Available *online* at : http://jnte.ft.unand.ac.id/

Jurnal Nasional Teknik Elektro

| ISSN (Print) 2302-2949 | ISSN (Online) 2407-7267 |

Techno-Economic Simulation of On-grid PV System at a New Grand Mosque in Bukittinggi using HOMER

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ARTICLE INFORMATION

Received: November 23, 2021
Revised: February 10, 2022
Available online: March 29, 2022

KEYWORDS

Mosque, On-grid, PV, Renewable Energy

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A B S T R A C T

Mosque is an important building for Muslims worldwide for doing religious activities, such as daily prayers, weekly discourses, and annual celebrations. In many places, mosques are considered appropriate buildings for rooftop solar photovoltaics (PV) installation. This study provides a techno-economic analysis of an on-grid PV system in a great mosque. As a case study, Masjid Tablighiyah Garegeh in Bukittinggi is chosen, which is currently under construction with an expected capacity of up to 1,400 people. This study uses HOMER software as a tool to assess optimum configuration for an on-grid PV system. There are four options that is considered in this study: PV-grid, PV-battery-grid, battery-grid, and grid only system . Optimization results showed that both configurations with PV have promising performance; however, an on-grid PV system without battery system is the most optimum configuration. A 40 kWp PV equipped with a 27 kW converter has the least net present cost with USD 6,902, while the cost of energy when implementing the system is only about USD 4.8 cent per kWh. By implementing the system, 57.2 MWh of electricity will be produced from the PV.

INTRODUCTION

Islam is a religion that has 1.6 billion followers worldwide, accounting for almost a quarter of the world's population; it is the majority religion in roughly 50 nations [1]. Muslims meet in the mosque for daily prayers, weekly discourses, annual celebrations, and other religious and social events. Mosques range in size from tiny enough to hold 50–100 attendees to large enough to keep tens of thousands of worshippers. There are an estimated 3.5 million mosques worldwide [2]. Given their pervasiveness in the Muslim world, governments have recognized that mosques merit consideration from an energy standpoint, and scientific review has been dedicated to mosques from various perspectives.

Mosques are considered appropriate buildings for rooftop solar PV installations due to the comparatively considerable roof area available [3]. From a financial standpoint, once the solar PV system is installed, it can significantly reduce the energy bill because the capital cost (or CAPEX) of solar PV systems is the single significant barrier [4]. Life cycle analyses for mosques, on the other hand, have been conducted [5]. In reality, more active efforts have been made, such as introducing the 'Smart Mosque' concept of Deloitte's [6]. This approach lowers mosques' energy footprints through energy efficiency and renewable energy projects.

There have been several studies that have looked into the economics of solar PV on mosque electrical systems. Given the prevailing pricing at the time, a study for PV deployment for all 1,400 mosques in Kuwait conducted in 2014 predicted a payback period of 13 years [7]. The study's goal was to evaluate peak-shaving possibilities through decentralized generating installations. Indeed, if the research were conducted today with current electricity rates and solar technology costs, the payback period would be quicker.

Another study [8] created a hybrid microgrid system for a Libyan mosque. Because the mosque is situated in a rural area and keeping a continuous diesel supply was costly, the authors advised integrating a PV system to decrease reliance on diesel. The dynamics and restrictions for a grid-connected mosque will differ from those for an off-grid mosque. Another research on a specific mosque in Malaysia found that installing a PV system would cut the energy bill by 47 percent [9].

The financial viability of solar PV systems on mosque rooftops has lately grown because of the technology's falling capital costs. In nations with relatively high energy prices, the commercial proposition becomes even more attractive. In Jordan, for example, where electricity prices have been rising since 2012, an average-sized mosque could pay an annual electricity bill of around USD 17,000. Jordanian government authorities recently declared that 6,300 mosques in Jordan would be using solar PV

https://doi.org/10.25077/jnte.v11n1.985.2022

to generate power [10]. Jordan has a particular interest in solar since it has good sun conditions and is nearly dependent on imports to fulfill its energy requirement [11].

Likewise, Morocco has an ambitious project to build solar panels on 600 mosques by 2019 and more in the future. It is worth mentioning that Morocco has about 50,000 mosques in total [12]. The German Federal Ministry for Economic Cooperation and Development is sponsoring a portion of this Moroccan mosque project. The Moroccan Ministry of Religious Affairs, which is in charge of paying mosques' energy expenses, was delighted to hear the news. Governments see 'green mosques' as a tool to improve energy awareness among the people and an implicit approach that can inspire greater acceptance and implementation of renewable energy technology [13]. Morocco, like Jordan, relies on imports for almost all of its energy demands [14].

To that purpose, this paper provides a complete techno-economic study of building a solar PV system of a mosque in Bukittinggi, Indonesia. This article aims to analyze both technical and financial aspects of installing PV systems on mosque connected to the grid. Finally, this analysis would serve as a foundation for policymakers to determine if a countrywide PV deployment program on mosques is proposed in a country and worldwide. One of the most essential parts of this study is that the conceptual modeling and technological assumptions were cross-checked and confirmed with an actual physical system involved with the project. Both analyses produced findings that were relatively consistent.

LOCATION

Garegeh is one of the villages located in Bukittinggi, West Sumatra, with 2,664 people. It has an existing mosque called the Masjid Tablighiyah which stands on 1,900 m^2 of land and only has a capacity of no more than 700 worshipers. Due to its limited capacity, there was planning for a total renovation to enlarge mosque capacity to 1,400 worshipers. Therefore, the old Masjid Tablighiyah was demolished, and the construction of a new mosque building has been carried out. Figure 1 shows the final mockup design of the new Masjid Tablighiyah, and Figure 2 shows the current construction progress of the Mosque.

Figure 1. Mockup of New Masjid Tablighiyah

Figure 2. Current Construction Progress of New Masjid Tablighiyah

DATA COLLECTION

The information compiled includes a load profile, solar irradiance, and temperature. A survey of existing electronic appliances in the area was used to create the load profile. Site inspections and interviews with the mosque committee are also part of the survey. Meanwhile, solar radiation and temperature statistics were obtained from the NASA database.

Electrical Load Data

The electrical system of the new Masjid Tablighiyah consists of three parts: main room, basement, and outdoor. Only the main room of the mosque was simulated as the electrical load in this study. The list of electrical appliances in the mosque's main room is described in Table 1.

Table 1. Electrical Appliances in Mosque's Main Room

Appliances	Power (W)	Quantity	Time Used
Lamp	17	4	5 – 9 pm
	22	48	5 – 9 pm
	15	60	5 – 9 pm
	24	64	5 – 9 pm
	33	12	6 am – 6 pm
	8	42	5 – 9 pm
LED Monitor	100	10	12 – 1 pm
Speaker	100	10	5 – 6 am; 12 – 1 pm; 3 – 4 pm; 6 – 8 pm
AC	350	1	24 hours
Computer	150	1	24 hours

Figure 3 shows the daily load profile of the mosque as simulated in HOMER. The mosque's load profile varies from that of a conventional household load profile. During the day, the mosque experiences various peak loads. Five peak load times each day are directly connected to the five times daily prayer time. The five peaks, varying from 1500 to 5400 W, occur between 5 and 6 a.m., 12 and 1 p.m., 4 and 5 p.m., and 6 and 8 p.m.

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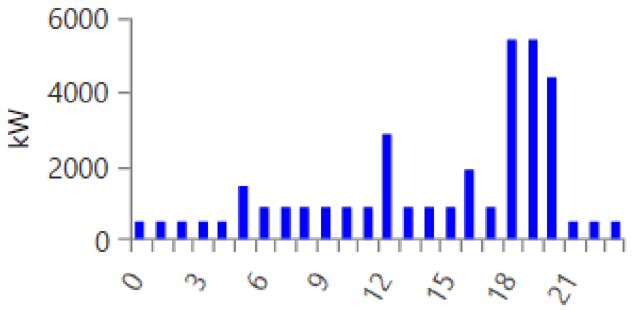

Figure 3. Daily load profile

Solar Potential Data

Figure 4 depicts the location's solar radiation profile. This site's average daily energy consumption is 4.91 kWh/m2/day. The solar radiation profile is essential in determining the quantity of PV that can be generated at the site. From February to October, the profile reveals increased daily radiation. Meanwhile, the wet season causes reduced average daily radiation in November, December, and January. Temperature information was also gathered; the area has an average temperature of 25.21° Celsius annually.

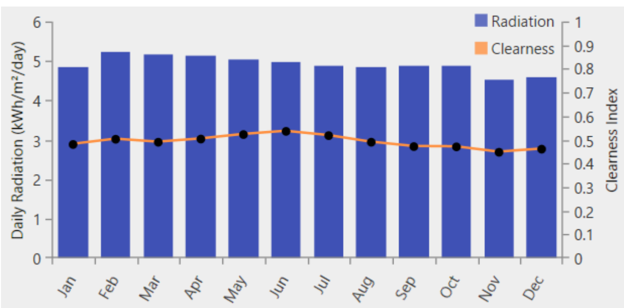

Figure 4. Solar Radiation profile

METHOD

On-Grid PV System

The on-grid PV system is made up of three major components: PV, a converter, and a battery storage system. Figure 5 is a schematic representation of an on-grid PV system. The technical and economic parameters of the system components are mentioned in Table 2.

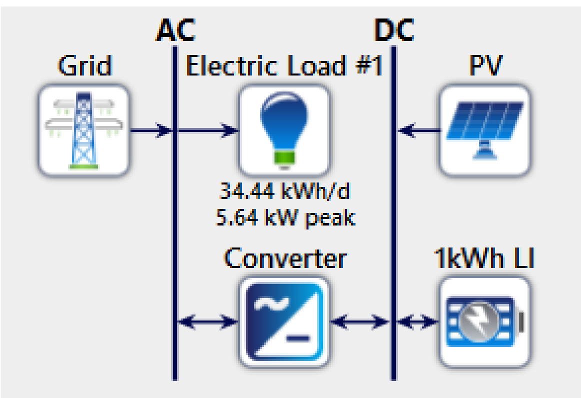

Figure 5. On-grid PV system

Table 2. Technical and Economic Assumptions [15]

No	Component	Specifications
1	**Photovoltaics**	
	- Size	0 to 90 kW
	- Derating factor (%)	80
	- Capital cost (USD/kW)	1,190
	- Replacement cost (USD/kW)	1,190
	- O&M cost (USD/year)	14.4
2	**Converter**	
	- Efficiency (%)	95
	- Capital cost (USD/kW)	227
	- Replacement cost (USD/kW)	227
3	**Battery**	
	- Batteries per string	10
	- Nominal capacity	1 kWh (167 Ah)
	- Capital cost (USD/kW)	126
	- Replacement cost (USD/kW)	126

Photovoltaics

The power output of the PV panel depends on the Global Horizontal Irradiation (GHI) data, which follows eq. 1 below.

$$P_{PV} = Y_{PV}\, f_{PV} \frac{G_T}{G_{T,STC}} \tag{1}$$

Y_{PV} represents the rated capacity of the PV array (kW), f_{PV} is the derating or loss factor of the PV array because of shadow, dirt, temperature changes, etc. (%), G_T is the solar radiation incident at the surface of the PV array (kW/m^2) and $G_{T,STC}$ is the incident radiation at standard test conditions (kW/m^2). The effect of temperature is not taken into consideration in this study.

The PV panel is intended to be placed on the Masjid Tablighiyah's rooftop. It is estimated around 454 m^2 of space is available for PV installation at the mosque rooftop. It is assuming that the average solar panel area has a high capacity to reduce the number of panels and have a small footprint. The expected total PV capacity installed at the mosque is 45.40 kW. Therefore, the PV system sizes in HOMER ranged from 0 to 45 kW.

Converter

The converter converts the direct current (DC) power from the PV system to alternating current (AC). The converter was designed to be the right size for the PV system. HOMER software used its internal optimization tools called the HOMER optimizer to size the converter.

Battery

The battery is used to store electricity from the PV system during off-peak load times and to utilize it at peak load times when coupled with the power grid. The HOMER optimizer is also used to determine the amount of battery needed for the system. The proposed battery storage has a nominal voltage of 6 volts and a nominal capacity of 6.94 kWh, 1,156 Ah. Lithium-ion batteries were used in this study because of their lower cost. They also feature a greater power density, a smaller size, a higher capacity, and less maintenance [16].

https://doi.org/10.25077/jnte.v11n1.985.2022

Grid

The grid is the primary source of power, and the PV system can complement it. For all days, the electricity grid price set for this study is USD 0.63/kWh [17], and the sell-back price is USD 0.63/kWh [18]. In this study, the net-metering system is also modeled using HOMER.

Project Assumptions

The project's lifespan is designed for 25 years, with a 3.5 % of interest rate yearly. There is no capacity shortage allowed throughout the year. Both dispatch strategies, which are load following (LF) and cycle charging (CC), are taken into account in this study. The currency is expressed in US dollars (1 USD = 14,322 IDR).

HOMER Software

HOMER is an optimization software developed by the National Renewable Energy Laboratory in the United States. The tool is used to design, simulate, and evaluate configuration options technically and financially; for off-grid and on-grid power systems; for remote, stand-alone, and distributed generation applications. Many projects around the world have been using HOMER for various purposes, such as solar PV system at a campus in Pakistan [19], battery-equipped hybrid system for family housing in Bulgaria [20], grid-connected PV system with energy storage for electric vehicle charging in residential Bangkok area [21], hybrid grid-connected microgrid in Turkey rural area [22], and various PV configurations in Saudi Arabia [23].

RESULTS AND DISCUSSION

PV-Grid System

The optimization outcomes are sorted by HOMER based on the lowest Net Present Cost (NPC) and Cost of Energy (COE). In addition to that, initial capital and renewable share are among the optimization outputs. Table 3 shows the optimal configuration of PV system design based on the HOMER result for the mosque. As a dispatch mechanism, the most optimal configuration applies cycle charging, meaning that the PV system will run at maximum capacity when necessary to fulfill the load requirement. Any surplus power will be used to charge the battery storage system.

Table 3. HOMER Results

Rank	Configuration	PV	Converter	Battery
1	PV-Grid	40 kWp	27 kW	
2	PV-Battery-Grid	40 kWp	27 kW	10
3	Grid only	-		
4	Battery-Grid	-	0.2 kW	10

The results indicate that the most optimal configuration for a grid-connected PV system for the mosque is a PV system without battery. The proposed capacity of PV is 40 kWp, despite the maximum capacity considering the available area on the rooftop is up to 90 kWp. The converter capacity needed for the system is 27 kW. The NPC of the on-grid PV system is estimated at USD 6,902, while the COE is expected to be at USD 4.8 cent per kWh electricity produced, which is lower than the base case. The capital cost of this system is USD 53,729, meanwhile the total operating cost of this configuration is USD -1,994, with the negative mark showing that the system would profit from selling excess power to the grid.

HOMER also calculated the annual AC load, power generated from PV, and the amount of energy purchased from the grid. Based on the calculation, the total power required in a year for the mosque is 12,570 kWh, while the power produced from PV is only 57,272 kWh. Therefore, it is expected that the proposed on-grid PV system at Masjid Garegeh could sell the excess power to the grid. Figure 5 shows the monthly average electric production of the proposed PV-grid system.

PV-Battery-Grid System

The second most optimal configuration is on-grid PV using battery system. the HOMER calculation suggested that if the mosque is using the battery, then the PV capacity should also 40 kWp while the converter is 27 kW. The amount of battery needed is only 10 unitsdue to a higher cost when using the battery. Therefore, the amount of electricity produced by PV in such configuration is also equal, around 57.2 MWh in a year.

The NPC of an on-grid PV system with battery is USD 11,313, while the COE is USD 7.9 cent/kWh. The capital cost needed to build this system is USD 54,989 and the operational cost throughout the year is USD -1,859, meaning that this configuration is also profitable for the mosque.

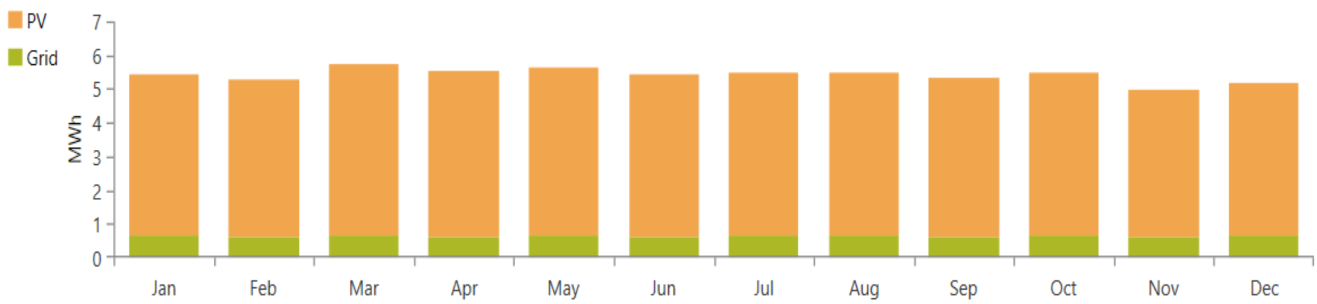

Figure 5. Monthly Average Electric Production

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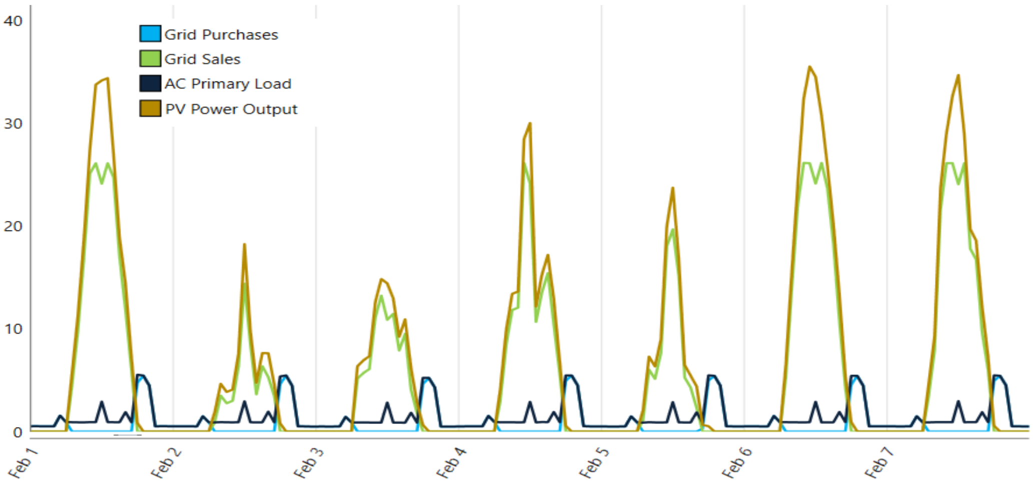

Figure 6. System Scheduling

System Scheduling

The system schedule is described in Figure 6. The proposed PV system will experience a peak production during the day while the electrical load will reach the peak at around 7-8 pm. HOMER calculates the amount of electricity sold to the grid and purchased from the utility, then accumulates the numbers for the whole year. The total electricity sold to the grid is estimated to reach 48.4 MWh per year, while the amount of grid purchases from the utility is about 7.6 MWh in a year. The average renewable fraction using the system throughout the year is 87.4%. The other 12.6% are not covered by the PV due to its limited operational time each day.

CONCLUSIONS

Two on-grid PV system configurations demonstrated encouraging results for installing a rooftop PV system at a mosque in this study. The optimal configuration for installation at Masjid Tablighiyah Garegeh is a 40 kWp grid-connected PV system without batteries. Compared to the on-grid PV system with battery, the NPC (USD 6,902) and COE (USD 4.8 cent/kWh) of the on-grid PV system are without battery are lower. However, both configurations will generate about 57.2 MWh of electricity from renewable energy. Meanwhile, this PV-grid system has an initial capital cost of USD 53,729. By calculating the excess power sold to the grid during the day and power purchase from the utility, it is expected that the proposed on-grid PV system could give financial benefit to the new Masjid Tablighiyah.

ACKNOWLEDGMENT

The authors would like to express gratitude to.

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