Off-grid solar power plant for refrigeration system: A case study in Bandung, Indonesia

A Setyawan* and T Sutandi
Department of Refrigeration and Air Conditioning Engineering, Politeknik Negeri Bandung, Bandung 40012, Indonesia

*andriyanto@polban.ac.id

Abstract. The tropical climate in Indonesia promises the availability of solar energy year-round. However, the utilization is very limited. This paper discusses an experimental investigation on the use of solar energy for supplying a refrigeration machine using an AC mini freezer with power input of 85 W supplied by 200 Watt-peak solar panel. The experiment was carried out in Bandung, Indonesia, and showed that the average energy density of solar radiation is 445 W/m² while the average output of the panel is 106.4 Watts. The daily average energy supplied to the battery is 1182 Wh, sufficient for continuous operation of the freezer in 13.9 hours. If the machine has an on/off cycle with a usage factor of 56.8%, as in the experiment, the energy could operate the machine within 24.4 hours.

1. Introduction
Driven by the population and the increase of citizen welfare, the demand of cooling in Indonesia increases significantly. It is estimated that the growth for air conditioning market in Indonesia reaches 10.6% during 2016-2022. Meanwhile, the refrigeration market was projected to grow by 12.1% within 2015-2020, as reported by Eurovent in 2018 [1].

In Indonesia, the RAC units are generally supplied by electrical energy from the National Electric Company [2]. Unfortunately, many areas in the country do not have access for electric supply. Almost half of the remote areas in Indonesia is still out of reach of electrical supply from the company, especially in Eastern of Indonesia [3]. Therefore, it is highly recommended to provide alternatives for energy supply rather than that of provided by the national company. One of the potential alternatives is solar energy, as most of islands in Indonesia have a relatively high solar radiation [4-6].

As a source of clean energy, the use of solar energy is highly recommended to reduce the global warming and greenhouse effect. The use of fossil fuel should be reduced and substituted by solar energy, including energy supply for the refrigeration and air conditioning sectors [7]. In general, the areas with high solar radiation provide more energy resulted by solar panel. On the other words, the areas will have higher temperature that need more energy for cooling systems [8]. Therefore, the solar energy is the most appropriate choice for tropical country.

Recently, the use of solar panel for producing environmental-friendly energy is supported by the cheaper price and higher efficiency [9]. The European Photovoltaic Industry Association reported that the price of solar panel decreases by 75% in less than 10 years [10]. Meanwhile, The Fraunhofer Institute of Solar Energy System reported 24% annual growth of PV installation within 2010-2017 [11]. This encourage the development of solar power plant worldwide [12]. The use of solar energy for
cooling purpose is promising and cost effective [13], and considerable studies have been reported [14,15]. In addition to the clean energy source, solar power plant can contribute to improve the reliability of energy supply, especially for remote areas. This energy source could also support the fishing industry that needs cooling to preserve the fish during period of sailing in the high seas.

The paper discusses the feasibility of the use of solar power plant for supplying energy for cooling purposes. A mini solar power plant with peak capacity of 200 Watt was employed to supply energy for a mini freezer with a compressor nominal power of 100 Watt.

2. Methodology

In this research, four solar panels each 50 WP were installed on the rooftop of 3-story building located in North Bandung, Indonesia. The experimental rig of the mini power plant is presented in Figure 1. The direct-current (DC) electricity resulted from the solar photovoltaic panel is fed into the solar charge controller (SCC) to control the voltage and current of the panel output. The SCC is also used to avoid overcharging of battery. The DC electricity from the SCC is then converted into AC electricity by a DC-to-AC inverter. The 220 V AC electricity is then supplied to the freezer compressor to operate the refrigeration cycle.

![Figure 1. Experimental rig for mini solar power plant supplying energy a mini freezer.](image)

The installed mini freezer with 100 W compressor power input was designed to operate 6 hours per day. An extra energy should be allocated for compensating losses in the SCC and inverter, as well as for operating the control devices. If it is assumed that the losses and additional devices need 20 Watts of power, then the total power needed is 120 W. For supplying 6 hours of freezer operation, it needs 120 W x 6 h = 720 Wh. If the losses in the whole system is assumed to be 30%, the total need of the power supply is then 936 Watts. This needs 936Wh/6h = 156 Watt-peak (WP) of solar PV panel. If each PV panel has a capacity of 50 WP, then the total panels needed is 156/50=3.12. Therefore, at least 4 PV panels with each 50 WP are needed to meet the power requirement. If the battery has a nominal voltage of 12 V, the capacity is calculated to be 720Wh/12V=65 Ah.

Each PV panel has a maximum voltage of 17.6 V and current of 2.9 A. Therefore, for ensuring a safe operation of the mini solar power plant, the SCC for this experiment has a maximum current limit of 20 A. The SCC uses the MPPT (maximum power point tracking) technology, in which the equipment could control the panel to produce the maximum power.

Although the maximum power for supplying the freezer is only 156 Watts, the inverter for this experiment was chosen to have a nominal power of 500 Watts. This is aimed to keep the equipment to operate below its maximum load to ensure the longer lifetime. In addition, the high capacity of inverter is also aimed to anticipate the addition of load for the future experiments. The electrical diagram of this experiment is depicted in Figure 2.
Figure 2. The electrical diagram for the experimental test rig.

The rig was provided with circuit breaker for limiting the current, relay module, and digital meter to observe the power and energy consumption of the freezer unit. In addition, the rig was also equipped with Arduino Mega 2560 microcontroller, DS-18B-20 temperature sensor, and LCD display to show the reading and to facilitate data input. Pressure gauges were also installed to monitor the operating condition of the freezer at the suction and discharge lines. The installed experimental rig is depicted in Figure 3.

Figure 3. The installed experimental rig: a. Sketch of the rig, b. the photograph of the experimental rig, c. PV panel.

3. Results and discussion
A sample average of solar radiation of 445.8 W/m² was found for 12-hour data collection in July 10, 2018, under clear sky condition. This value is equivalent to 5.33 kWh/m². Based on previously
available data, the average solar radiation of Bandung is 5.17 kWh/m² in July [5]. Therefore, the experiment has a difference of about 3.2%.

As shown in Figure 4, the solar radiation has its maximum of 992-1038 W/m² value at 11.30 to 12.20. At period between 10.00 and 13.50, the radiation is higher than 600 W/m². Meanwhile, at 06.00 to 08.50 and 16.00 to 18.00, the radiation is below 300 W/m². If 400 W/m² is considered as a minimum value for economic operation of solar panel, the period of 09.30 to 15.00 is recommended. The probability distribution function (PDF) of the solar radiation is shown in Figure 5. Observation of this figure shows that the most frequent radiation data is at the range of 0 to 300 W/m². It is also shown that 24.6% of the total data are in the range of 800-1100 W/m². Detailed observation of Figure 5 also reveals that 35.6% of the data are at the radiation higher than 500 W/m² and the remaining 64.4% are lower than 500 W/m².

![Figure 4. Solar radiation measured from 06.00 to 18.00.](image)

The output voltage and current of the solar panel are presented in Figure 6. The panel produces DC electricity with an average voltage of 13.8 V and average current of 3.9 A for period of 06.00 to 18.00. Narrowing the use of PV panel to 08.00-16.00 results in average voltage of 15.1 V and average current of 5.02 A. Further narrowing the interval to 10.00-14.00 gives the average voltage and current of 15.1 V and 5.24 A, respectively. The maximum interval for the voltage and current is at period of 10.00-14.00, with the average voltage and current of 15.2 V and 5.3 A, respectively.

The variation of voltage and current in the experiment gives the charging power as shown in Figure 7. An average of 98 W charging is found for 12-hour period from 06.00-18.00. For the period of 08.00-16.00, the average charging power is 130.5 W with a range of 83.6 to 157 W. If a minimum charging power of 100 W is desired, then the period of 08.30-15.30 is suggested.
The charging experiment for the battery is presented in Figure 8. Started at 09.00, the initial battery capacity was measured to be 45%. After 4 hours and 20 minutes, the battery is fully charged to 100%. The total capacity of the battery is 60 Ah. As the nominal voltage is 12 V, therefore the energy stored in the battery at full capacity is 720 Wh. As the initial charge is 45%, therefore 55% (or 396 Wh) is needed to fully charge the battery. During the period of 09.00 to 13.20, the average power resulted from the PV panel is 126.5 W. Meanwhile, the average power needed to charge the battery is 92 W.

3.1. Operating freezer with battery
Two 60-Ah batteries were used to operate the AC freezer by utilizing an inverter to convert electric energy from DC to AC. The freezer has a total load of 137.16 W, in which 66.09 W is wall load, 63.17
W is product and respiration loads, and 7.9 W is infiltration load. To test the use of the battery, the freezer cabin temperature is set at -12°C. As could be seen in Figure 9, the cabin temperature decreases as the freezer is ON. Reaching setpoint at minute 190, the thermostat is in open position, and the freezer is OFF. As the freezer is OFF, the cabin temperature increases, and the freezer is ON again at minute 200. The ON-OFF cycle is repeated based on the cabin temperature sensed by the thermostat. In 600-minute test, 12 ON-OFF cycles were observed. The freezer was in OFF condition at about 144 minutes, or 24% of total test time. If the calculation is carried out based on the stable condition after minute-180, the average power required to operate the freezer is 48.4 W. Therefore, a battery with capacity of 720 Wh could operate the freezer in 720 /48.4 = 14.87 hours. If 40% battery level is considered as a minimum, then the battery could operate the freezer in 8.92 hours, less than 12 hours in the night. Therefore, two batteries of each 60 Ah is suggested for continuous operation of the freezer.

![Figure 9. Detail cabin temperature.](image)

The total energy consumed by the freezer in 600-minute test was calculated to be 613.2 Wh. Meanwhile, the available energy from the battery is 1382 Wh (96% of 1440 Wh). As the freezer was operated, it absorbed energy from the battery and thus reduced the stored energy in the battery. As shown in Figure 10a, the battery percentage of stored energy in battery decreases from 96% to 50% in 600 minutes. It means that 46% of 1440 Wh or 662.4 Wh energy was absorbed by the freezer. The energy loss for this test is calculated to be 662.4-613.2 = 49.3 Wh or 7.4%. It could be caused by loss in wiring or other circuit components. Detailed observation of Figure 10 reveals that the ON-OFF cycles could be determined by the chart. Under ON condition, the energy stored in the battery tend to decrease. On the other hand, under OFF condition the energy is almost constant, as could be seen by flat line in Figure 10b.

![Figure 10. a. Percent battery capacity for 10-hour test, b. Detail of battery capacity during ON-OFF cycle.](image)
4. Conclusions and recommendations
The experimental test on the use of 200 WP solar panel for supplying energy for a mini freezer has been carried out in Bandung, Indonesia. Under shiny day, the test shows an average solar radiation of 5.33 kWh/m$^2$ with a peak at 992-1038 W/m$^2$, 35.6% radiation data are higher than 500 W/m$^2$, and 24.6% are higher than 800 W/m$^2$. For 12-hour period from 06.00 to 12.00, the average power for charging is 98 W. The average power increases to 130.5 W at 08.00 to 16.00, with a maximum of 157 W and minimum of 83.6 W. If 100 W is considered as a minimum, the period of 08.30-15.30 is recommended. In the experiment of battery charging, 126.5 W of average power from the PV panel was resulted in the period of 09.00 to 13.20. Testing of 60-Ah battery to energize the freezer with a minimum battery capacity setting of 40% results in the operating time of 8.92 hours. Therefore, two batteries each of 60 Ah are needed for continuous operation in the night.

The experiment was only conducted under clear sky in July. Therefore, in the future, the precise year-round solar radiation figures for Bandung should be provided in order to have a comprehensive data concerning to the feasibility of the use of solar energy for refrigeration and other applications.

References
[1] Eurovent 2018 Indonesia Refrigeration & HVAC market report (European Industry Association)
[2] Separuh Desa di Indonesia Belum Teraliri Listrik 2016 [Online] Retrieved from: https://m.tempo.co/read/news/2016/05/21/090772892/separuh-desa-di-indonesia-belum-teraliri-listrik
[3] Jacob G 2010 Solar resources in Indonesia. Solar Energy Technology. Training Course on Renewable Energy Part II (MEMR CASINDO)
[4] Rumbayan M and Nagasaka K 2011 Estimation of Daily Global Solar Irradiation in Indonesia with Artificial Neural Network (ANN) Method Proceeding of the International Conference on Advanced Science, Engineering and Information Technology
[5] Rumbayan M, Abudureyimu A and Nagasaka K 2016 Mapping of solar energy potential in Indonesia using artificial neural network and geographical information system Renewable and Sustainable Energy Reviews 16 1437–1449
[6] Prastawa A, Dalimi R and Rezavidi A 2014 Single Hidden Layer Artificial Neural Network Technique for Solar Energy Potential Prediction in Indonesia Isesco Journal of Science and Technology 10 17) 2-10.
[7] Fong K F, Lee C K, Chow T T, Lin Z and Chan L S 2010 Solar hybrid air-conditioning system for high temperature cooling in subtropical city Renewable Energy 35 2439–2451.
[8] Bilgili M 2011 Hourly simulation and performance of solar electric-vapor compression refrigeration system Solar Energy 85 2720–2731
[9] Singh GK 2013 Solar power generation by PV (photovoltaic) technology: A review Energy 53 1-13
[10] European Photovoltaic Industry Association, Global Market Outlook for Solar Power 2015 – 2019
[11] Fraunhofer ISE 2019 Photovoltaic Report Fraunhofer Institute for Solar Energy Systems, ISE, Freiburg
[12] Aguilar FJ, Aledo S, and Quiles PV 2017 Experimental analysis of an air conditioner powered by photovoltaic energy and supported by the grid Applied Thermal Engineering 123 486-497
[13] Infante-Ferreira C A and Kim D -S 2014 Techno-economic review of solar cooling technologies based on location-specific data International Journal of Refrigeration 39 23-37
[14] Opoku R, Anane S, Edwin I A, Adaramola M S and Seidu R 2016 Comparative techno-economic assessment of a converted DC refrigerator and a conventional AC refrigerator both powered by solar PV International Journal of Refrigeration 72 1-11
[15] Kim D S and Infante-Ferreira C A 2008 Solar refrigeration options – a state-of-the-art review. International Journal of Refrigeration 31 3–15