OFF-GRID SOLAR PANEL INSTALLATION, COST AND OPTIMIZATION

UNIVERSITY OF CALGARY, ENERGY ENGINEERING, ENER 200

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Project Details

The following information contains details needed to solve the problem.

Project Goal

The goal of this project was to design an optimized solar system that would provide more than enough power for a luxury 550sqft Las Vegas cabin to go off the grid.

Product Description

To sufficiently power an off grid 500 square foot cabin in Las Vegas, Nevada by the means of solar cells and batteries. The is done converting energy from the sun to useable electrical energy. This location was chosen due to it's ideal solar generation potential which leads the national average of sunlight on an annual basis. Additionally, costs were minimized where appropriate to lessen the pay out length and to maximize our returns. This would make a solar project feasible for the average Las Vegas home owner who has an interest in going off-grid.

Sunlight Potential

Sunlight can be collected by the panels most efficiently from 9am to 3pm (6 hours) [3]. Las Vegas receives 85% direct sunlight during daytime hours [2]. The "Percent of Sunlight" number is a calculated percentage of time, which is recorded between sunrise and sunset, where sunshine reaches the ground. With this, an additional 15% error was added for extreme cases such as unusually high amounts of cloudy days. This means our panels can collect sun 4.2 hours per day. The universal solar radiation constant is 1000 Watts/m^2 or 93 Watts/ft^2 at ground level. Not all this potential energy can be harvested due to inefficiencies with solar cell technology which is covered in the efficiencies section of this report.

Table 1 Sunlight

	Percent of Sunlight (%)	City	Sunlight Total Hours/Year	Sunlight Hours/Day
Non-adjusted Average	85	Las Vegas	3825	6
Adjusted Average	70	Las Vegas	2677	4.2

Optimum Tilt Angle

To get the maximum amount of sunlight energy out of solar panels without the use of a tracker, the panels must be placed at a angle where the majority of potential energy can be harvested. The optimum angle changes throughout the year based on the season and location. There are some simple formulas to find the optimum tilt angel by using latitude of the location, but in this case, the team used the solar electricity handbook calculator to fin the ideal angle. As a result, the team found the monthly and seasonal optimum tilt angle for our location to be 54 degrees to vertical axis facing south. [10]

Figure 1 Optimum tilt [10]

Additionally, the team found how much energy can be gained in kWh/m2/day. This information was used to address the potential need for a sun tracker which would follow the sun as it moved across the sky absorbing more energy. Four variables were compared, horizontal, vertical, optimized angle, and variable panels were considered to determine the value and efficiency of each. As noted in the table below the sun tracker only absorbed 6% more sunlight than the optimized angle panel and therefore the team disregarded the need for a sun tracker as it increases costs and complicates the system making it impractical for home use.

Table 2 Angle Comparison

Angle (degrees)	Avg. Annual Power Generation (kWh/m2/year)	Percentage of Max. Electrical Generation (%)
Flat Surface	1883.76	83.627
Vertical Surface	1372.67	60.938
Optimum Angle (54 degrees)	2131.13	94.608
Adjusted Angle (Throughout Year)	2252.58	100

Load

As a reference when calculating total load for the cabin, the team used the average monthly electrical usage in Nevada which was 935 kWh in 2017 [9]. Since Las Vegas is an ideal location for solar, the team wanted to have all the luxury appliances that would be found in a middle to upper class residence. This included air conditioning, kitchen appliances, washer/dryer, an entertainment center and other small appliances. Load was calculated using the kW rating of our in-home appliances chosen and the average monthly usage of each item. With that, our monthly usage came out to 783 kWh [4]. Note that our cabin usage is lower than the Nevada average two occupant residence due to the small size of our house.

Table 3 Load

	Average Load (kWh/Month)	City
Average Nevada Residence	935	Las Vegas
Cabin	783	Las Vegas

Solution

The following information pertains to information solving our initial task.

Panel

The panel selected is determined by two main components, its output power, and its efficiency. The power of the panel is rated in W and must be able to meet the load (6.61kW). Efficiency is the amount of solar radiation the panel can convert to usable electric energy at standard conditions. This is important as it affects the output power and the amount of space needed to meet the load. The panel selected for the design and its specifications are located below.

Mechanical Properties

Cells	6 x 10
Cell vendor	LG
Cell type	Monocrystalline
Cell dimensions	156 x 156 mm / 6 x 6 in
# of busbar	3
Dimensions (L x W x H)	1640 x 1000 x 35 mm 64.57 x 39.37 x 1.38 in
Static snow load	5400 Pa / 113 psf
Static wind load	2400 Pa / 50 psf
Weight	16.8 ± 0.5 kg / 36.96 ± 1.1 lb
Connector type	MC4 connector IP 67
Junction box	IP 67 with 3 bypass diodes
Length of cables	2 x 1000 mm / 2 x 39.37 in
Glass	High transmission tempered glass
Frame	Anodized aluminum

Certifications and Warranty

Certifications	IEC 61215, IEC 61730-1/-2, UL 1703, ISO 9001, IEC 61701, IEC 62716
Module fire performance (UL1703)	Type 2
Product warranty	10 years
Output warranty of Pmax (measurement Tolerance ± 3%)	Linear warranty* NEW

* 1) 1st year: 98%, 2) After 2nd year: 0.7%p annual degradation, 3) 81.2% for 25 years

Temperature Coefficients

NOCT	45 ± 2 °C
Pmpp	-0.41 %/°C
Voc	-0.29 %/°C
Isc	0.04 %/°C

Electrical Properties (STC *)

	300 W
MPP voltage (Vmpp)	32.0
MPP current (Impp)	9.40
Open circuit voltage (Voc)	39.8
Short circuit current (Isc)	9.98
Module efficiency (%)	18.3
Operating temperature (°C)	-40 ~ +90
Maximum system voltage (V)	1000 (IEC), 600 (UL)
Maximum series fuse rating	20
Power tolerance (%)	0 ~ +3

* STC (Standard Test Condition): Irradiance 1000 W/m², module temperature 25 °C, AM 1.5
* The nameplate power output is measured and determined by LG Electronics at its sole and absolute discretion.

Electrical Properties (NOCT*)

	300 W
Maximum power (Pmpp)	220
MPP voltage (Vmpp)	29.3
MPP current (Impp)	7.50
Open circuit voltage (Voc)	36.9
Short circuit current (Isc)	8.05
Efficiency reduction (from 1000 W/m² to 200 W/m²)	< 2%

* NOCT (Nominal Operating Cell Temperature): Irradiance 800 W/m², ambient temperature 20 °C, wind speed 1 m/s

Figure 2 Panel specifications [3]

The design

The layout for the cabin is 500sqft with a 550sqft roof which is where the panels are to be mounted. Given a load of 9516kWh/year or 6.2kW at 4 hours of sunlight per day 21 panels are needed taking up a total of 370sqft of space. This is an ample amount of space that takes up most of the roof but leaves additional space for other installation components. Using power on the grid within the cabin costs $96.35/month [5], once a solar system is implemented the levelized energy cost over 25 years is $39.65/month which is 41% savings. Additional details about the minimum values can be found in the appendix.

The values above are the minimum values to sustain the home with no reserve, as part of the design the team wanted additional power to be generated and stored in batteries in case of an absence of sun. The team contacted an organization, [3] to size a system slightly larger than our minimum to sustain off grid use and the results are portrayed below.

Figure 3 Solar system design results [3]

The adjusted system generates 10650kWh per year which is 1134kWh more than what is required of the system. This means an additional 3.07kWh is generated per day, therefore enough energy for an entire extra day of energy without sun is available every 8.5 days. The total cost of the solar panels with installation is $22100 without rebates and $14300 with local incentives applied. The updated system that produces extra power requires 23 panels for a 6.61kW load that takes up 409sqft plus installation space [1].

Battery Bank

The battery bank allows power to be stored in case of autonomy. The battery bank for this system is designed to store 1 day of power, this means all the appliances in the cabin can operate on the energy stores in the battery for an entire day without the operation of the solar panels. Key information that went into the sizing and designing of the battery bank was solar panel energy output, at 29kW/d and system consumption, at 26 kW/d. Several battery chemistries were considered, Lithium Ferro Phosphate (LFP), Flooded Lead Acid (FLA) and *Aquion* saltwater batteries. Two main case studies were conducted before selecting the battery system. Saltwater batteries, though they were cheap, environmentally friendly, and had a 100% Depth of Discharge (DoD) margin, were disregarded

Figure 4. LFP Battery [7]

due to their sensitivity to sudden charging and discharging. The remaining two gave promising results, but at different costs.

PHI 2.7™ kWh battery (figure 4) is a top of the line lithium ion battery in the market. With 98% efficiency, 100% DoD margin, long life span, and an enormous potential for scalability. This was battery was the first choice. To employ this 24V 105Ah battery in the system, 14 batteries in parallel would be required (appendix A). A limitation with is battery is that they are only designed to work in parallel fashion. Therefore, only the amp-hours can be increased but not the voltage. Since the batteries can not be configured in series, the battery bank must be rated at 24V. At this voltage 1357Ah would be required to store energy for 1 day of autonomy and thus 14 batteries of 104Ah each would be needed. Though a 100% discharge would not damage this battery, an 80% DoD allow the battery to be run 10,000 cycles. Unfortunately, despite all the advantages of an LFP battery, it was not selected due to the immense cost of $46,000 (more than double the cost of the solar panels) [7].

Figure 5 Lead Acid Battery [8]

The Flooded Lead Acid battery was selected for this system (figure 5). Calculations reveal that the Trojan SIND 6V and 708Ah battery and would satisfy 1.3 days of autonomy with 16 batteries arranged in 8 series of 2 parallel strings (appendix B). The manufacturer instructs not to arrange these batteries into more than 2 parallel strings, as a difference of charge in the two parallel strings would reduce battery life. Though the FLA batteries have a comparatively much lower DoD, are not environmentally friendly a have a shorter life span, they would cost $12704 (less than a third of LFP system). This battery can run through 3500 cycles at 50% DoD but the life span can be increased by reducing the DoD. For example, at 25% this battery can operate 7500 cycles. This relationship, as provide by the manufacture, specific to this battery is depicted in figure 6 [8].

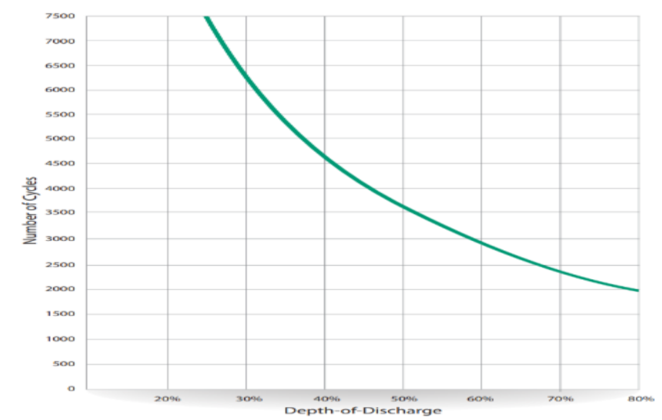

Figure 6. DoD vs Cycle Life of FLA battery

Inverter

An inverter is required in a solar panel system. The efficiency of inverters is very high (>95%), the purpose of the inverter is to convert the DC current from the power to useable AC power for the home. Off grid solar inverters must be used in the system as they contain extra components such as charge monitors and additional wiring, this means they are also more expensive [11]. The inverter is located in between the batteries and the home and is usually mounted on an exterior wall. The inverter is sized based on the load of your system in kW (6.61) therefore the selected inverter for our system is a Schneider Electric inverter rated at 6.8kW displayed below. This inverter costs $4500 without rebates.

Figure 6 Inverter [11]

Efficiency

The solar panel efficiency rating measures what percentage of sunlight hitting a panel gets turned into electricity. Most solar panels are between 14-18 percent efficient and costs change as such. When designing a solar system efficiency is an important number to consider as it directly impacts the amount of space required for the system. Efficiency is considered when optimizing a system as the load determines how much energy is required and the efficiency determines how many panels are needed. A system is optimized when the efficiency of the panel is as low as possible (less expensive) but the area available for panels is not exceeded. There are some factors that affect solar panel efficiency [6]:

- Solar Panel Pitch and Orientation

  For maximum performance, solar panels can be adjusted twice a year. In the summer the sun is high and more sunlight can be harvested by tilting the solar panels to a lower angle. Accordingly, during the winter the panels are to be adjusted to a higher angle. To optimize angle efficiency solar trackers can be used.

- Temperature

  Higher temperatures increase the conductivity of the semiconductor, and makes it more difficult for the electrons to flow through the cell. High temperatures can decrease cell efficiency 10% to 25%.

- Shade

  Solar cells are connected in series, and will operate at the current level of the weakest cell, if one solar cell is shaded it will adversely influence the output of all other cells.

- Front surface soiling

  Solar cells cannot absorb light as effectively when the surface of the solar panels is covered with dirt or other debris that blocks sunlight and therefore production is decreased.

Conclusion

In conclusion the team was required to design an off grid solar system in Las Vegas Nevada that suited a luxury 500sqft cabin. The team successfully accomplished the project by analyzing the sun patterns of Las Vegas and finding the amount of useable sun and the ideal angle for the panels to be oriented. The final orientation and pitch of the roof was calculated to be 54 degrees facing south. The team then took this information and calculated a minimum load, and conducted manual calculations to find the minimum amount of power that needs to be supplied for a single year (9515kWh). The team wanted the household to be able to operate at 100% consumption without sun for a single day. An online tool was used to estimate the design and cost of a system that could produce more power (10650kWh). The system generated an additional 1134kWh of power annually which was enough for one full day of power every 8.5 days. 16 flooded lead acid batteries will be connected to the system to store the additional power and can run 7500 cycles at 25% DoD. The off grid solar inverter that was selected is a Schneider electric model rated at 6.8 kW which is within the load limit. Finally, panel efficiency was discussed which communicated how to keep panels operating at the highest efficiency possible for the best results. The final cost for the system design is 39,304USD without rebates and approximately 31,000USD with rebates included.

Appendix

[A] *Calculations for LFP Battery:*

Monthly Consumption: 793kWh/month, 26.4kWh/day

Reserves: 1 day worth of power

Power Capacity = (1d)(26.4kWh/d) = 26.4kWh

Amp Hours = $\frac{26.4\text{kWh}}{24\text{V}} = 1100\text{Ah}$

Battery: 105Ah and 24V (LFP)

Strings in Series: $\frac{\text{System Voltage}}{\text{Battery Voltage}} = \frac{24\text{V}}{24\text{V}} = 1$

Depth of Discharge Margin: 1100Ah/0.8 = 1357Ah

Parallel Strings: $\frac{\text{Amp Hours Required}}{\text{Amp Hour per Battery}} = \frac{1357\text{Ah}}{105\text{Ah}} = 14$

1 in series $\times$14 in parallel = 14 Batteries in total

$14 \times \$3000 = \$42000$

[B] *Calculations for FLA Battery:*

Monthly Consumption: 793kWh/month, 26.4kWh/day

Reserves: 1 day worth of power

Power Capacity = (1d)(26.4kWh/d) = 26.4kWh

Amp Hours = $\frac{26.4\text{kWh}}{48\text{ V}} = 550\text{Ah}$

Battery: 708 Ah and 6V (Flooded Lead Acid)

Strings in Series: $\frac{\text{System Voltage}}{\text{Battery Voltage}} = \frac{48\text{V}}{6\text{V}} = 8$

Depth of Discharge Margin: 550Ah/0.5 = 1100Ah

Parallel Strings: 2 max (as suggested by manufacturer)

$\frac{1100\text{Ah}}{2} = 550$ Ah (per string)

8 in series $\times$2 in parallel = 16 Batteries in total

$16 \times \$794 = \$12704$

Actual Capacity:

34.0kWh or 1.3 days

House uses 793 kwh per month or 9516 kWh per year.

Las Vegas energy costs 0.1215$/kWh. Our system costs 96.35$ per month on the grid.

26.1 kWh per day. 6 hours of usable sunlight from 9am to 3pm. Las Vegas gets 85% sunlight +15% error for unpredictable error. 4.2 hours of usable sunlight.

26.1 kWh divided by 4.2 hours is 6.2 kW system.

6.2 kW system needs 21, solar panels. 370sqrft of solar panels plus additional 35sqrft installation space.

Gross cost of 22077$ divided by 21 panels is 1051.29$ per panel including installation. With rebates 680.81$ per panel.

Solar panel energy costs 0.05$/kWh (levelled over 25 years because baseline cost is fixed). Our system with solar panels costs 39.65$ per month off grid. Which is a 41% savings (within first year assuming energy prices do not increase.)

These calculations are bare minimum the estimate above provides an additional 1134kwh as a buffer in case additional power is required.

26.1 kWh per day minimum. 29.17 kWh provided by system. Every day 3.07 kWh extra is produced assuming all power is used. This means every 8.5 days there is enough backup power to provide the house with one day of power in case of no sun.

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