DAS also measures the energy utilization of the fridge, freezer, clothes-washer, induction cooker, dishwasher, lighting, and other domestic home appliances. Watt node and current transformers are utilized for measuring energy generation. Also, more than 30 loggers record different weather data like wind speed and direction, load demand, humidity, input solar energy, export or import of energy to the grid [10].

4. Solar System Description

Solar energy is used to provide energy to all appliances in the house, and the extra power is exported to the grid. The HCT eco-house PV system is a grid-connected system that comprises 76 polycrystalline solar panels with a total DC-rated capacity of 22.8KW. The generated monthly solar energy varies between 2167kWh and 4500kWh at the optimum weather and clean solar panels case. A net (bi-directional) meter is used to monitor and calculate the excess energy exported to the gird and the imported energy from the grid during the nighttime or high load demand. An aerial view of the solar system at the HCT eco-house is shown in Fig. 6.

Fig. 6. An aerial view of the HCT eco-house

Table 2 provides specifications of PV panels used in the HCT eco-house project.

Table 2: PV panels specifications

Parameter	Value	Parameter	Value
Polycrystalline silicon panels (number)	76	Open circuit voltage (Voc)	45.3V
Short circuit current (Isc)	8.94A	Peak voltage (Vmpp)	36.5V
Peak current (Immp)	8.21A	Maximum system voltage	600V
Peak power (Pmax)	300W	Manufacturing efficiency %	15.19%

Figure 7 shows the schematic diagram of the HCT eco-house grid-connected solar system.

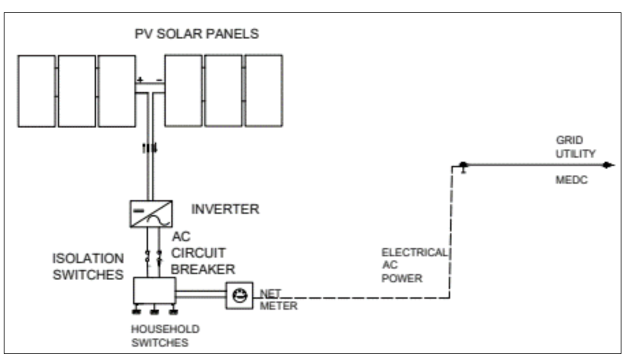

Fig. 7. Connection diagram of grid-tied solar system installed in HCT eco-house.

The maximum power of a solar panel depends on the orientation of the panels, which is tilted to 23°towards the south in a fixed array. The 76 polycrystalline silicon PV panels are connected to five single-phase grid-connected inverters installed in the HCT eco-house. In each inverter, two strings of PV panels are connected. Eight PV panels are connected in series for each string for the first three inverters. Each string consists of seven panels connected in series for the remaining two inverters, as shown in Fig. 8.

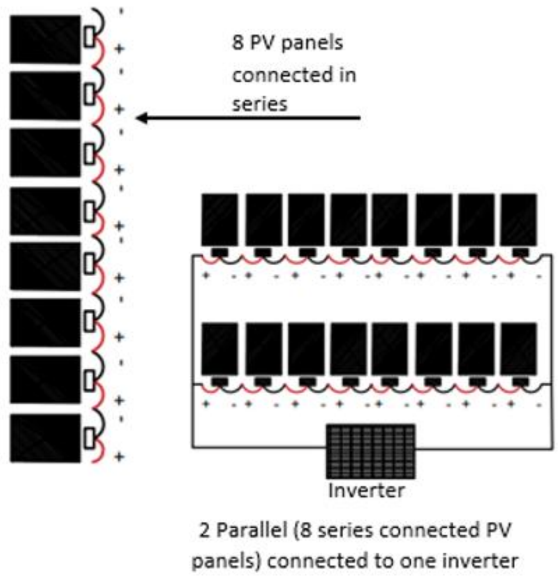

Fig 8. Configuration of the PV solar system connection

Growatt 500 MTL type inverter consists of two independent MPPT trackers, which make it a suitable option for panels installed in different orientation and roof levels. The photo of the Growatt 500 MTL is given in Fig. 9.

Fig.9. Photo of the grid-tied inverter

The inverter also regulates the amount and voltage fed to the house. More specifications of the inverter are listed in table 3.

Table 3: Inverter specifications

Parameter	**Value / Specifications**
Model Name	GROWATT 5000 MTL
Max. DC power	5200W
Max. DC voltage	600V
PV voltage range MPPT	120V – 550V
Max. Number of parallel strings	2/2
Number of MPPT trackers	2
Max. DC power of each MPPT	3000W
Max. the input current of each MPPT tracker	15A
Nominal AC output power	4600W/ 5000W
Max. Output current	20A
Nominal AC voltage range	180V – 280V
AC. Grid frequency	50HZ
AC. Connection	Single-phase

5. Impacts of Weather Conditions

Many studies have extensively discussed the impacts of weather conditions [12-14]. It is critical to consider the weather conditions carefully in assessing the performance of any solar system because the solar and wind are highly variable due to rotation of the earth, solar irradiation, and other factors. Also, the performances of the solar panels are affected by the sudden changes in the climates conditions of passing clouds or changes in wind, humidity, temperature, etc.

Figure 10 presents the variation of the average solar irradiance and the average outdoor temperature between October 2017 to September 2018 in Muscat.

Both curves vary in the same shape. However, the highest solar irradiance and a temperature range from May to August with a maximum value of 289W/m^2 and 41°C, respectively. The lowest average temperature was recorded in January, and it equals 22°C

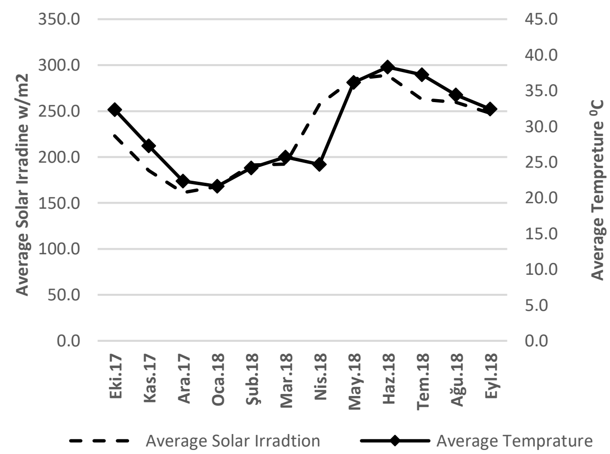

Fig.10. Average solar irradiance and Average temperature

The relation between the PV solar energy generation in kWh and the outdoor temperature is presented in Fig. 11. The average monthly solar energy production varies between 1800kWh in December and 4500kWh in June. As per recorded solar energy data, the highest solar energy production was recorded in June, because of the highest solar radiations and longer hours of production during the day time. However, the effect of higher temperature in June was minimum.

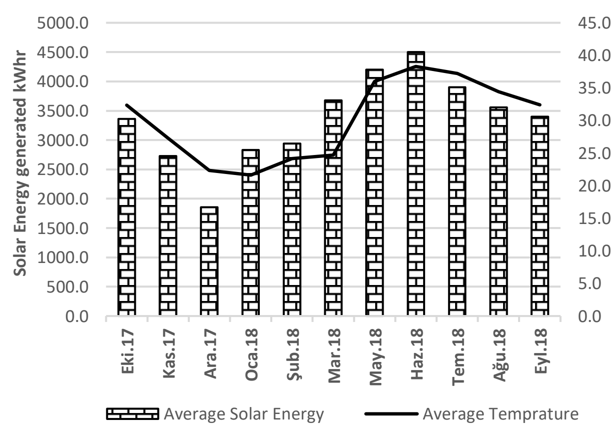

Fig. 11. Average monthly temperature and generated solar energy

However, in harsh conditions, it was realized that the efficiency of the solar cells is reduced by 32.04% if the temperature increase more than 45ºC and that also may lead to reduce the life of the solar cells [11], [15-16].

Figure 12 shows the effect of sudden disturbances in the measured solar irradiance on 22nd June 2018, which is most likely due to the passing of the clouds. The power system in the house was mentioned as stable. However, results obtained by

[17] showed that voltage and current distortion increases as the number of solar panels inverters connected to the system increases.

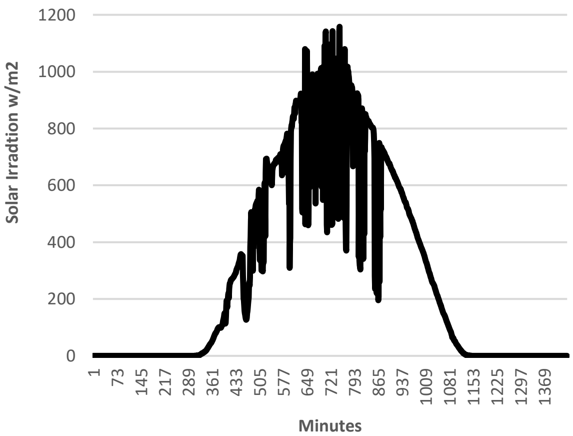

Fig. 12. Solar irradiance on 22nd June 2018

Figure 13 presents the average monthly wind speed for the 12 months.

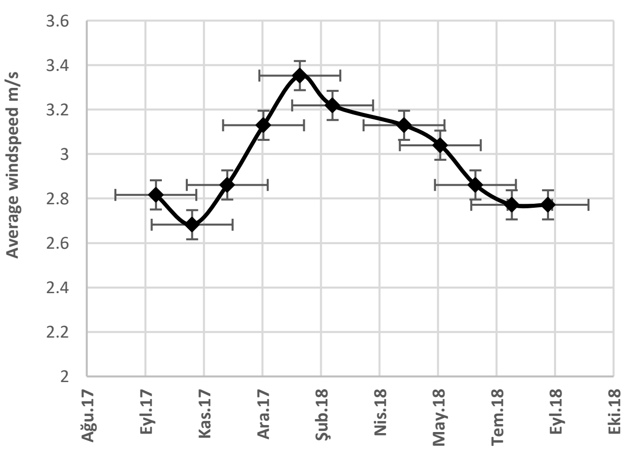

Fig. 13. Average monthly wind speed in Muscat

Wind energy varies in different seasons. It is relatively high in winter than summer season. However, the average yearly wind speed is around 2.72m/s. Furthermore, the wind speed varies during the same day. An example is given in Fig. 14, which shows the variation of the hourly wind speed of in two days in 15th July and 15th August. For both days, the wind speed was higher during the daytime (between 10- 4pm) than the other time.

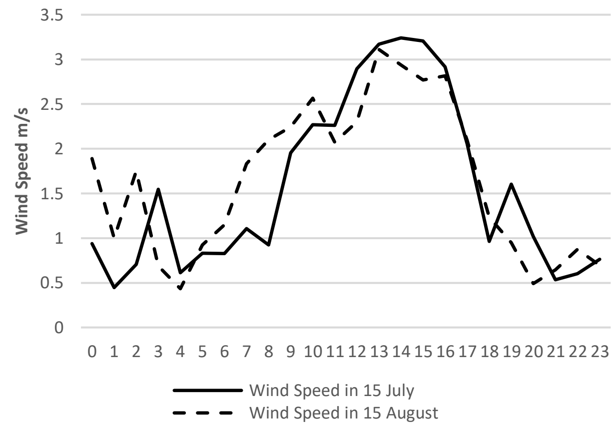

Fig.14. The variation of the wind speed of two days

Generally, The feasibility of wind for power generation in Muscat is low, as discussed in [17-19]. However, there is an advantage of wind blow in enhancing the performance of the solar photovoltaic systems. The wind positively decreases the impact of the heat on the surface of the solar panel due to high temperature, which leads to enhancing the performance of solar panels as discussed in [20- 22].

Figure 15 shows the variation of the relative humidity % in the same period for Muscat and Nizwa areas. Muscat lies more to the coastal regions. The humidity in Muscat is measured higher than Nizwa, which is near the desert. The annual average relative humidity is around 57% for Muscat and 50% for Nizwa. The other notice is that as the temperature increases, humidity also increases.

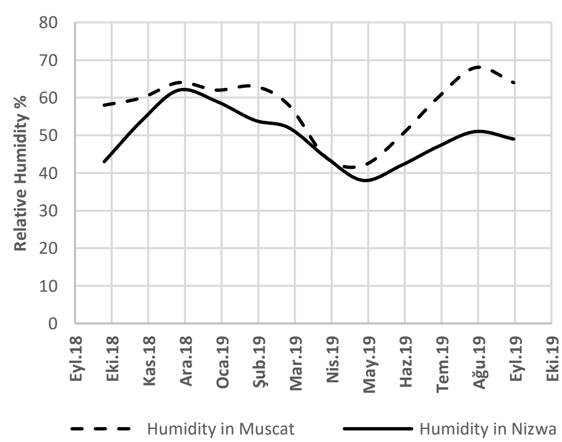

Fig. 15. Average humidity in Muscat and Nizwa

In general, humidity can affect the efficiency of solar panels in two ways; either due to deposition of water droplets on the surface of solar panels. The humidity can affect the production of PV panels; when water comes in contact with the cellular components of the photovoltaic panels, the efficiency of the cell decreases, thus effecting energy production. The color of the cell envelope also occurs when the UV condition exceeds 15kW/m^2 and the wavelength ranges between 280 nm and 385nm [24].

Many studies [25-27] have been also conducted to find the impacts of relative humidity on the performance of solar panels. In a hot and humid climate, the moisture deepens into the layers of the cells and thus disintegrates. The other effect of humidity is the degradation of the metal used for building the solar panels as the moisture that perforates (penetrate) into the photovoltaic cells provides the source for salt to accumulate and create chemical damage, thus resulting in the fatalistic effect on metal bonding inside the solar cells [25].

6. Load Analysis, Exported and Imported Energy

The average load in each month varies depending on the appliances used for a certain period. In the harsh weather in Oman, the air conditioners and the lighting systems represent the highest load. Generally, for the HCT eco-house the load is relatively low at the beginning of October till March, and then it increases in the period from April to September. In comparison to the traditional Omani houses, HCT eco-house energy analysis estimate Building Energy Index (BEI) of 87.20kWh/m^2/yr, whereas BEI of same size regular house or traditional Omani house in Muscat equal to 225.1kWh/m^2/yr. The BEI of the HCT eco-house is 28% smaller than the Passive House Institute (PHI) standard because of its salient sustainable features [10].

The monthly exported, imported energy is calculated, and net energy in kWh is presented in Fig. 16. The analysis shows that the total annual net exported energy to the utility grid was equal to 1540KWh. For a zero net energy eco-house, this shows a positive net energy zero energy building compared to the traditional house as stated in [10] .

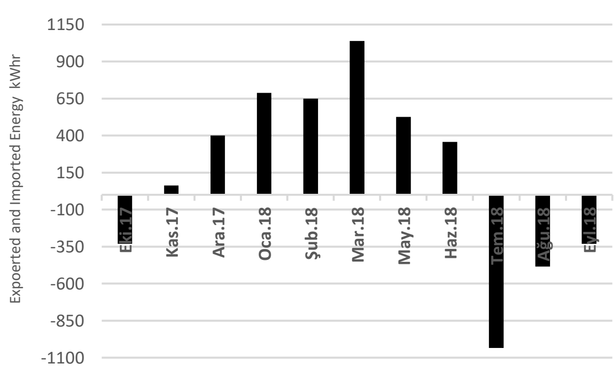

Fig. 16. Monthly net energy in kWh

7. Effect of Soiling on PV Perfromance & Efficiency Calculation

Some of the energy losses in the PV system are reflection loss, resistive loss, recombination loss, mismatch losses, thermal loss, titling of angle, inverter efficiency, array mismatch, and dust deposition [28-31]. These can adversely affect the efficiency of solar panels. Dust deposit occurs on the top surface of the solar panel, which reduces the absorption and thus causes short circuit current at some times. The dust deposition on the surface of solar panels can also lead to energy loss. PV solar systems work less efficiently, especially in the remote desert areas where huge soiling and windy weather are expected. Also, the chances of rain and other climate conditions can impact the solar system's performance. The impacts vary from winter to summer, so solar energy generation is affected [32].

Ref [33] has extensively discussed the impact of long-term dust accumulation. It was conducted under different cleaning cycles on installed solar PV systems at Sultan Qaboos University in Oman. The system was monitored for a total of 16 months. The key finding is that under 29-day, 32-day, 72-day, and 98-day cleaning cycles, the average percentages of energy loss due to soiling were 9.5%, 18.2%, 31.13%, and 45.6%, respectively.

Many methods were used to measure the solar system's efficiency [34-38]. The fill factor, the maximum voltage, maximum current, and the maximum power (Pm) were used to measure the efficiency of the portable solar unit. However, in this work, the efficiency of the HCT eco-house solar system is calculated with equation (1)[34] .

$$\mu = \frac{Pout}{Pin} = \frac{Pele}{Grad \times A \times N} \tag{1}$$

Pele is the electrical solar-generated energy, Grad is the solar irradiation, A is the area of the single solar panel, and N is the total number of solar panels.

Figure 17 shows the picture of the un-cleaned PV solar panels of the eco-house.

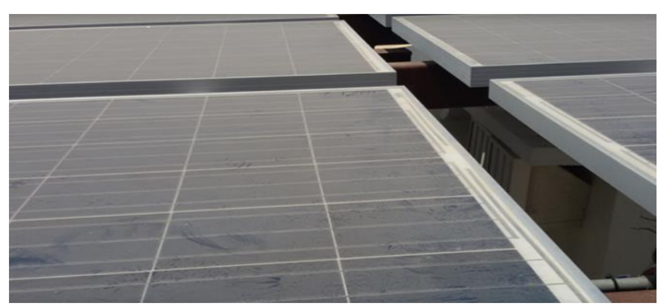

Fig.17. The dust on the surface of the solar panels

Figure 18 shows the monthly average efficiency of the solar system. The efficiency varies between 4.5% to 8%. Measured results show a drop in solar system efficiency between 47%- 70% because the solar panels were left un-cleaned for many months. However, the solar irradiation was good in the same period.

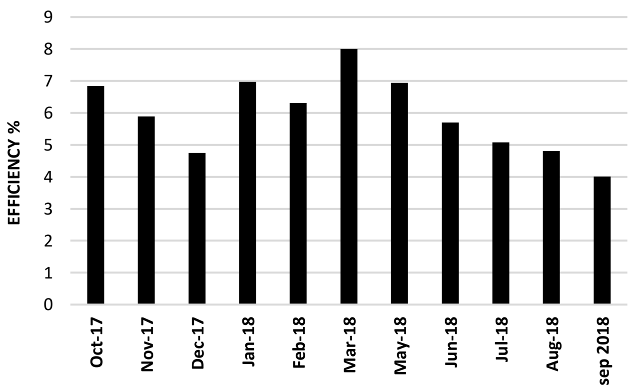

Fig. 18. Monthly average efficiency of the solar system

8. Conclusion

In this research work, the performance of the 22.8kW grid-tied PV system installed on the roof of the HCT eco-house in Muscat- Oman was investigated. The measured data from September 2017 to October 2018 was used. The average monthly exported and imported energy was calculated since the HCT eco-house has a grid-connected solar system. Calculation showed that the amount of net exported and imported monthly energy in kWh saved around 1500kWh in the same period. The countable impact of high ambient temperature on solar energy generation by the PV system was investigated. As per analysis of the recorded solar energy data, the highest solar energy production in kWh was recorded in June, because of the highest solar radiations and longer hours of production during the day time in compare to the other months. However, the effect of higher temperature in June was limited.

The average monthly wind speed for the 12 months was determined, and the impact of the wind speed on solar energy production in Muscat was found to be minimum. However, the availability of the wind may lead to an advantage of enhancing the performance of the solar photovoltaic output systems, as the wind increases the performance of solar panels by reducing the temperature on the surface of the solar panel.

The impacts of the relative humidity were also tested, and it was found that the annual average humidity is around 57%, and it was maximum in the mid of the year in the summer time. The effect of the humidity was found limited to the performance of the solar system.

The impacts of soiling and other sources of energy losses on PV systems were investigated. The system's efficiency was dropped by more than 50% when panels were left uncleaned for a more extended period.

The research team recommends increasing the solar system's efficiency in two ways: the first is to clean the PV panels once every two weeks to maintain a high efficiency as advised by the manufacturer. Today, IoT can enhance solar systems and save lots of resources. The other method is to cool the PV panels, increasing their efficiency by 3% compared to un-cooled ones. Also, it is possible to reduce the PV temperature by more than 10ºC by putting pipes behind the cell for ventilation. Hence the high saving of energy could be achieved

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