Design and Optimization of a Sun-Tracking Solar PV System Which Offsets Annual Electricity Usage

University of Victoria
Faculty of Engineering
ENGR 446 (Fall 2021)
Victoria, BC

Student Name:	Clayton Moxley
Student Number:	V00876017
Discipline:	Mechanical Engineering
Email:	Ctmoxley@gmail.com
Date:	December 2, 2021

In partial fulfillment of the requirements of the B.Eng. Degree

Dec 2, 2021

Ash Senini
ENGR 446 Instructor
Faculty of Engineering
University of Victoria
Victoria, BC

Re: ENGR 446 Final Report

Dear Ash,

Please accept the following technical report, "Design and Optimization of a Sun-Tracking Solar PV System Which Offsets Annual Electricity Usage", in fulfillment of the ENGR 446 course requirements. I am in my final term (4C) of my mechanical engineering degree and this report aims to showcase the engineering knowledge I have developed in the areas of renewable and sustainable energy systems.

In Alberta, most of the electricity generated comes from natural gas power plants which produce greenhouse gas emissions and contribute to the province's carbon footprint. Solar energy systems are currently underutilized in the province despite having the second highest annual solar radiation in Canada. One of the issues with fixed-panel solar photovoltaic (PV) systems is that they have a significant capital cost and long payback periods which can make it difficult for consumers to afford an installation.

This report investigates the feasibility of using a higher efficiency sun-tracking solar PV system to offset the average annual electricity usage of a single-family home in Calgary, Alberta. Detailed analysis is performed to determine the sun-tracking algorithm, required PV components, array land usage, maximum power generated, and financial cost of the system.

This project has provided a valuable opportunity to utilize engineering for something I am passionate about by designing a residential renewable energy system for the city I live in. Thank you for taking the time to evaluate this report and I hope that you find it both interesting and informative.

Sincerely,

Clayton Moxley
4th year Mechanical Engineering Student

Table of Contents

Table of Figures

List of Tables

Executive Summary

This report details the design a sun-tracking photovoltaic (PV) system which can generate power equal to the average annual electricity usage for a residence in Calgary, Alberta. Utilizing tracking for a PV system provides a reduction in the number of required panels which significantly reduces the capital cost and payback period of the system. The specific goals for the project are to design a sun-tracking PV system which can generate a minimum of 7200 kWh of electricity per year while utilizing less than 80 m^2 of area. The maximum payback period for the capital cost of the system is specified to be 25 years.

Two types of sun-tracking systems, open-loop and closed-loop, are assessed based on their theoretical power generation, weather dependency, operational energy requirements, ease of installation, and maintenance. The open-loop tracking system is chosen as the best solution due to its simplicity and increased theoretical power generation under varying weather conditions.

Analysis is conducted to determine the tracking algorithm for the specific location, the amount of radiation that can be utilized, and the array land usage. The array is found to require 26.41 m^2 of available land area, which is significantly less than the project goal of 80 m^2. System Advisor Model (SAM) software is used to simulate the tracking PV system using typical meteorological year data with eight Longi 440 W bifacial PV panels and a Sunny Boy 3500 kW inverter.

The simulation results show that the system is capable of producing a net annual AC power of 7466 kWh, exceeding the total electrical consumption of 7200 kWh specified by the project goals. The financial simulation uses a debt fraction of 100%, with a mortgage of 25 years at 5%, which provides a payback period of 9.5 years with a capital cost of $8398.92 CAD. The resultant payback period of the sun-tracking PV system satisfies the project goal of having a payback period less than 25 years.

The designed system is effective in producing power with minimal land usage and a low capital cost, which provides Albertan homeowners with an accessible way to offset their energy usage and remove their reliance on volatile electricity pricing. Solar tracking systems are found to be ideal for installations where the cost of land is low and module prices are high. For larger PV arrays or commercial application, a full-tracking system is not economical due to larger shading profiles that lead to increased spacing between adjacent subarrays and increased maintence costs.

To increase the accuracy of the results from this study, an in-depth 3D shade analysis would need to be completed in the SAM software which requires knowledge of shading objects at a specific location. This would allow for a more accurate representation of the actual power that the PV system could generate. Further work is also needed to determine the types of actuators and mounting system that would be utilized by this full-tracking array as this would provide a more accurate representation of the system capital cost, payback period, and the net power generation.

Glossary

Actuator	**Device that converts electricity to mechanical motion**
Array	Group of solar PV panels which are connected in strings
Attenuation	Reduction in radiation intensity due to scattering
Azimuth	Angular position with respect to south cardinal direction
Bifacial	PV cell able to produce electricity from both sides
Closed-Loop	Control system which is regulated by feedback
Equinox	Date when Earth's equator is coincident with solar plane
Insolation	Radiation received at the earth's surface
Inverter	Component which converts between AC and DC power
Irradiance	Amount of radiation per unit area
Normal	Perpendicular to an object; also known as orthogonal
Open-Loop	Control system which is not regulated by feedback
Solstice	Date when sun reaches its extreme annual altitudes
Zenith	Directly above the observer; complimentary to altitude

List of Abbreviations

Alternating Current	**AC**	**Current which periodically changes direction**
Apparent Solar Time	**AST**	Time based on apparent motion of the sun
Daylight Savings Time	**DS**	Sixty-minute time adjustment based on time of year
Diffuse Horizonal Irradiance	**DHI**	Radiation received from the sun by a horizontal surface
Direct Current	**DC**	Current which is one-directional
Direct Normal Irradiance	**DNI**	Radiation received from the sun by a normal surface
Equation of Time	**ET**	Difference in apparent solar time and average solar time
Global Horizontal Irradiance	**GHI**	Total radiation received from the sun by a horizontal surface
Global Positioning System	**GPS**	Satellite-based system which provides global position
Inertial Measurement Unit	**IMU**	Electronic device which measures force and angular rate
Kilowatt-Hour	**kWh**	SI unit of energy
Light Dependent Resistors	**LDR**	Resistor which changes resistance based on light intensity
Local Longitude	**LL**	Longitude at specified location
Local Solar Time	**LST**	Time based on position of sun relative to the location
Photovoltaic	**PV**	Conversion of light into electricity using semiconductors
Plane of Irradiance	**POA**	Incident irradiance on a solar array
Standard Longitude	**SL**	Longitude of local time zone
System Advisor Model	**SAM**	Solar system performance and financial simulation software
Top of Pole Mount	**TPM**	Solar PV mount consisting of a single pole
Typical Meteorological Year	**TMY**	Meteorological data for every hour in a year for a location

List of Symbols

Altitude Angle	α	$^\circ$	**Sun's angular position with respect to horizontal**
Azimuth Angle	z	$^\circ$	Sun's angular position with respect to south
Beam Radiation	G_b	W/m^2	Solar radiation not scattered by the atmosphere
Day Number	N	–	Day of the year number
Declination Angle	δ	$^\circ$	Seasonal change in the Sun's altitude angle
Diffuse Radiation	G_d	W/m^2	Solar radiation scattered by the atmosphere
Equation of Time Parameter	B	min	Conversion parameter from day number
Ground Reflectance	ρ	–	Measure of ground reflectivity
Ground-Reflected Radiation	G_g	W/m^2	Solar radiation reflected by the ground
Hour Angle	h	$^\circ$	Distance from apparent solar noon
Incident Angle	θ	$^\circ$	Angle between the sun and a surface normal
Latitude	L	$^\circ$	Latitude of a location
Surface Azimuth Angle	Z_s	$^\circ$	Surface angular position with respect to south
Surface Tilt Angle	β	$^\circ$	Surface angular position with respect to horizontal
Zenith Angle	Φ	$^\circ$	Sun's angular position with respect to vertical

1 Introduction

1.1 Background

In Alberta, over 90% of the electricity is generated from natural gas and coal power plants which produce greenhouse gas emissions and contribute to the province's carbon footprint [1]. Due to the large reliance on fossil fuels for electricity generations, fluctuations in natural gas prices, and subsequently electricity prices, can create uncertainty and place financial strain on Alberta residents. Installation of a solar photovoltaic (PV) system allows Albertan homeowners to offset the energy usage of their residence, effectively removing their reliance on volatile electricity pricing and decreasing their home's carbon footprint.

Figure 1. Fixed-Panel (Left) and Dynamic (Right) PV Systems [2] [3]

Fixed PV panels are the most common configuration used in residential and commercial applications since the system is simple and minimal maintenance is required (Figure 1). Due to the relative mechanical simplicity of these systems, they usually offer a longer lifespan than a dynamic system [4]. However, static panels will generate significantly less power than a dynamic system over time [5]. Since the sun's position changes constantly during the day, a fixed panel does not effectively utilize the full radiation that is available and typically produce much less power than they are rated for.

The position of the sun in the sky can be expressed in the azimuthal coordinate system in terms of the altitude (elevation) angle, α, and the azimuth angle, z, as shown in Figure 2. The altitude of the sun can also be expressed in terms of the zenith angle, Φ, which is the complementary of the altitude angle $(\Phi = 90° - \alpha)$. The angular orientation of a PV panel is defined by the surface azimuthal angle, Z_s, and the tilt angle, β (Figure 2) [6].

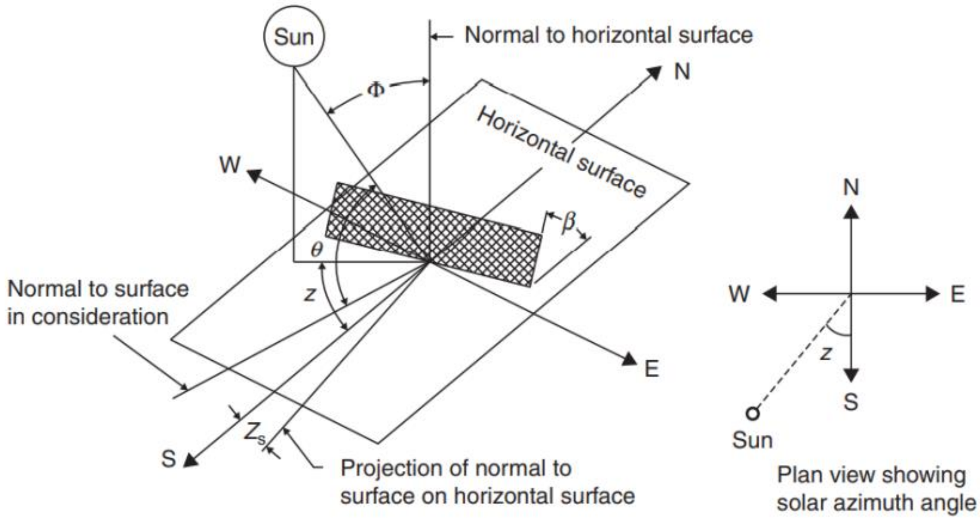


Figure 2. Solar Panel and Sun Angular Coordinates [6]

The intensity of incoming radiation on a PV panel is largely dependent on the angle of incidence, θ, which is defined as the angle between the surface normal of the PV panel and the sun's rays [6]. This angle is of importance in solar system design as it is typically used to determine the optimum orientation which produces maximum power generation. In the northern hemisphere, maximum annual power generation for a fixed panel PV system is achieved by orienting the panel facing south ($Z_s = 0$) with a tilt angle equal to the latitude of the location ($\beta = latitude$) [6].

To optimize the power of the generation of PV panels throughout the day, the use of dynamic sun-tracking systems are often considered which orient the panel in a way such that the incident angle is constantly minimized. This causes incoming radiation to be always incident on the panel, providing a reduction in scattered and reflected radiation from the panel surface. A study comparing the efficiency of dual axis tracking, single axis tracking, and fixed panels found that the dual axis and single axis systems had power gains of 43.87% and 37.53% respectively when compared to a fixed panel at the optimal tilt angle [7].

1.2 Objective

Alberta has the second highest availability of solar radiation in Canada, making it an ideal location for solar PV systems [8]. Fixed panel PV systems produce less power than they are rated for due to the large angle of incidence during the morning and evening hours of the day. This leads to an increase in the number of PV panels required to meet the desired power output of the system. Utilizing a sun-tracking solar system in Alberta would lead to a reduction in the number of panels required to completely offset a residence's electrical usage due to the increased power generation per panel. This would significantly reduce the capital cost required for the system and subsequently the payback period.

1.2.1 Purpose

The purpose of this project is to design a residential solar PV system and determine the tracking algorithm which can generate power equal to the average annual electricity consumption for a residence in Alberta while minimizing the number of panels required.

1.2.2 Goals

The goals for the project are determined based on the average monthly electricity usage and roof size for a single detached home in Alberta. The specific project goals are to design a PV system which:

- Generates a minimum of 7200 kWh of electricity per year.
- Provides a payback period of less than 25 years.
- Has an array footprint of less than 80 m^2.

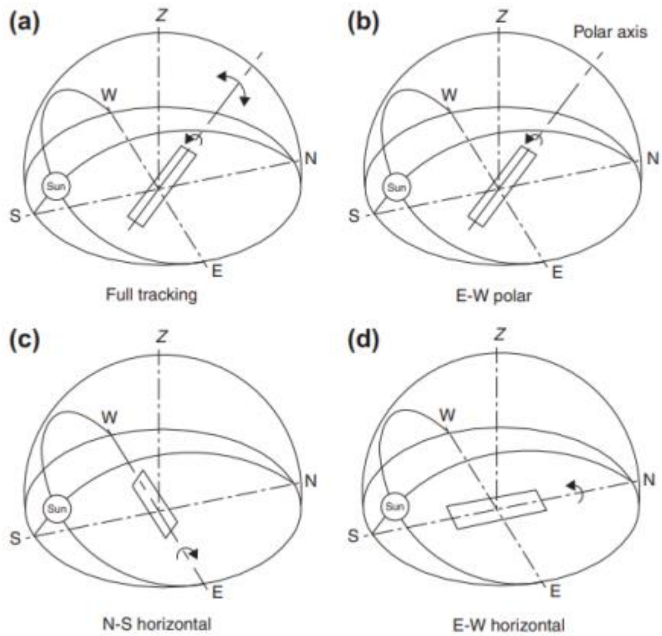
1.2.3 Limitations

This report will only focus on the design of the proposed solar PV system using off-the-shelf components and will not consider the design of the mounting system. The theoretical power generation of the designed system based on the selected components will be considered and will not include a physical model to validate the results. Power consumption of the actuators which would provide dynamic positioning will not be included in the scope of this project due to a lack of physical components required for testing.

The effects of shading on the panels due to objects such as trees or adjacent structures will not be considered when determining the power generation of the PV array. Power generation reductions due to weather effects such as snow and rain will not be included, but historical weather data for simulating power generation under cloudy conditions will be included. All analysis for the proposed system will assume an average single-family detached household with four members, having a square footage of 1700 ft^2 (158 m^2) [9]. Half of the household square footage will be assumed as area that is available for the array. The average annual electricity usage of the household that will be used for analysis is 7200 kWh [10].

1.3 Potential Solutions

Solar tracking systems are classified based on the number of axes which are utilized for positioning as well as which method of control strategy is employed, either open-loop or closed-loop [11]. Open-loop control systems do not require feedback (sensor-less) whereas closed-loop systems rely on feedback from sensors. As shown in Figure 3, the full tracking configuration collects the maximum amount of solar energy and is the basis by which the single axis systems are compared.



Tracking Mode	Percentage to Full Tracking		
	E	SS	WS
Full tracking	100	100	100
E–W polar	100	91.7	91.7
N–S horizontal	89.1	97.7	60.9
E–W horizontal	73.8	74.0	86.2

E = equinoxes, SS = summer solstice, WS = winter solstice.

Figure 3. Power Generation Comparison for Solar Tracking System Configurations [6]

For this project, only full tracking will be considered since it provides the highest power generation of all the tracking types. The two potential solutions for this problem are detailed in the following sections.

1.3.1 Open-Loop Full Tracking System

This system does not require any sensor input or feedback and determines the position of the sun based on the celestial geometry determined by the time, date, latitude, and longitude at the location (Figure 4). This system can also incorporate historical meteorological weather data to optimize the panel orientation.

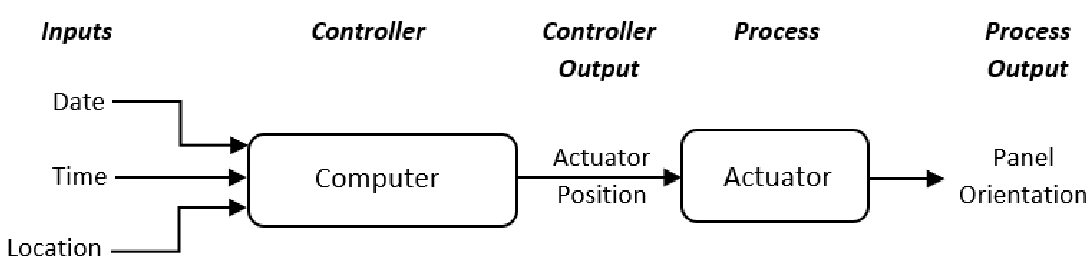


Figure 4. Open-Loop Tracking System Block Diagram

A small computing module (such as a Raspberry Pi) calculates the sun's position and commands the actuators to move the panel to the desired angular position. Two actuators are used to control the orientation of the panel by rotation about one or two axes, allowing the panel surface to remain normal to the direction of the sun throughout the day.

1.3.2 Closed-Loop Tracking System

This system typically utilizes at least two optical sensors as feedback to determine the position of the sun in the sky based on the difference in irradiance received between the adjacent sensors. Light dependent resistors (LDR) are commonly used as the optical sensors due to being inexpensive and widely available. The optical sensors can either be oriented with different angles or have a shading device between them (Figure 5)[12].

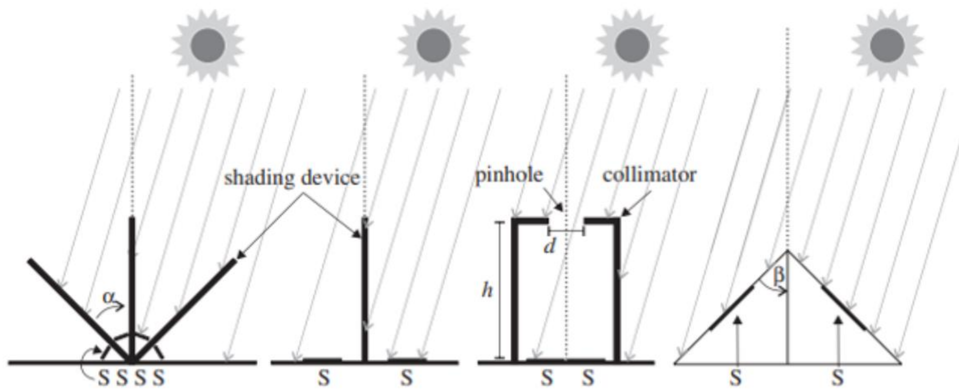


Figure 5. Optical Sensor Configurations for Sun Tracking [12]

A microcontroller is used to read the analog inputs and convert the voltages generated by the two photoresistors into light intensity readings. When the voltages of the photoresistors are different, actuators are used to move the orientation of the panel until the sensors are electrically balanced. At this point the sun is determined to be situated directly between them.

1.4 Initial Assessment

A decision matrix is chosen as the method for initially assessing the proposed solutions. Each of the proposed solutions will be compared to determine the best solution. The criteria used for ranking each solution in the decision matrix is detailed in order of importance in the following sections.

1.4.1 Power Generation

This criterion corresponds to how much power can theoretically be produced under optimal conditions by each of the systems. Closed-loop systems can theoretically produce more power in conditions where the highest radiation is not coming directly from the sun throughout the day due to light scattering from clouds or reflected light from other sources. This could temporarily provide increased power generation compared to the closed-loop system but if conditions changed the panel would need to move back to its optimal position before reaching maximum power again. Open-loop systems would be consistently pointed in the direction of the sun regardless of any atmospheric or meteorological effects.

1.4.2 Operational Energy Required

This criterion corresponds to how much power is required by each system to operate the control system and actuators. Under ideal conditions both systems will utilize similar electrical consumption to drive the actuators, although the closed-loop system could be subject to increased actuator usage due to light scattering.

1.4.3 Weather Dependency

This criterion corresponds to what extent the power generation of the system affected by weather. The closed-loop system is highly dependent on weather conditions since it can affect the readings obtained by the optical sensors. Open-loop systems are weather independent since the movements are preprogrammed.

1.4.4 System Cost

This criterion corresponds to the total capital cost required for the system. For both the open-loop and closed-loop systems, the capital cost required is approximately the same since both utilize the same components. The cost difference between the computing module with global positioning system (GPS) and an inertial measurement unit (IMU) or microcontroller with optical sensors is negligible.

1.4.5 Ease of Installation

This criterion corresponds to whether the system requires accurate orientation, programming, or calibration during installation. For the open-loop system, accurate calibration of the system during the installation is essential which includes both date, time, and azimuthal orientation. The closed-loop system does not require calibration of the frame but does require accurately positioning the sensors to ensure that they are parallel to the panel.

1.4.6 Maintenance Requirements

This criterion corresponds to how much maintenance is required on an annual basis. Both systems would require approximately the same amount of maintenance as both would utilize dual actuator control. The open-loop system could require additional maintenance in the form of calibration since it requires a GPS unit and IMU sensor to determine the position of the panel.

1.4.7 Decision Matrix Results

Based on the criterion detailed in the previous sections, a decision matrix is completed with the associated weightings and priorities as shown in Table 1. Ratings are completed by assigning a number for each solution from 1 (worst) to 2 (best).

Table 1. Initial Assessment Decision Matrix

	Power Generation	Operational Energy	Weather Dependency	System Cost	Ease of Installation	Maintenance Requirements	Total
Criteria Priority	6	5	4	3	2	1	
Open-Loop	1	2	2	2	2	1	
Weighted Rating	6	10	8	6	4	1	**35**
Closed-Loop	2	1	1	2	1	2	
Weighted Rating	12	5	4	6	2	2	**31**

Based on the results from the decision matrix analysis, the best choice from the potential solutions defined for this project is the open-loop system.

2 Discussion

2.1 Chosen Solution

Based on the results from the initial assessment, the open-loop solar tracking system is considered as the best solution and will be utilized to meet the project objectives and goals. This system uses the local date, time, latitude, and longitude as input parameters to a computer which calculates the corresponding position of the sun in the sky. The angular orientation of the panel which produces an incident angle of 0º is calculated using the current solar position. Two linear actuators rotate the panels about two perpendicular axes to achieve the desired panel orientation.

Figure 6. Residential Sun-Tracking Array [13]

The solar array utilized with this tracking system consists of an array of 440 W Longi PV modules on a single top of pole (TPM) mount to reduce the array footprint, similar to the system shown in Figure 6. A grid-tie inverter is utilized to transform the array direct current (DC) power output into alternating current (AC) power that can be used by the residence or fed into the electrical grid. The location which the system performance is simulated for is the Calgary International Airport, having a latitude of 51.05°, standard longitude of -105°, and local longitude of -113.94°.

2.2 Panel Orientation

For two-axis tracking systems, the system aims to ensure that the incident angle between the panel and the direction of the sun is equal to zero. This allows the panel to be normal to the sun's beam radiation and absorb the maximum possible radiation throughout the day. The incident angle between the sun and the panel normal is expressed using (1) [6]:

$$\theta = \cos^{-1}[\sin(L)\sin(\delta)\cos(\beta) - \cos(L)\sin(\delta)\sin(\beta)\cos(Z_s) + \cos(L)\cos(\delta)\cos(h)\cos(\beta) + \sin(L)\cos(\delta)\cos(h)\sin(\beta)\cos(Z_s) + \cos(\delta)\sin(h)\sin(\beta)\sin(Z_s)] \tag{1}$$

To achieve an incidence angle of 0º, the panel surface azimuth angle, Z_s, is set equal to the solar azimuth angle z, and the surface tilt angle, β, is set equal to the solar zenith angle, Φ [6]. The solar azimuth and zenith angles can be calculated directly using the date, time, latitude, and longitude at the array location. Determination of the angles at each point of the day requires the use of the apparent solar time (AST) which is based on the apparent angular motion ofthe sun across the sky [6].

At solar noon (12:00 PM AST) the sun is located on the meridian of the observer, which typically does not align with the local noon at the location (12:00 PM LST) [6]. To convert the local time to apparent standard time, the day number and longitude are used in conjunction with the equation of time. The expression for converting AST to LST is shown in (2) [6].

$$AST = \ LST + ET \pm 4(SL - LL) - DS \tag{2}$$

The terms in the AST conversion correspond to the standard longitude (SL), the local longitude (LL), the daylight savings time adjustment (DS)(which is either 60 minutes or zero), and the equation of time (ET). The equation of time term is expressed in minutes and calculated using (3) [6].

$$ET = 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(\mathrm{B}) \tag{3}$$

The input parameter to the equation of time, *B*, is obtained using the day of the year number, N, and is expressed in degrees using (4) [6].

$$\mathrm{B} = \frac{360}{364}(N - 81) \tag{4}$$

To determine the sun's position in the sky at any point during the year, the location latitude, *L*, declination angle, *δ*, and hour angle, *h,* must be known. The declination angle refers to the seasonal change in the altitude angle of the sun's path as the earth orbits around the sun and has a range of 23.45° [6]. In the northern hemisphere, the declination angle is negative during the winter months, positive during the summer months, and zero during the equinoxes [6]. The declination angle is calculated using the day number of the year, *N,* shown in (5) [6].

$$\delta = 23.45\sin\left(\frac{360}{364}(284 + N)\right) \tag{5}$$

The hour angle at a location refers to the relative rotation of the earth that would bring the sun directly onto the observer's meridian or offset from solar noon expressed in AST. Determination of the hour angle is simply 15° per hour or 0.25° per minute, with positive hour angles denoting hours after solar noon as shown in (6) [6].

$$h = 15(AST - 12) \tag{6}$$

Using the equations for declination angle, hour angle, and the local latitude of the location, the surface tilt angle, β, and surface azimuth angle, Z_s, are calculated using the following equations shown in (7) and (8) [6].

$$\beta = \Phi = \cos^{-1}(\sin(L)\sin(\delta) + \cos(L)\cos(\delta)\cos(h)) \tag{7}$$

$$Z_s = z = \sin^{-1}\left(\frac{\cos(\delta)\sin(h)}{\sin(\Phi)}\right) \tag{8}$$

Plots of the surface tilt and azimuth angles as a function of the local standard time in Calgary are shown in Figure 7 and Figure 8 for the solstices and equinoxes, corresponding to March 21, June 21, September 21, and December 21. The excel worksheet used to calculate the surface angles can be found in Appendix A.

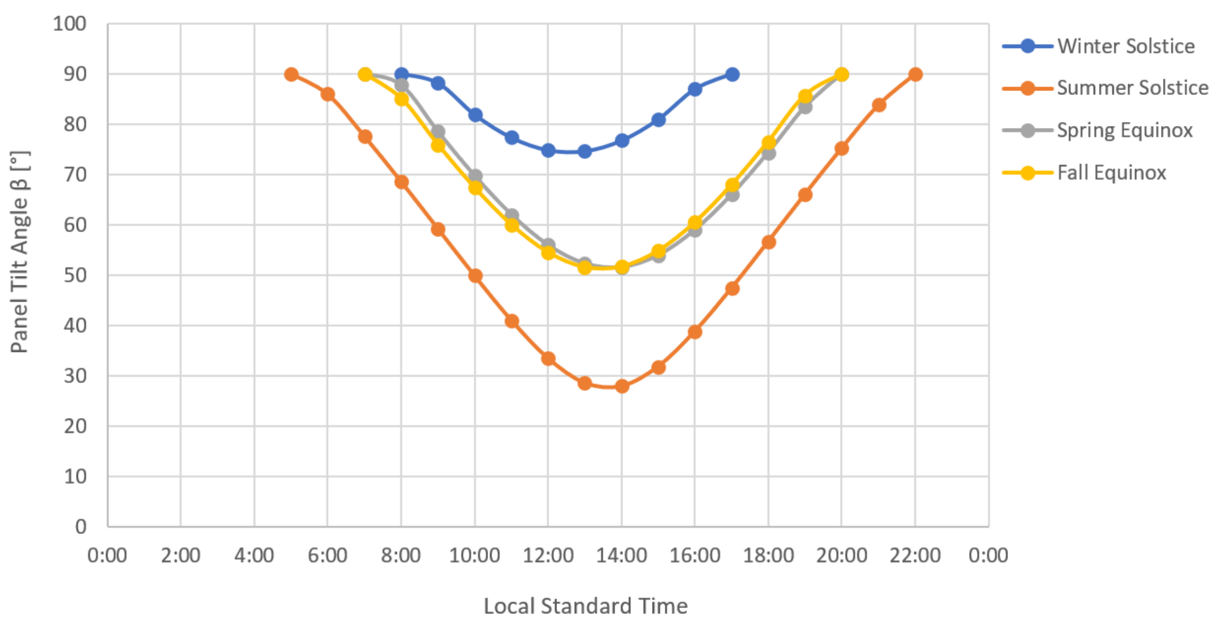


Figure 7. Surface Tilt Angle During Solstices and Equinoxes

As can be seen in Figure 7, the minimum tilt angles for the summer solstice and equinoxes are shifted forward in time due to the daylight savings time adjustment to the local time. The end points of each data series correspond to the local sunrise and sunset times during each of the dates. During the summer, the angular tilt range is significantly higher than during the equinoxes and winter solstice. The azimuthal angle range of the surface is also higher during the summer solstice due to the higher elevation path the sun takes across the sky (Figure 8).

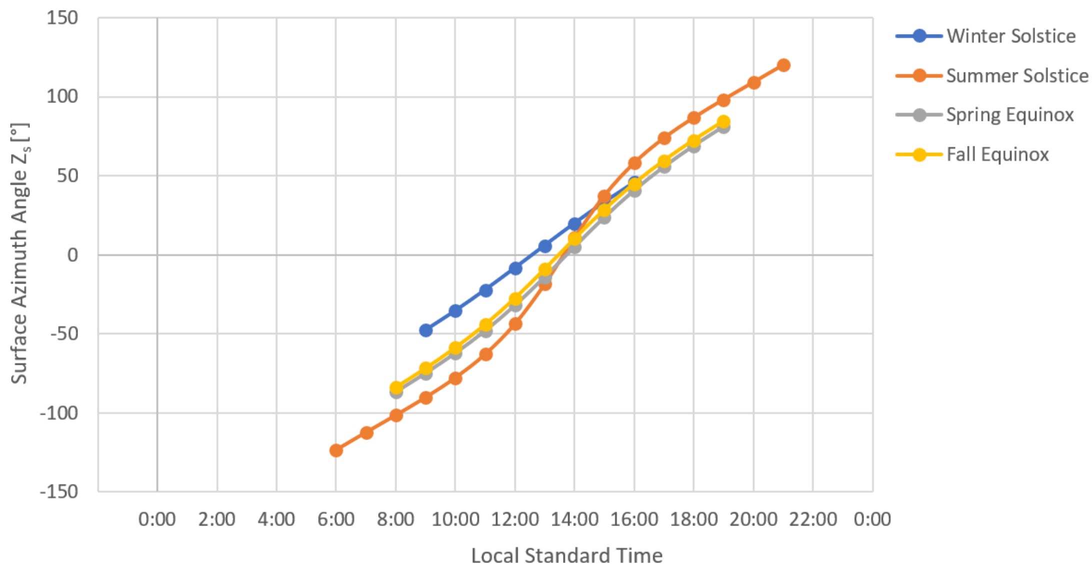


Figure 8. Surface Azimuth Angle During Solstices and Equinoxes

2.3 Tracking Algorithm

The algorithm utilized by the computing module to determine the surface tilt and azimuth angles at each discrete time step is summarized by the flowchart shown in Figure 9.

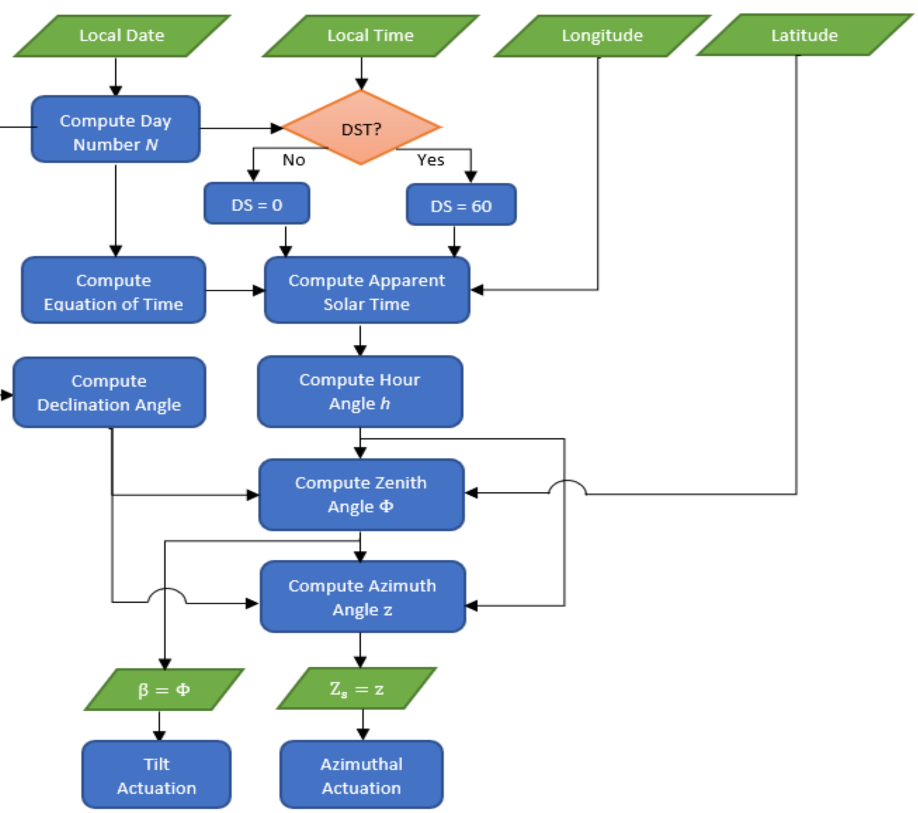


Figure 9. Algorithm For Panel Orientation While Tracking

2.4 PV System Design

Design of the PV system includes specification of the type of PV panels, the array configuration, and the inverter used to convert the DC power of the array into AC power usable by the residence and grid. This system does not incorporate a battery bank since it uses a grid-tie connection.

2.4.1 Array Size

To determine the required nominal DC output power of the dual-axis tracking array, sizing can first be performed for a fixed-panel array which provides a rough starting point for the system design and simulation. From the specified objectives for this project, the total average annual electricity usage of the residence is 7200 kWh per year. For a fixed-panel system facing south with optimum tilt angle equal to the location latitude, the average annual number of full sunlight hours in Alberta is 1291 kWh/kW/year [14]. The nominal DC output power of the south-facing fixed-panel system with optimum tilt angle can be calculated by dividing the total average annual electricity usage by the average number of full sunlight hours. This provides a rough DC capacity estimate of 5.6 kW for the fixed-panel system.

The panels that will be used in the PV system analysis are specified as Longi 440W Bifacial panels. Using the maximum output power rating of the panels, the total number of panels required to meet the nominal output capacity is 12.72 panels. These values provide a rough estimate of the system size so this value will be rounded down to an integer number of twelve panels. Since full-tracking systems can have increased power gains over fixed panel systems (detailed in Section 1.1) the nominal DC capacity of the tracking system will be reduced by 33%. This provides a nominal DC output capacity for the tracking system of 3.52 kW using eight 440 W panels. The PV array size that will be simulated in the SAM software is summarized in Table 2.

Table 2. Full Tracking Array Size and Nominal Capacity

System Type	Number of Panels	Nominal Array Capacity (kW_{DC})
Full-Tracking	8	3.52

2.4.2 Array Electrical Configuration

The array configuration is determined by selecting an appropriate inverter and ensuring that the string voltage does not exceed the specified input DC voltage. For the full-tracking system, the inverter is selected to be a SMA Sunny Boy 3800US (SLG-310-0322 [240V]) which is specific for grid-tie usage and has a maximum DC power capacity of 4.2 kW [15]. The maximum PV array string voltage accepted by this inverter is 480 V [15]. Using the Longi PV modules specified in Section 2.1, the maximum power voltage per module is 41.0 Vdc (Appendix B) which provides to a string voltage of 328 Vdc for 8 modules wired in series (Figure 10). This value is within the range of acceptable DC voltages for the inverter up to 480 Vdc [15].

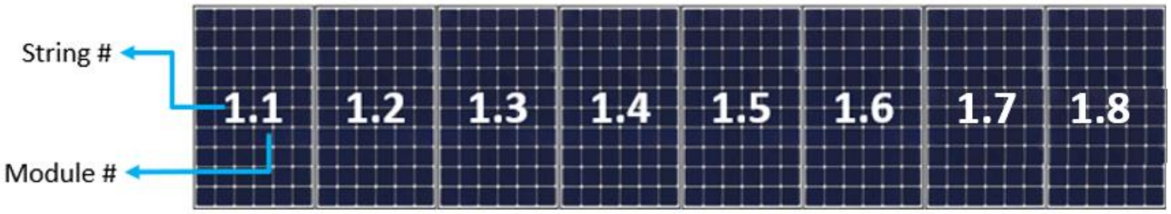


Figure 10. Array String Size and Numbering

The DC to AC ratio is the ratio of the total DC power output from the PV array to the total AC power output from the inverter. With a total DC power output of 3.52 kW from the array and a total AC power output of 3800W from the inverter, the DC to AC ratio is equal to 0.91. A ratio between 1 and 1.25 allows for under-sizing of the inverter to save on the costs of the system. This assumes that the PV array will rarely produce at full capacity (typical due to changing temperature, weather conditions, and shading). For the full-tracking system, the ratio is designed to be less than one to ensure that if the array is producing at full capacity less voltage is clipped.

2.5 Land Usage

The amount of space that is required for the full-tracking array is determined from the shadow length cast by the array during low solar altitude angles. For arrays that consist of multiple rows or subarrays, the spacing between subsequent subarrays can be quite significant if using full tracking. As specified in Section 2.1, the full-tracking array used in this project will utilize a single mount which supports eight panels. This allows the total land usage to be minimized as no subarrays are present that could be affected by shading.

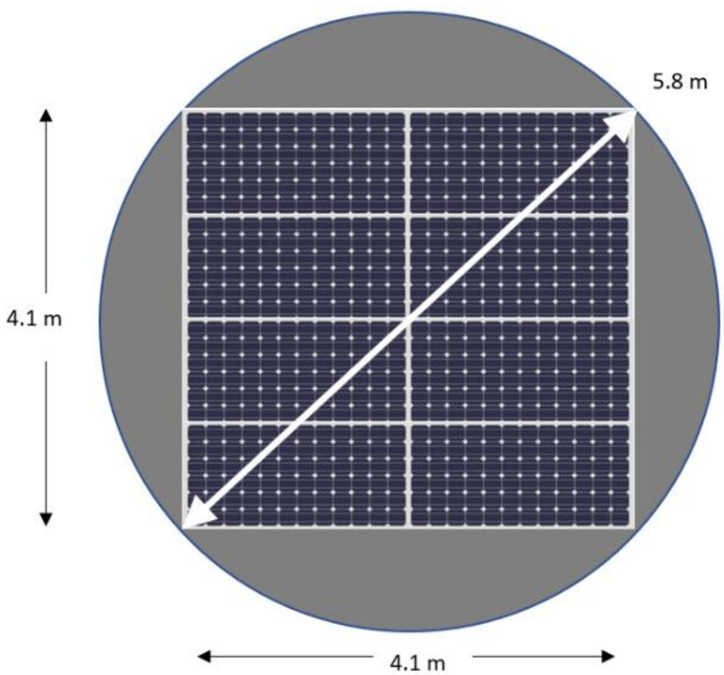


Figure 11. Required Area for TPM Tracking Array

The minimum space required by the full tracking array is determined by calculating the area of a circle having a diameter equal to the diagonal length of the array (Figure 11). This allows the array to fully rotate about each axis without collision with any nearby objects. The minimum area required for the specified full-tracking array is 26.41 m^2 as shown in Table 3, which is significantly below the maximum land usage of 80 m^2 specified by the project goals.

Table 3. Array Dimensions and Required Area

Array Length (m)	Array Width (m)	Array Diagonal (m)	Required Array Area (m^2)
4.1	4.1	5.80	26.41

2.6 Available Radiation

With two-axis tracking achieving a consistent incident angle of zero degrees, the intensity of radiation during the hours of daylight is maximized. The number of hours of sunlight that are available throughout the year vary, and can be calculated using (9) [6]:

$$Day\ Length = \frac{2}{15}\cos^{-1}(-\tan(L)\tan(\delta)) \quad (9)$$

For Calgary, having a latitude of 51.5°, a plot of the day length throughout the year is shown below in Figure 12. The average number of hours of daylight per year in Calgary is 12, ranging from 7.67 hours on the winter solstice to 16.32 hours on the summer solstice.

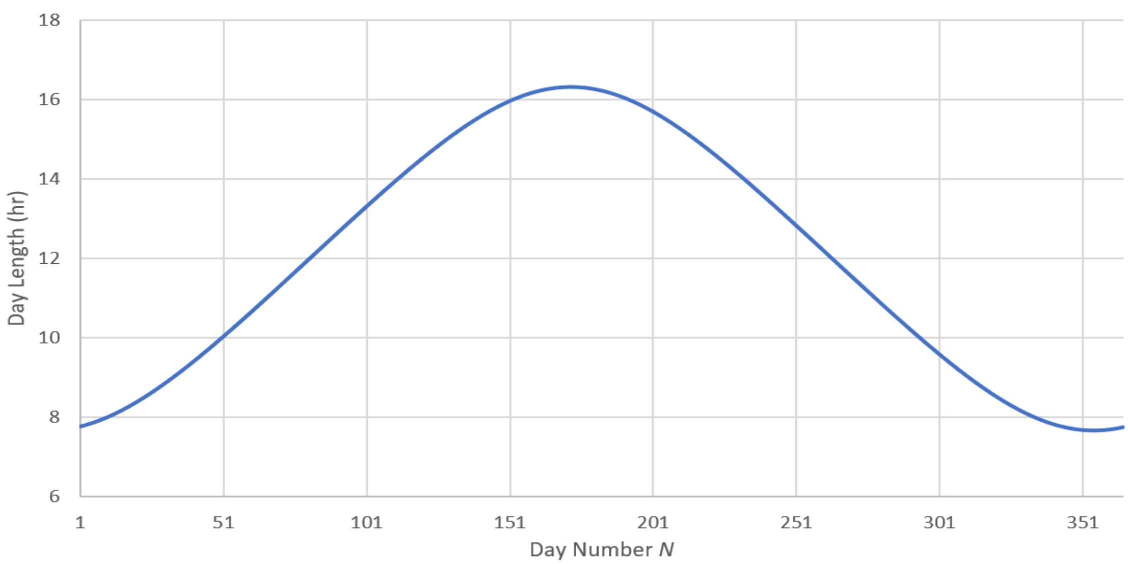


Figure 12. Day Length Throughout the Year

Due to atmospheric attenuation, not all hours of daylight provide the panels with maximum power generation. This is due to the increased air mass that the light must travel through at low solar altitudes which causes significant light scattering[6]. The intensity of insolation (radiation at the earth's surface) received by the panels throughout the day is affected by the air mass as well as variable weather conditions.

Determining the theoretical insolation intensity received by the panels is complex and thus for solar system design, typical meteorological year (TYM) data is used. The TYM data utilized by SAM to simulate the radiation intensity is taken from historical data taken from the Calgary International Airport weather station. The total insolation is also referred to the plane of array (POA) insolation which consists of beam radiation, G_b, ground-reflected radiation, G_g, and diffuse radiation, G_d (Figure 13) [6].

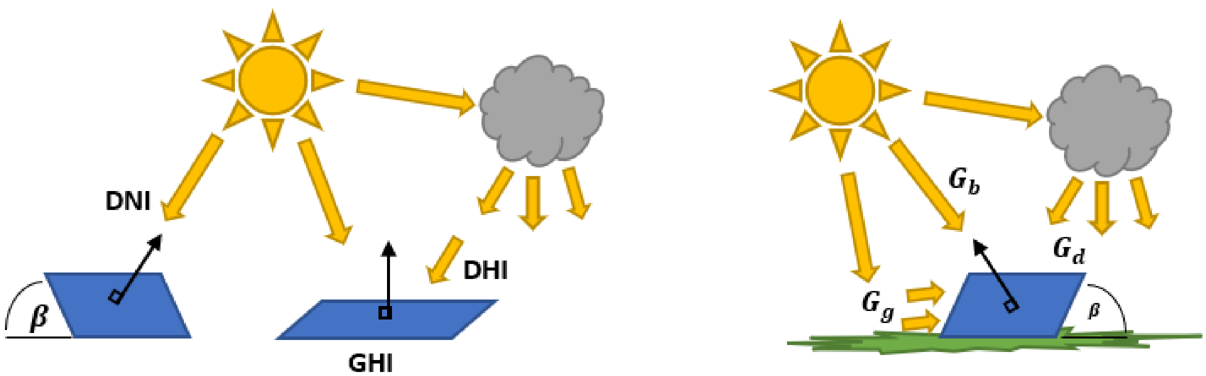


Figure 13. POA Radiation Components

Mathematically the intensity of POA insolation can be expressed using (10) [6]:

$$G_{POA} = G_b + G_g + G_d \tag{10}$$

For a tilted surface, these insolation values can be calculated using TYM data through the following relations expressed in (11), (12), and (13) [6]:

$$G_b = DNI \cos(\theta) \tag{11}$$

$$G_g = GHI * \rho_g * \frac{(1-\cos(\beta))}{2} \tag{12}$$

$$G_d = DHI * \frac{(1+\cos(\beta))}{2} \tag{13}$$

Where DNI is the direct normal irradiance, DHI is the diffuse horizontal irradiance, GHI is the global horizontal irradiance, and ρ_g is the ground reflectance. Typical ground reflectance values used are 0.2 but can range to 0.5 for highly reflective conditions [6]. Since the insolation intensity changes continuously, it is typical practice to use monthly averages for the nominal POA irradiance. Running the residential PV system simulation in the SAM software using the dual-axis tracking system consisting of eight 2 m^2 panels (16 m^2 total) in Calgary, the POA total front side irradiance is calculated for each month using the TYM data (Table 4).

Table 4. Tracking Array Nominal POA Irradiance by Month

Month	Nominal POA Total Irradiance (kWh/mo)
January	1847.09
February	2108.82
March	3238.55
April	3803.23
May	4558.16
June	4592.57
July	4893.3
August	4540.6
September	3408.92
October	2702.79
November	1946.18
December	1595.6
TOTAL	39513.78

As shown in Table 4, the highest POA irradiance occurs during the summer month of July and decreases significantly to a minimum in December, which is expected due to the lower number of sunlight hours and lower solar altitude during the winter.

2.7 SAM Simulation Results

To determine whether the proposed solution meets the specified goals and aims of the project, the System Advisor Model (SAM) software is utilized to simulate the system. The full list of input parameters utilized by the software is detailed in Appendix C. The simulation results are examined in the following sections.

2.7.1 Array Power Generation

The simulation results provided by SAM using the system inputs detailed in the previous sections, show that the dual-axis array can produce a net DC energy of 7794 kWh and net AC energy of 7466 kWh annually which exceeds the minimum requirement of 7200 kWh specified by the project goals (Table 5).

Table 5. Array Annual Power Generation

System Type	Annual Net DC Energy (kWh/yr)	Annual Net AC Energy (kWh/yr)	Annual Electrical Load (kWh/yr)
Dual-Axis Tracking	7794	7466	7201

A comparison between the net DC and net AC energy each month is shown in Figure 14. The difference in the net energy generated is due to the losses from the inverter efficiency and transmission in wires (Appendix D).

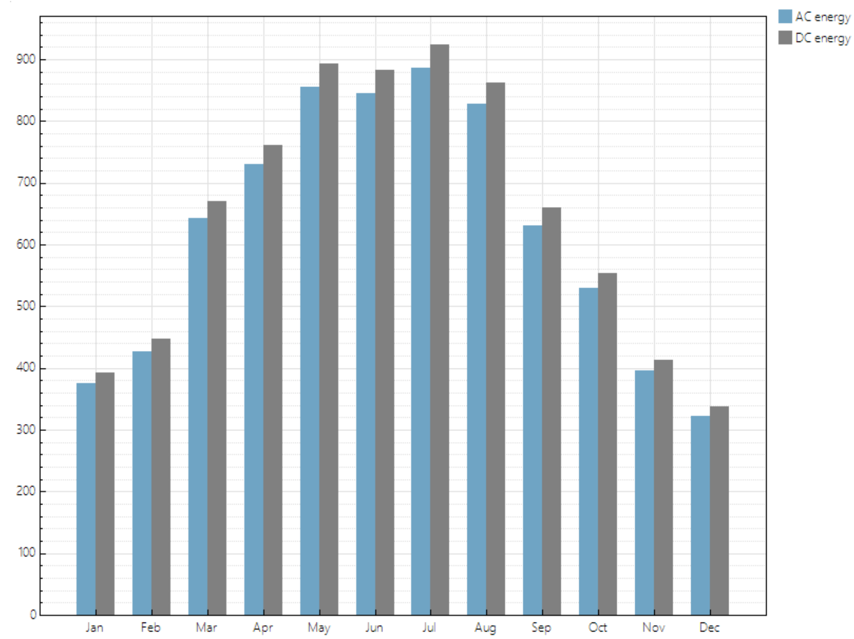


Figure 14. Annual Net AC and DC Power Generated by PV System

Although the net annual AC energy exceeds the specified annual electrical load, for each month this is not the case. As can be shown in Figure 15, the low production of the array in the winter months leads to more electrical energy being consumed than is produced. Since the designed PV system is a grid-tie application, this is not an issue since any excess power generated throughout the year is applied as a credit to any subsequent energy bills.

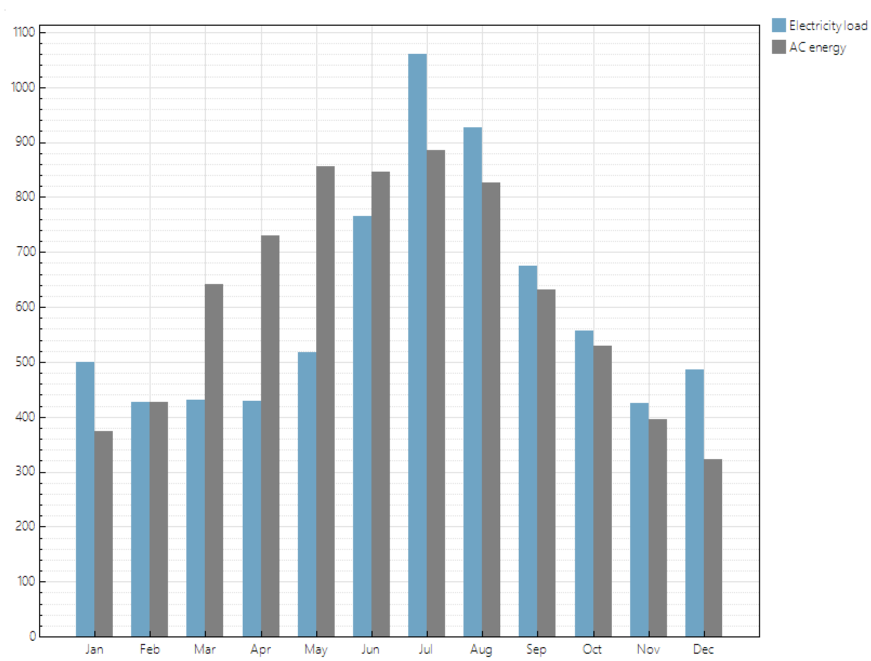


Figure 15. Comparison of Monthly AC Energy and Electrical Load

2.8 Financial Cost

The financial cost of the PV system only accounts for the panels, inverter, and utilizes the default financial costs for balancing the system and installation. The net capital cost of the system excluding the mounting system is detailed in Table 6 [15] [16].

Table 6. Capital Costs of the Designed PV System

Item	Capacity Cost	Total Cost
Direct Capital Costs		
PV Modules	-	2800.00
Inverter	-	2489.00
Balance of System Equipment	0.31	1091.03
Installation Labour	0.19	668.69
Installer Margin and Overhead	0.27	950.25
Indirect Capital Costs		
Sales Tax (GST) 5%	-	399.95
TOTAL:	2.39	8398.92

The default financial parameters are used to simulate the payback period of the system using a debt fraction of 100% with a loan term of 25 years at 5%. Electricity buy and sell rates are taken from Direct Energy current values which is listed as $0.1/kWh [17]. Running the financial simulation in SAM, the estimated payback period for the dual-axis tracking system is 9.5 years, illustrated in Figure 16. This payback period for the solar tracking system is significantly less than the minimum payback period of 25 years specified by the project goals.

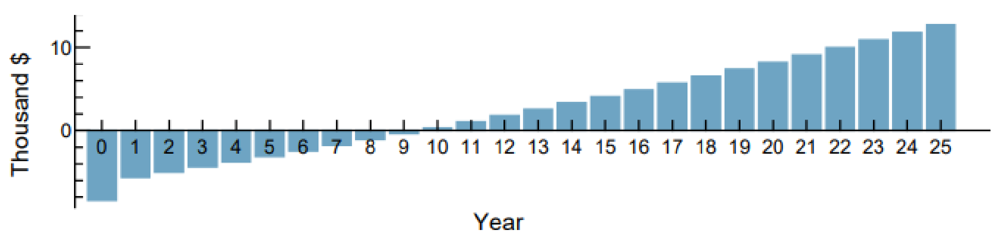


Figure 16. Solar Tracking System Payback Cash Flow

One of the limitations of the financial study is that it does not account for the price of the actuators and mounting system that would be utilized by this system. Accounting for these additional capital costs would increase the payback period of the system, but would likely still be within the defined project goal of less than 25 years. Typically the costs of solar PV mounting systems are significantly less than the module and inverter costs. Further work is required to determine a more accurate capital cost of the system and the resulting payback period.

3 Conclusion

As shown in the discussion, the proposed solution meets each of the minimum requirements specified by the project goals outlined in Section 1.2.2 . The full-tracking array consisting of eight 440 W PV panels can produce a total of 7794 kWh of DC energy with a nominal DC capacity of 3.52 kW. The net AC energy this system can deliver to the residence and grid is 7466 kWh per year, which exceeds the total annual electrical load of 7200 kWh specified by the project goals. The array only requires 26.41 m^2 of available land area, which is significantly less than the project goal of 80 m^2. The relatively small footprint of the array makes the designed PV system desirable for locations that have limited land space.

The results of the financial simulation provide a payback period of 9.5 years for the $8398.92 capital cost of the full-tracking system which satisfies the project goal of having a payback period less than 25 years. This simulation assumes a debt fraction of 100%, with a mortgage of 25 years at 5%. The payback period is calculated using current buy and sell electricity rates in Alberta, having a value of $0.10/kWh. Limitations of the financial study are that the capital cost of the mounting system and actuators are not included.

Although this system utilizes a relatively small land area to produce a large amount of energy, this type of system cannot be readily applied in all situations. For larger PV arrays, a full-tracking system is not economical due to larger shading profiles. The increased efficiency of tracking panel from a higher tilt angle causes a significantly larger shadow during low solar altitudes. This causes adjacent subarrays to be placed further away, utilizing more land area.

Solar tracking systems are ideal for installations where the cost of land is low and module prices are high. The increased efficiency of the tracking systems allows for a reduction in the capital cost due to a reduction in the number of panels required to meet the desired output AC capacity. This makes full-tracking solar systems appealing for smaller residential applications as the land is typically already purchased (backyard of a residence) and the payback period is significantly lower compared to a fixed-panel system. For the tracking system analyzed in this report, maintenance of the system would be low due to only two actuators being used. For commercial large-scale applications, land costs would likely be higher than the costs of modules making a simple fixed-panel system a better choice. In this application, the fixed panel systems would also have significantly less maintenance required due to being a static mechanical system.

4 Recommendations

The results of the tracking system analysis show that the proposed solution satisfies the project aims and objectives, but this system is largely idealized. In a real application of this system, the presence of any nearby objects or buildings near the residence location that could produce shading on the array would need to be detailed and an in-depth 3D shade analysis would need to be completed in the SAM software. This would allow for a more accurate representation of the actual power that the PV system could generate.

The proposed solution can also only be mounted on the ground since it utilizes a TPM mount which requires ground penetrations. The scope of this project neglects to include the design of the mechanical system and structure that supports the array and further work would need to be completed to determine if a full-tracking system could be utilized on a residential roof. To improve the accuracy of the analysis perfomed in this report, work should be completed to determine the types of actuators and mounting system that would be utilized by this full-tracking array. This would provide a more accurate representation of the system capital cost, payback period, and the net power generation.

Bibliography

[1] Canada Energy Regulator, "Provincial and Territorial Energy Profiles – Alberta," Canada Energy Regulator, 17 March 2021. [Online]. Available: https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-alberta.html. [Accessed 14 October 2021].

[2] T. Puiu, "What Are The Pros and Cons of Solar Energy? Here's Everything You Need to Know," ZME Science, 19 April 2019. [Online]. Available: https://www.zmescience.com/ecology/renewable-energy-ecology/solar-panels-pros-and-cons-056654/. [Accessed 30 November 2021].

[3] Clean Point Energy, "Solar Tracker Installation," Clean Point Energy, 2019. [Online]. Available: https://cleanpointenergy.com/services/suntracker/. [Accessed 30 November 2021].

[4] M. McHale, "What's the Difference Between Single and Dual Axis Trackers?," Solar Flex Rack, 12 November 2015. [Online]. Available: https://solarflexrack.com/whats-the-difference-between-single-and-dual-axis-trackers/. [Accessed 14 October 2021].

[5] B. Ludt, "What is a solar tracker and how does it work?," Solar Power World, 16 January 2020. [Online]. Available: https://www.solarpowerworldonline.com/2020/01/what-is-a-solar-tracker-and-how-does-it-work/. [Accessed 15 October 2021].

[6] S. A. Kalogirou, ""Chapter 2 - Environmental Characteristics"," in *Solar Energy Engineering - Second Edition*, Boston, Academic Press, 2014, pp. 51-123.

[7] A. B. I. S. Wafa Batayneh, "Investigation of a Single-Axis Discrete Solar Tracking System for Reduced Actuations and Maximum Energy Collection," *Automation in Construction,* vol. 98, no. 0926-5805, pp. 102-109, 2019.

[8] Canada Energy Regulator, "Market Snapshot: Which cities have the highest solar potential in Canada?," Canada Energy Regulator, 20 June 2018. [Online]. Available: https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2018/market-snapshot-which-cities-have-highest-solar-potential-in-canada.html. [Accessed 15 October 2021].

[9] Point 2 Staff, "Global Perspective: How Large Are Canadian Homes?," Point 2 Homes, 17 February 2017. [Online]. Available: https://www.point2homes.com/news/canada-real-estate/how-large-are-canadian-homes.html. [Accessed 15 October 2021].

[10] ATCOenergy, "ENERGY 101," ATCOenergy, 2021. [Online]. Available: https://www.atco.com/en-ca/for-home/energy-101.html. [Accessed 15 October 2021].

[11] C. F. W. K. Chaowanan Jamroen, "A Novel UV Sensor-Based Dual-Axis Solar Tracking System: Implementation and Performance Analysis," *Applied Energy,* vol. 299, no. 0306-2619, p. 117295, 2021.

[12] M. I. Yuwaldi Away, "Dual-Axis Sun Tracker Sensor Based on Tetrahedron Geometry," *Automation in Construction,* vol. 73, no. 0926-5805, pp. 175-183, 2017.

[13] C. Clissitt, "Tracker Costs," The Eco Experts, 24 September 2021. [Online]. Available: https://www.theecoexperts.co.uk/solar-panels/tracker-costs. [Accessed 1 November

2021].

[14] B. Cass and R. Beckers, "How to Size a Solar System That Really Works!," Solacity Inc., 2019. [Online]. Available: https://www.solacity.com/how-to-size-a-solar-system-that-really-works/. [Accessed 29 October 2021].

[15] Beyond Oil Solar, "SMA Sunny Boy 3800-US-10 Inverter," Beyond Oil Solar, 2021. [Online]. Available: https://beyondoilsolar.com/wp-content/uploads/2013/05/SUNNYBOY3000-3800-4000-US.pdf. [Accessed 30 October 2021].

[16] D. Harcos, Interviewee, *Sales Rep.* [Interview]. 27 September 2021.

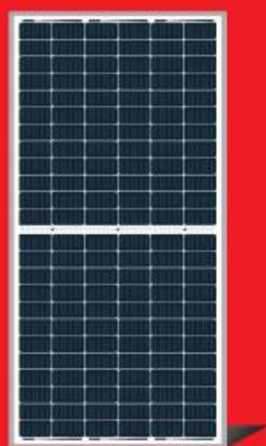
[17] Alberta Utilities Comission, "Current Rates Electric," Alberta Utilities Comission, 1 November 2021. [Online]. Available: https://www.auc.ab.ca/Pages/current-rates-electric.aspx. [Accessed 1 November 2021].

Appendix A – Surface Tilt and Azimuth Angles Calculations

Local Time	Winter Solstice					Summer Solstice					Spring Equinox					Fall Equinox				
11:00	AST	Hour	h	beta	z	AST	Hour	h	beta	z	AST	Hour	h	beta	z	AST	Hour	h	beta	z
0:00	#NUM!	-11.00	-158.75	90.00	-160.58	#NUM!	-10.00	-144.50	90.00	-147.81	#NUM!	-10.00	-146.00	90.00	-146.00	#NUM!	-10.00	-142.00	90.00	-142.00
1:00	0:25	-12.00	-173.75	90.00	-174.27	#NUM!	-11.00	-159.50	90.00	-161.26	#NUM!	-11.00	-161.00	90.00	-161.00	#NUM!	-11.00	-157.00	90.00	-157.00
2:00	1:25	-11.00	-158.75	90.00	-160.58	0:22	-12.00	-174.50	90.00	-174.96	0:16	-12.00	-176.00	90.00	-176.00	0:32	-12.00	-172.00	90.00	-172.00
3:00	2:25	-10.00	-143.75	90.00	-147.15	1:22	-11.00	-159.50	90.00	-161.26	1:16	-11.00	-161.00	90.00	-161.00	1:32	-11.00	-157.00	90.00	-157.00
4:00	3:25	-9.00	-128.75	90.00	-134.32	2:22	-10.00	-144.50	90.00	-147.81	2:16	-10.00	-146.00	90.00	-146.00	2:32	-10.00	-142.00	90.00	-142.00
5:00	4:25	-8.00	-113.75	90.00	-122.89	3:22	-9.00	-129.50	90.00	-134.94	3:16	-9.00	-131.00	90.00	-131.00	3:32	-9.00	-127.00	90.00	-127.00
6:00	5:25	-7.00	-98.75	90.00	-65.06	4:22	-8.00	-114.50	85.97	-123.19	4:16	-8.00	-116.00	90.00	-116.00	4:32	-8.00	-112.00	90.00	-112.00
7:00	6:25	-6.00	-83.75	90.00	-65.78	5:22	-7.00	-99.50	77.63	-112.13	5:16	-7.00	-101.00	90.00	-101.01	5:32	-7.00	-97.00	90.00	-97.00
8:00	7:25	-5.00	-68.75	90.00	-58.76	6:22	-6.00	-84.50	68.61	-101.26	6:16	-6.00	-86.00	87.80	-86.63	6:32	-6.00	-82.00	85.14	-83.64
9:00	8:25	-4.00	-53.75	88.19	-47.75	7:22	-5.00	-69.50	59.24	-90.02	7:16	-5.00	-71.00	78.51	-74.76	7:32	-5.00	-67.00	75.94	-71.61
10:00	9:25	-3.00	-38.75	81.93	-35.45	8:22	-4.00	-54.50	49.88	-77.60	8:16	-4.00	-56.00	69.75	-62.08	8:32	-4.00	-52.00	67.40	-58.60
11:00	10:25	-2.00	-23.75	77.38	-22.25	9:22	-3.00	-39.50	41.02	-62.76	9:16	-3.00	-41.00	62.03	-47.97	9:32	-3.00	-37.00	60.05	-43.99
12:00	11:25	-1.00	-8.75	74.90	-8.31	10:22	-2.00	-24.50	33.46	-43.63	10:16	-2.00	-26.00	55.98	-31.93	10:32	-2.00	-22.00	54.54	-27.38
13:00	12:25	0.00	6.25	74.70	5.94	11:22	-1.00	-9.50	28.56	-18.46	11:16	-1.00	-11.00	52.29	-13.96	11:32	-1.00	-7.00	51.60	-8.95
14:00	13:25	1.00	21.25	76.82	19.97	12:22	0.00	5.50	27.93	10.82	12:16	0.00	4.00	51.57	5.11	12:32	0.00	8.00	51.70	10.21
15:00	14:25	2.00	36.25	81.05	33.31	13:22	1.00	20.50	31.82	37.54	13:16	1.00	19.00	53.92	23.75	13:32	1.00	23.00	54.84	28.55
16:00	15:25	3.00	51.25	87.05	45.76	14:22	2.00	35.50	38.83	58.17	14:16	2.00	34.00	58.96	40.74	14:32	2.00	38.00	60.49	45.03
17:00	16:25	4.00	66.25	90.00	57.11	15:22	3.00	50.50	47.44	73.95	15:16	3.00	49.00	65.99	55.71	15:32	3.00	53.00	67.94	59.51
18:00	17:25	5.00	81.25	90.00	65.06	16:22	4.00	65.50	56.73	86.87	16:16	4.00	64.00	74.33	68.98	16:32	4.00	68.00	76.54	72.43
19:00	18:25	6.00	96.25	90.00	65.78	17:22	5.00	80.50	66.13	98.33	17:16	5.00	79.00	83.43	81.15	17:32	5.00	83.00	85.76	84.42
20:00	19:25	7.00	111.25	90.00	121.24	18:22	6.00	95.50	75.27	109.23	18:16	6.00	94.00	90.00	94.02	18:32	6.00	98.00	90.00	98.00
21:00	20:25	8.00	126.25	90.00	132.28	19:22	7.00	110.50	83.83	120.19	19:16	7.00	109.00	90.00	109.00	19:32	7.00	113.00	90.00	113.00
22:00	21:25	9.00	141.25	90.00	144.95	20:22	8.00	125.50	90.00	131.68	20:16	8.00	124.00	90.00	124.00	20:32	8.00	128.00	90.00	128.00
23:00	22:25	10.00	156.25	90.00	158.32	21:22	9.00	140.50	90.00	144.30	21:16	9.00	139.00	90.00	139.00	21:32	9.00	143.00	90.00	143.00

	WS	SS	Equinox	Equinox
Day Num	355	172	80	264
B	270.989	90	-0.98901	180.989
ET	1.02913	-1.5	-7.84366	7.895443
AST Adj	-34.7309	-97.26	-103.604	-87.8646
delta	-23.4498	23.44978	-0.40365	-0.20183
hour angle				
beta				

Appendix B – Longi 440W Panel Data Sheet

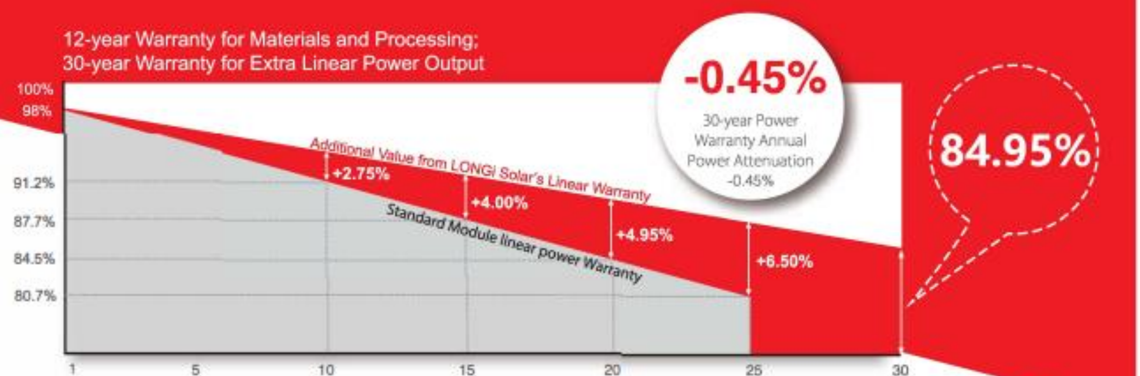


LR4-72HBD
425~455M

Hi-MO 4
NEW

High Efficiency
Low LID Bifacial PERC with
Half-cut Technology

12-year Warranty for Materials and Processing;
30-year Warranty for Extra Linear Power Output



Complete System and Product Certifications

IEC 61215, IEC 61730, UL 61730

ISO 9001:2008: ISO Quality Management System

ISO 14001: 2004: ISO Environment Management System

TS62941: Guideline for module design qualification and type approval

OHSAS 18001: 2007 Occupational Health and Safety

* Specifications subject to technical changes and tests. LONGi Solar reserves the right of interpretation.

Front side performance equivalent to conventional low LID mono PERC:
- High module conversion efficiency (up to 20.9%)
- Better energy yield with excellent low irradiance performance and temperature coefficient
- First year power degradation <2%

Bifacial technology enables additional energy harvesting from rear side (up to 25%)

Glass/glass lamination ensures 30 year product lifetime, with annual power degradation < 0.45%, 1500V compatible to reduce BOS cost

Solid PID resistance ensured by solar cell process optimization and careful module BOM selection

Reduced resistive loss with lower operating current

Higher energy yield with lower operating temperature

Reduced hot spot risk with optimized electrical design and lower operating current

LONGi

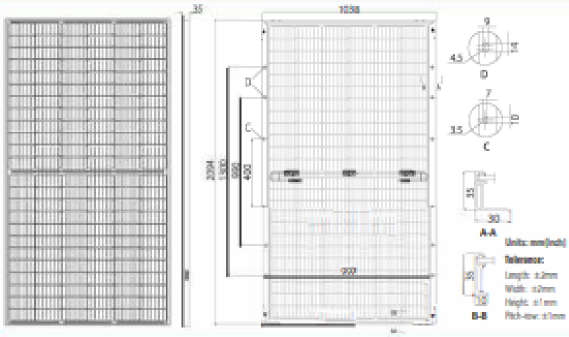
HES PV

Note: Due to continuous technical innovation, R&D and improvement, technical data above mentioned may be of modification accordingly. LONGi have the sole right to make such modification at anytime without further notice; Demanding party shall request for the latest datasheet for such as contract need, and make it a consisting and binding part of lawful documentation duly signed by both parties.

20200410V11 for US

LR4-72HBD **425~455M**

Design (mm)



Mechanical Parameters

Cell Orientation: 144 (6×24)
Junction Box: IP68, three diodes
Output Cable: 4mm², 300mm in length, length can be customized
Glass: Dual glass
2.0mm coated tempered glass
Frame: Anodized aluminum alloy frame
Weight: 27.5kg
Dimension: 2094×1038×35mm
Packaging: 30pcs per pallet
150pcs per 20'GP
660pcs per 40'HC

Operating Parameters

Operational Temperature: -40℃ ~ +85℃
Power Output Tolerance: 0 ~ +5 W
Voc and Isc Tolerance: ±3%
Maximum System Voltage: DC1500V (IEC/UL)
Maximum Series Fuse Rating: 25A
Nominal Operating Cell Temperature: 45±2℃
Safety Class: Class II
Fire Rating: UL type 3
Bifaciality: 70±5%

Electrical Characteristics

Test uncertainty for Pmax: ±3%

Model Number	LR4-72HBD-425M		LR4-72HBD-430M		LR4-72HBD-435M		LR4-72HBD-440M		LR4-72HBD-445M		LR4-72HBD-450M		LR4-72HBD-455M	
Testing Condition	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax/W)	425	317.4	430	321.1	435	324.9	440	328.6	445	332.3	450	336.1	455	339.8
Open Circuit Voltage (Voc/V)	48.7	45.6	48.9	45.8	49.1	45.9	49.2	46.0	49.4	46.2	49.6	46.4	49.8	46.6
Short Circuit Current (Isc/A)	11.22	9.06	11.30	9.13	11.36	9.18	11.45	9.25	11.52	9.30	11.58	9.36	11.65	9.41
Voltage at Maximum Power (Vmp/V)	40.4	37.7	40.6	37.9	40.8	38.0	41.0	38.2	41.2	38.4	41.4	38.6	41.6	38.8
Current at Maximum Power (Imp/A)	10.52	8.42	10.60	8.49	10.66	8.54	10.73	8.60	10.80	8.65	10.87	8.70	10.93	8.76
Module Efficiency(%)	19.6		19.8		20.0		20.2		20.5		20.7		20.9	

STC (Standard Testing Conditions): Irradiance 1000W/m², Cell Temperature 25℃, Spectra at AM1.5

NOCT (Nominal Operating Cell Temperature): Irradiance 800W/m², Ambient Temperature 20℃, Spectra at AM1.5, Wind at 1m/S

Electrical characteristics with different rear side power gain (reference to 445W front)

Pmax /W	Voc/V	Isc /A	Vmp/V	Imp /A	Pmax gain
467	49.4	12.09	41.2	11.34	5%
490	49.4	12.67	41.2	11.88	10%
512	49.5	13.24	41.3	12.42	15%
534	49.5	13.82	41.3	12.96	20%
556	49.5	14.40	41.3	13.50	25%

Temperature Ratings (STC)

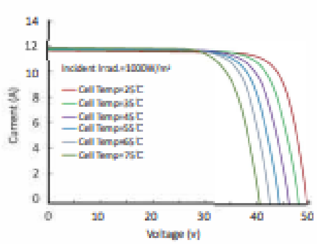
Temperature Coefficient of Isc	+0.050%/℃
Temperature Coefficient of Voc	-0.284%/℃
Temperature Coefficient of Pmax	-0.350%/℃

Mechanical Loading

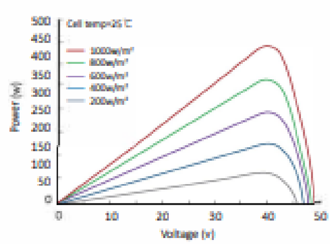
Front Side Maximum Static Loading	5400Pa
Rear Side Maximum Static Loading	2400Pa
Hailstone Test	25mm Hailstone at the speed of 23m/s

I-V Curve

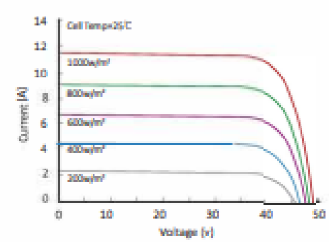
Current-Voltage Curve (LR4-72HBD-440M)



Power-Voltage Curve (LR4-72HBD-440M)



Current-Voltage Curve (LR4-72HBD-440M)



LONGi

HES PV

t. 1.866.258.0110
f. 866.437.5531
e. sales@hespv.ca
w. hespv.ca

Note: Due to continuous technical innovation, R&D and improvement, technical data above mentioned may be of modification accordingly. LONGi have the sole right to make such modification at anytime without further notice; Demanding party shall request for the latest datasheet for such as contract need, and make it a consisting and binding part of lawful documentation duly signed by both parties.

20200410V11 for US

Appendix C – SAM Parameter Inputs

Header Data from Weather File

Latitude	51.05 DD		Station ID	288121
Longitude	-113.94 DD		Data Source	NSRDB
Time zone	GMT -7			
Elevation	1064 m			
Time step	60 minutes			

For NSRDB data, the latitude and longitude shown here from the weather file header are the coordinates of the NSRDB grid cell and may be different from the values in the file name, which are the coordinates of the requested location.

Annual Averages Calculated from Weather File Data

Global horizontal	3.58 kWh/m²/day
Direct normal (beam)	4.65 kWh/m²/day
Diffuse horizontal	1.32 kWh/m²/day
Average temperature	3.8 °C
Average wind speed	2.3 m/s

Optional Data

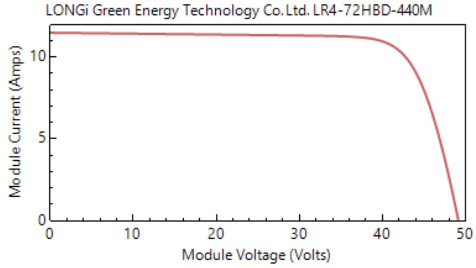
Maximum snow depth	NaN cm
Annual albedo	0.427205

*NaN indicates missing data.

Module Characteristics at Reference Conditions

Reference conditions: Total Irradiance = 1000 W/m2, Cell temp = 25 C

LONGi Green Energy Technology Co.Ltd. LR4-72HBD-440M



		Temperature coefficients	
Nominal efficiency	20.8498 %		
Maximum power (Pmp)	439.930 Wdc	-0.331 %/°C	-1.456 W/°C
Max power voltage (Vmp)	41.0 Vdc		
Max power current (Imp)	10.7 Adc		
Open circuit voltage (Voc)	49.2 Vdc	-0.259	-0.127 V/°C
Short circuit current (Isc)	11.4 Adc	0.041 %/°C	0.005 A/°C

Bifacial Specifications

☑ Module is bifacial

Transmission fraction	0.013 0-1
Bifaciality	0.75 0-1
Ground clearance height	1 m

Temperature Correction

◉ Nominal operating cell temperature (NOCT) method

○ Heat transfer method

See Help for more information about CEC cell temperature models.

NOCT Method Parameters

Mounting standoff	Ground or rack mounted
Array height	One story building height or lower

Transient Thermal Model Correction

Module unit mass 11.092 kg/m²

The module unit mass is used for the transient thermal model, which is only applied for weather file time steps less than or equal to 20 minutes. The default value is 11 kg/m².

Heat Transfer Method Parameters

Mounting configuration	Rack	Rows of modules in array	1
Heat transfer dimensions	Module Dimensions	Columns of modules in array	10
Mounting structure orientation	Structures do not impede flow underneath module	Temperature behind the module	20 °C
Module width	1 m	Space between module back and roof surface	0.05 m
Module length	2.11 m		

Physical Characteristics

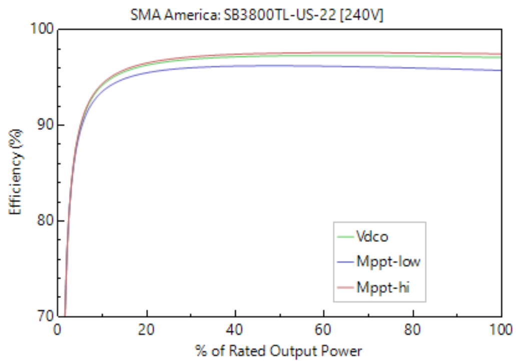
Material	Mono-c-Si	Module area	2.110 m²	Number of cells	72

Additional Parameters

T_noct	44.8 °C	I_L_ref	11.4655 A	R_s	0.241605 Ohm
A_ref	1.79376 V	I_o_ref	1.37027e-11 A	R_sh_ref	178.332 Ohm

The model assumes a reference bandgap voltage Eg_ref = 1.121 eV, and temperature coefficient for bandgap of -0.0002677 eV/K.

Efficiency Curve and Characteristics



Number of MPPT inputs: 1

CEC weighted efficiency: 97.053 %

European weighted efficiency: 96.676 %

Datasheet Parameters

Maximum AC power	3850	Wac
Maximum DC power	3964.41	Wdc
Power use during operation	17.8856	Wdc
Power use at night	1.155	Wac
Nominal AC voltage	240	Vac
Maximum DC voltage	480	Vdc
Maximum DC current	9.91101	Adc
Minimum MPPT DC voltage	100	Vdc
Nominal DC voltage	400	Vdc
Maximum MPPT DC voltage	480	Vdc

Sandia Coefficients

C0	-3.08138e-06	1/Wac
C1	-4.8e-05	1/Vdc
C2	0.000124	1/Vdc
C3	-0.001632	1/Vdc

Note: If you are modeling a system with microinverters or DC power optimizers, see the Losses page to adjust the system losses accordingly.

CEC Information

CEC name: SMA America: SB3800TL-US-22 [240V] CEC hybrid: empty CEC type: Utility Interactive CEC date: n/a

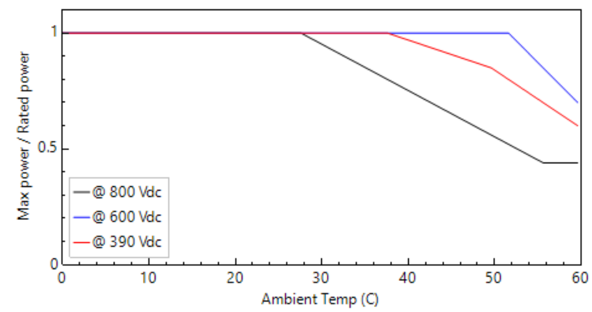
Inverter Temperature Derate Curves

Import... Export... Copy Paste

Rows: 3

Cols: 5

Vdc(V)	Tstart(C)	Slope(1/C)	Tstart(C)	Slope(1/C)
800	28	-0.02	56	0
600	52	-0.0375	60	0
390	38	-0.0125	50	-0.025



Update plot

Table supports up to four temperature - slope pairs per row.

AC Sizing

Number of inverters	1
DC to AC ratio	0.91

Size the system using modules per string and strings in parallel inputs below.

☐ Estimate Subarray 1 configuration

Sizing Summary

Nameplate DC capacity	3.519	kWdc	Number of modules	8	
Total AC capacity	3.850	kWac	Number of strings	1	
Total inverter DC capacity	3.964	kWdc	Total module area	16.9	m^2

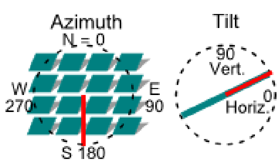
DC Sizing and Configuration

To model a system with one array, specify properties for Subarray 1 and disable Subarrays 2, 3, and 4. To model a sytem with up to four subarrays connected in parallel to a single bank of inverters, for each subarray, check Enable and specify a number of strings and other properties.

Electrical Configuration

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
	(always enabled)	☐ Enable	☐ Enable	☐ Enable
Modules per string in subarray	8			
Strings in parallel in subarray	1			
Number of modules in subarray	8			
String Voc at reference conditions (V)	393.6			
String Vmp at reference conditions (V)	328.0			

Tracking & Orientation



○ Fixed
○ 1 Axis
◉ 2 Axis
○ Azimuth Axis
○ Seasonal Tilt

☐ Tilt=latitude

Tilt (deg)	20
Azimuth (deg)	180
Ground coverage ratio (GCR)	0.01
Tracker rotation limit (deg)	45
Backtracking	☐ Enable

Ground coverage ratio is used (1) to determine when a one-axis tracking system will backtrack, (2) in self-shading calculations for fixed tilt or one-axis tracking systems on the Shading page, and (3) in the total land area calculation. See Help for details.

Electrical Sizing Information

Maximum DC voltage	480.0	Vdc
Minimum MPPT voltage	100.0	Vdc
Maximum MPPT voltage	480.0	Vdc

Voltage and capacity ratings are at module reference conditions shown on the Module page.

No system sizing messages.

Array Dimensions for Self Shading, Snow Losses, and Bifacial Modules

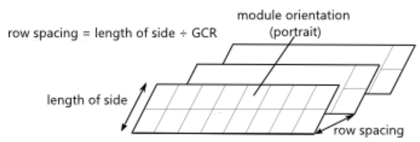
The product of number of modules along side and bottom and number of rows should be equal to the number of modules in subarray.

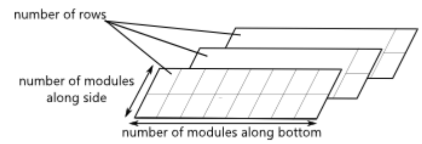
Module orientation	Landscape	Portrait	Portrait	Portrait
Number of modules along side of row	4	2	2	2
Number of modules along bottom of row	2	9	9	9

Calculated System Layout

Number of rows	1	0	0	0
Modules in subarray from System Design page	8	0	0	0
Length of side (m)	4.10853	4.10853	4.10853	4.10853
GCR from System Design page	0.01	0.3	0.3	0.3
Row spacing estimate (m)	410.853	13.6951	13.6951	13.6951

Module aspect ratio	2	
Module length	2.05426	m
Module width	1.02713	m
Module area	2.11	m²





Irradiance Losses

Soiling losses apply to the total solar irradiance incident on each subarray. SAM applies these losses in addition to any losses on the Shading and Snow page.

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
Monthly soiling loss	Edit values...	Edit values...	Edit values...	Edit values...
Average annual soiling loss	5	5	5	5

Bifacial modules only

Average annual rear irradiance loss due to soiling, mismatch, or external shading (%)	0	0	0	0

DC Losses

DC losses apply to the electrical output of each subarray and account for losses not calculated by the module performance model.

Module mismatch (%)	2	2	2	2
Diodes and connections (%)	0.5	0.5	0.5	0.5
DC wiring (%)	2	2	2	2
Tracking error (%)	0	0	0	0
Nameplate (%)	0	0	0	0
DC power optimizer loss (%)	0	All four subarrays are subject to the same DC power optimizer loss.		
Total DC power loss (%)	4.440	4.440	4.440	4.440

Total DC power loss = 100% * [1 - the product of (1 - loss/100%)]

Default DC Losses

Apply default losses to replace DC losses for all subarrays with default values.

Apply default losses for: Central inverters | Microinverters | DC optimizers

AC Losses

AC losses apply to the electrical output of the inverter and account for losses not calculated by the inverter performance model.

AC wiring 1 %

Direct Capital Costs

Module	8	units	0.4	kWdc/unit	3.5	kWdc	350.00 $/Unit	$ 2,800.00
Inverter	1	units	3.8	kWac/unit	3.8	kWac	2,489.00 $/Unit	$ 2,489.00

	$	$/Wdc	$/m²	
Balance of system equipment	0.00	0.31	0.00	$ 1,091.03
Installation labor	0.00 +	0.19 +	0.00 =	$ 668.69
Installer margin and overhead	0.00	0.27	0.00	$ 950.25

Subtotal $ 7,998.97

Contingency

Contingency 0 % of subtotal $ 0.00

Total direct cost $ 7,998.97

Indirect Capital Costs

	% of direct cost	$/Wdc	$	
Permitting and environmental studies	0	0.24	0.00	$ 844.67
Engineering and developer overhead	0 +	0.98 +	0.00 =	$ 3,449.05
Grid interconnection	0	0.00	0.00	$ 0.00

Land Costs

Land area 0.417 acres

Land purchase	$ 0/acre +	0 +	0.00 +	0.00 =	$ 0.00
Land prep. & transmission	$ 0/acre	0	0.00	0.00	$ 0.00

Sales Tax

Sales tax basis, percent of direct cost 100 % Sales tax rate 5.0 % $ 399.95

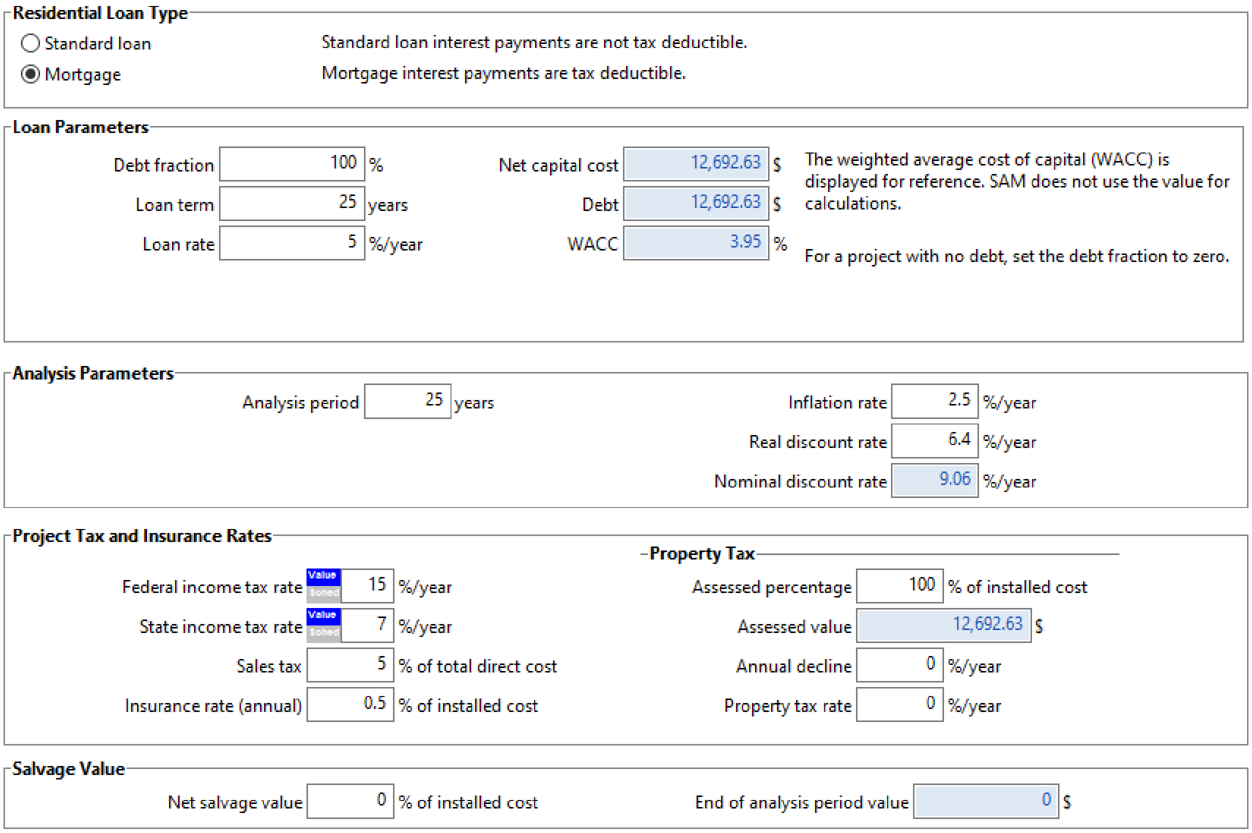
Total indirect cost $ 4,693.67

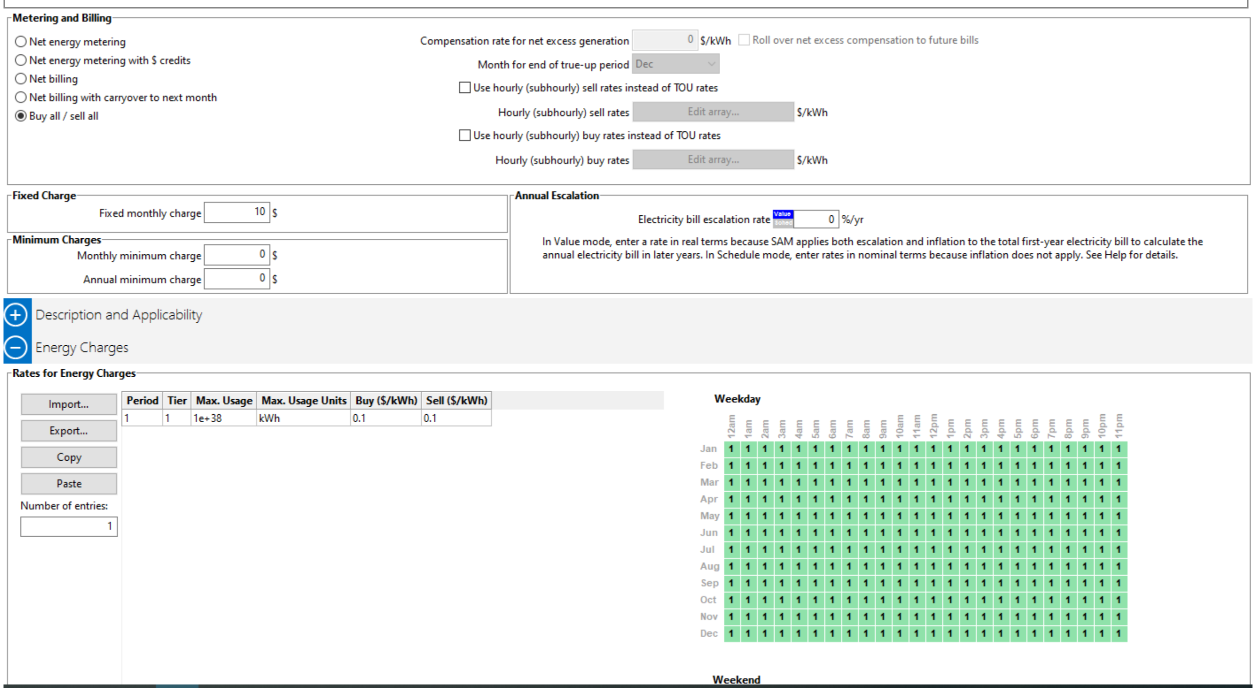
Total Installed Cost

The total installed cost is the sum of the direct and indirect costs. Note that it does not include any financing costs from the Financial Parameters page.

Total installed cost $ 12,692.63

Total installed cost per capacity $ 3.61/Wdc


Residential Loan Type
Standard loan
Standard loan interest payments are not tax deductible.
Mortgage
Mortgage interest payments are tax deductible.
Loan Parameters
Debt fraction 100 %
Loan term 25 years
Loan rate 5 %/year
Net capital cost 12,692.63 $
Debt 12,692.63 $
WACC 3.95 %
The weighted average cost of capital (WACC) is displayed for reference. SAM does not use the value for calculations.
For a project with no debt, set the debt fraction to zero.
Analysis Parameters
Analysis period 25 years
Inflation rate 2.5 %/year
Real discount rate 6.4 %/year
Nominal discount rate 9.06 %/year
Project Tax and Insurance Rates
Federal income tax rate 15 %/year
State income tax rate 7 %/year
Sales tax 5 % of total direct cost
Insurance rate (annual) 0.5 % of installed cost
Property Tax
Assessed percentage 100 % of installed cost
Assessed value 12,692.63 $
Annual decline 0 %/year
Property tax rate 0 %/year
Salvage Value
Net salvage value 0 % of installed cost
End of analysis period value 0 $


Metering and Billing
Net energy metering
Net energy metering with $ credits
Net billing
Net billing with carryover to next month
Buy all / sell all
Compensation rate for net excess generation 0 $/kWh
Roll over net excess compensation to future bills
Month for end of true-up period Dec
Use hourly (subhourly) sell rates instead of TOU rates
Hourly (subhourly) sell rates Edit array... $/kWh
Use hourly (subhourly) buy rates instead of TOU rates
Hourly (subhourly) buy rates Edit array... $/kWh
Fixed Charge
Fixed monthly charge 10 $
Minimum Charges
Monthly minimum charge 0 $
Annual minimum charge 0 $
Annual Escalation
Electricity bill escalation rate 0 %/yr
In Value mode, enter a rate in real terms because SAM applies both escalation and inflation to the total first-year electricity bill to calculate the annual electricity bill in later years. In Schedule mode, enter rates in nominal terms because inflation does not apply. See Help for details.
Description and Applicability
Energy Charges
Rates for Energy Charges
Import...
Export...
Copy
Paste
Number of entries: 1
Period Tier Max. Usage Max. Usage Units Buy ($/kWh) Sell ($/kWh)
1 1 1e+38 kWh 0.1 0.1
Weekday
12am 1am 2am 3am 4am 5am 6am 7am 8am 9am 10am 11am 12pm 1pm 2pm 3pm 4pm 5pm 6pm 7pm 8pm 9pm 10pm 11pm
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Weekend

Electric Load Data

Energy usage [Edit array...] kW

☐ Normalize supplied load profile to monthly electricity bill data

Scaling factor (optional) 0.665

Monthly energy usage [Edit values...] kWh

[View load data...]

Monthly Load Summary

	Energy (kWh)	Peak (kW)
Jan	500.20	1.23
Feb	427.18	1.17
Mar	430.76	1.21
Apr	428.10	1.53
May	516.85	1.79
Jun	765.88	2.69
Jul	1,060.53	2.86
Aug	926.59	2.79
Sep	675.74	2.44
Oct	557.17	1.70
Nov	425.85	1.14
Dec	486.66	1.25
Annual	7,201.51	2.86

Annual Adjustment

Load growth rate Value 0 %/yr

In Value mode, the growth rate applies to the previous year's annual kWh load starting in Year 2. In Schedule mode, each year's rate applies to the Year 1 kWh value. See Help for details.

Appendix D – SAM Simulation Report

System Advisor Model Report

Detailed Photovoltaic	3.52 kW Nameplate	51.05, -113.94
Residential	$2.39/W Installed Cost	UTC -7

Performance Model

Modules	
LONGi Green Energy Technology Co._ Ltd. LR4-72HBD-4	
Cell material	Mono-c-Si
Module area	2.11 m²
Module capacity	439.93 DC Watts
Quantity	8
Total capacity	3.52 DC kW
Total area	16 m²

Inverters	
SMA America: SB3800TL-US-22	
Unit capacity	3.850000 AC kW
Input voltage	100 - 480 VDC DC V
Quantity	1
Total capacity	3.85 AC kW
DC to AC Capacity Ratio	0.91
AC losses (%)	1.00

Array	
Strings	1
Modules per string	8
String Voc (DC V)	393.60
Tilt (deg from horizontal)	0.00
Azimuth (deg E of N)	180
Tracking	2 axis
Backtracking	-
Self shading	-
Rotation limit (deg)	-
Shading	yes
Snow	no
Soiling	yes
DC losses (%)	4.44

Performance Adjustments	
Availability/Curtailment	none
Degradation	none
Hourly or custom losses	none

Annual Results (in Year 1)	
GHI kWh/m²/day	3.58
POA kWh/m²/day	159.00
Net to inverter	7,790 DC kWh
Net to grid	7,460 AC kWh
Capacity factor	24.2
Performance ratio	0.91

Financial Model

Project Costs	
Total installed cost	$8,398
Salvage value	$0

Analysis Parameters	
Project life	25 years
Inflation rate	2.5%
Real discount rate	6.4%

Project Debt Parameters (Mortgage)	
Debt fraction	100%
Amount	$8,398
Term	25 years
Rate	5%

Tax and Insurance Rates	
Federal income tax	15 %/year
State income tax	7 %/year
Sales tax (% of indirect cost basis)	5%
Insurance (% of installed cost)	0.5 %/year
Property tax (% of assessed val.)	0 %/year

Incentives	
Federal ITC	26%

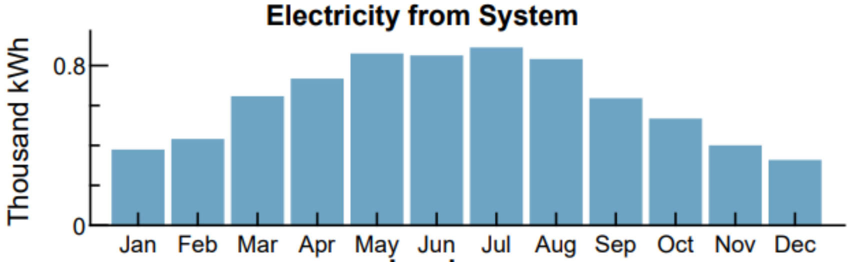
Electricity Demand and Rate Summary
Annual peak demand 2.9 kW
Annual total demand 7,201 kWh
Generic Residential
Fixed charge: $10/month
All generation sold, all load purchased
Flat energy buy rate: $0.100000/kWh
Flat energy sell rate: $0.100000/kWh

Results	
Nominal LCOE	7 cents/kWh
Net present value	$3,600
Payback period	9.5 years

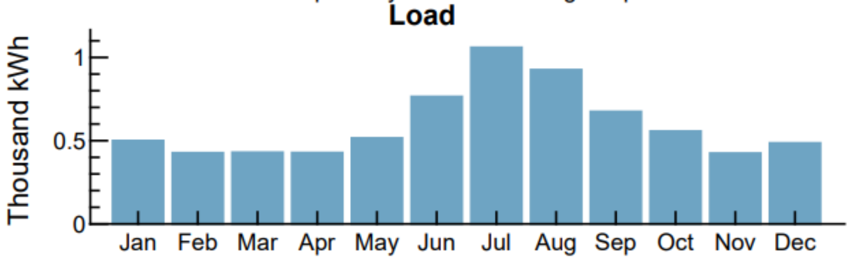
Detailed Photovoltaic	3.52 kW Nameplate	51.05, -113.94
Residential	$2.39/W Installed Cost	UTC -7

Year 1 Monthly Generation and Load Summary

Electricity from System



Load



Year 1 Monthly Electric Bill and Savings ($)

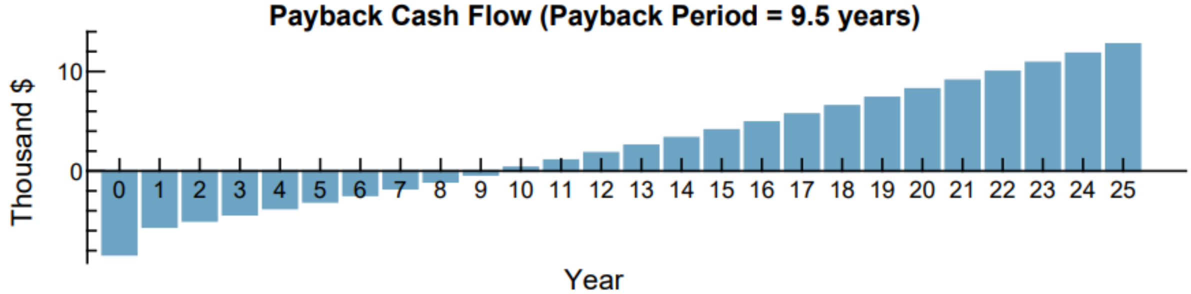
Month	Without System	With System	Savings
Jan	60	22	37
Feb	52	9	42
Mar	53	-11	64
Apr	52	-20	72
May	61	-23	85
Jun	86	2	84
Jul	116	27	88
Aug	102	19	82
Sep	77	14	63
Oct	65	12	52
Nov	52	13	39
Dec	58	26	32
Annual	840	93	746

NPV Approximation using Annuities

Annuities, Capital Recovery Factor (CRF) = 0.1023		
Investment	$0	Sum:
Expenses	$-700	$300
Savings	$200	NPV = Sum / CRF:
Energy value	$800	$3,000

Investment = Installed Cost - Debt Principal - IBI - CBI
Expenses = Operating Costs + Debt Payments
Savings = Tax Deductions + PBI
Energy value = Tax Adjusted Net Savings
Nominal discount rate = 9.06%

Payback Cash Flow (Payback Period = 9.5 years)



Detailed Photovoltaic | 3.52 kW Nameplate | 51.05, -113.94

Residential | $2.39/W Installed Cost | UTC -7