Design and Analysis of a Small-Scale PV System

HAMK
HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

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Zhihao Wu

HAMK
HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

ABSTRACT

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Author	Zhihao Wu	**Year** 2020
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Supervisor(s)	Katariina Penttilä	

ABSTRACT

San Francisco 's unique natural conditions and perfect policy subsidies have promoted the rapid development of its residential solar market. In order to respond to the enormous demand of the market, this thesis aims to design a small-scale solar system at a reasonable price and with an optimized power output that will meet electricity demand for a household in San Francisco.

The first half of the article mainly discusses the data that affects the photovoltaic system and the selection of components for the grid-connected photovoltaic system. The second half uses PVsyst simulation software to analyze and calculate the capacity and economic value of the designed photovoltaic system.

The results obtained are that the designed system meets the research objectives in terms of economic benefits, safety, and power output. The design concepts of this paper on photovoltaic systems can be applied to any location.

Keywords Design, Photovoltaic, San Francisco, Simulation.

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List of Abbreviations

AC	Alternating Current
AWG	American Wire Gauge
CO_2	Carbon dioxide
CPUC	California Public Utilities Commission
DC	Direct Current
FIT	Feed-in Tariff
kWh	Kilowatt-hour
MW_{DC}	Megawatt (Direct Current)
MPPT	Maximum Power Point Tracking
NREL	National Renewable Energy Laboratory
OCPD	Overcurrent Protection Device
PV	Photovoltaic
ROI	Return of Investment
SO_2	Sulphur dioxide
STC	Standard Test Condition
U.S.	United States

1 INTRODUCTION

Human civilization began with the use of fire; the ancestors of humans accidentally found burning tinder, they mastered how to light a fire. Energy from combustion could roast raw meat and keep humans warm, which greatly extended the human lifespan.

As time goes, the method of human harness energy is becoming more and more mature, tremendously boosted the development of technology. Nowadays, energy resources are not limited to fossil fuels like wood; in general, these can be classified into two types: renewable energy and non-renewable energy.

Solar energy, as one form of renewable energy, is highly favored by most countries due to its traits of being renewable and abundant. Different from traditional power like coal, solar energy is the radiance from the sun, harnessed by modern technologies, and finally, transformed into electricity or heat. A PV panel is the critical technology in the solar power generation system, which makes it possible to output electricity relying on inexhaustive sunlight.

1.1 Background of project

With the increasing demand for the global energy market, natural resources such as fuel are being overexploited; However, most of the natural resources in the world are limited, overexploitation of those non-renewable resources is leading to a shortage of energy. Besides, power stations like a fossil-fuel power station have emitted large amounts of CO_2 and other harmful gases by burning coal. Excessive CO_2 emissions cause the greenhouse effect, which is regarded as the root cause of the global warming phenomenon. What is more dangerous is that harmful gas emissions such as SO_2 form acid rain after a series of reactions in the atmosphere, which gradually erodes nature and jeopardizes human health. As a consequence, a majority of developed nations is committed to developing solar power plants to replace some fossil-fuel power stations.

The clean, abundant, and inexpensive features win not only solar energy favor with the industrial sector but also the civilian sector. The vast potential of solar energy in the residential field can be demonstrated in three aspects. From an environmental perspective, nearly no carbon dioxide or any harmful gas emission during the energy production process. From an economic perspective, the total price of a PV system is affordable to most families, and there is not excessive expenditure on system maintenance. From the standpoint of convenience, PV panels are lightweight and space-saving; the whole system can be placed on the roof

or just anywhere faced the sun. As a result, solar energy is the most popular renewable energy for households.

The solar industry in the U.S. is booming. The U.S. is the second-largest solar market in the word regarding the total residential solar installed capacity. As shown in Figure 1, in the third quarter of 2019, residential solar installed capacity has reached a peak with 700 MW_{DC}, of which California contributes the most with 300 MW_{DC}. (SEIA, 2019)

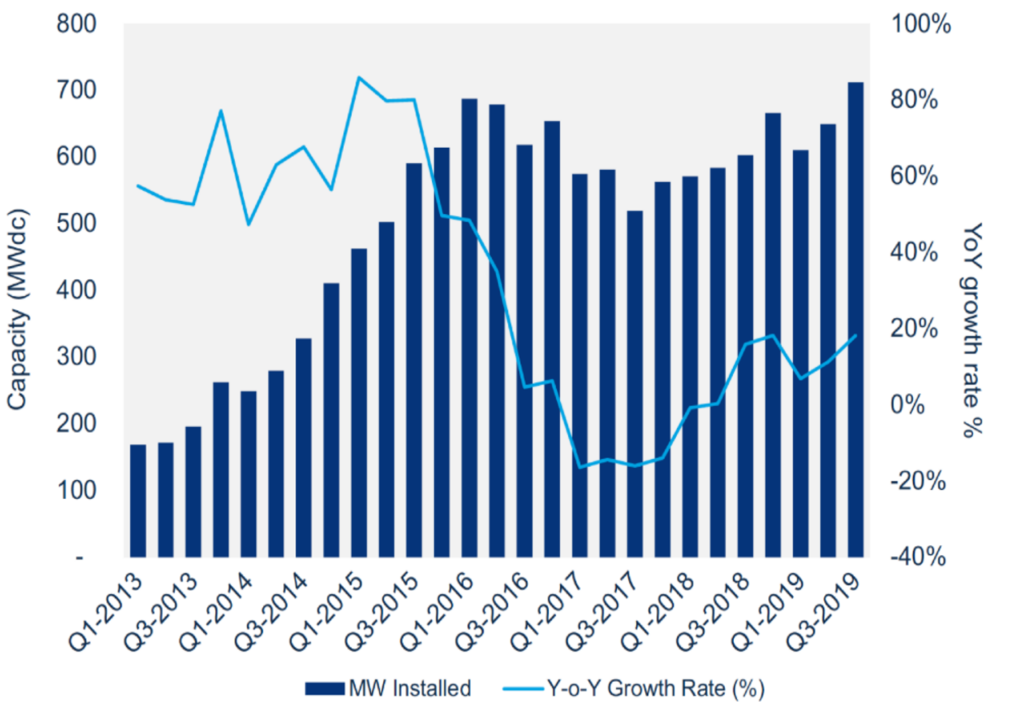

Figure 1. Volumes of U.S. residential solar installation (SEIA, 2019)

The popularity of the solar industry in California is traceable. On the one hand, California's mild climate gives it a unique advantage in the solar industry; adequate sunlight provides excellent conditions for the high power output of solar systems. On the other hand, California's government policies on solar power drive development of it. California Energy Commission recently issued regulations that all new houses or apartments of three stories or fewer, together with houses under renovations, are forced to install PV systems (Roberts, 2020). Over and above, the federal solar tax credit program provides a waiver of taxes equivalent to 26% of the cost of solar systems for households installing solar systems in 2020 (Zientara, 2020).

1.2 Objectives of project

On this thesis project, the aim was to study the principles of a solar panel, then to design an affordable solar system with optimal power that would meets the electricity demand for a typical residential house in San

Francisco, simulate and calculate the power output and the economic benefits of the PV system.

2 INFORMATION ON INSTALLATION LOCATION

2.1 Typical residential building

There was no specific target as to the installation location in this project; thus, in this thesis project, San Francisco on Google Maps was used as a benchmark to observe and select typical a San Francisco house. By observing various residential areas in San Francisco, the typical San Francisco house selected had the following characteristics as shown in Figure:

- Residential buildings in San Francisco are of a similar height and close to each other.
- Trees are planted on both sides of the road or garden.
- The house faces west by south, with an azimuth of 259°.
- The rooftop area of the building is 15 x 5.5 m.

Figure 2. ‘Typical’ residential building in SF from Google map

2.2 Solar Irradiance

Solar irradiance data can be classified into three main types: DHI, DNI, and GHI.

DHI stands for Diffuse Horizontal Irradiance, which means the amount of solar Irradiance received by the horizontal surface after sunlight is scattered by the atmosphere. (Vashishtha, 2012)

DNI is an abbreviation of Direct Normal Irradiance; it is measured as the amount of solar Irradiance received by the surface, which is always perpendicular to the sunlight. During the measurement, the influence of the atmosphere is not concerned. Thus, the measure does not include the diffuse solar irradiance. (Vashishtha, 2012)

GHI, Global Horizontal Irradiance is a combination of DHI and DNI, indicating the total amount of solar irradiance received by the horizontal surface. Thus, GHI is the most commonly used data in solar power generation calculation. (Vashishtha, 2012)

Based on the newest data from Databasin, Table 1 below shows the daily GHI in different months and the average daily GHI in the year 2019.

Table 1. Global Horizontal Irradiance data in San Francisco (Databasin, 2020)

	Global Horizontal Irradiance ($kWh/m^2/day$)
January	2.175
February	2.902
March	4.596
April	6.045
May	6.843
June	7.361
July	7.197
August	6.432
September	5.285
October	3.846
November	2.575
December	1.99
Annual average	4.78

2.3 Annual average electricity consumption per household

Household electricity demand is a decisive factor in the sizing of the PV system. In order to ensure the accuracy of the electricity demand, the

following data given in Figure 3 shows the average monthly household electricity consumption in San Francisco from 2015 to 2017.

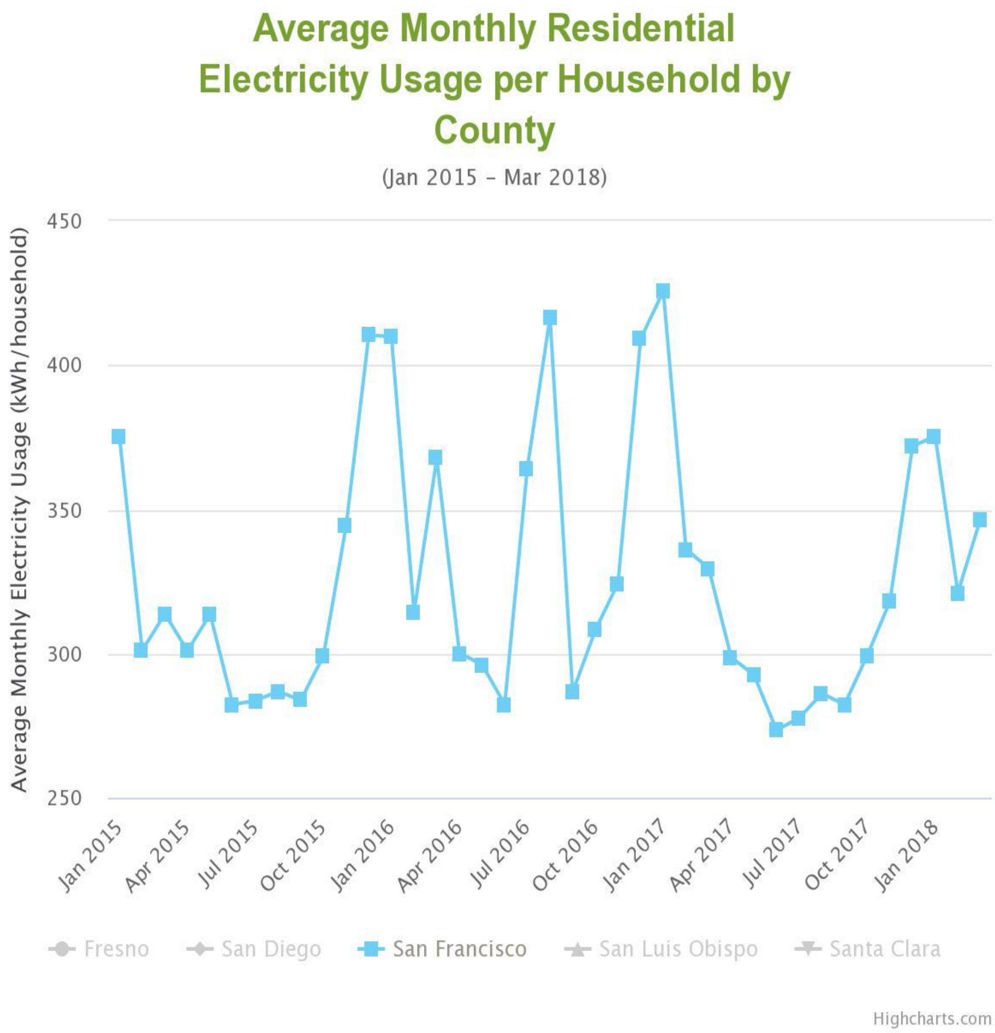

Figure 3. Monthly residential electricity consumption per household in San Francisco (Equinox Project, 2018)

As a result, the average daily electricity consumption of a household in a year is calculated as follows:

$$\begin{aligned} &\textit{Average daily electricity consumption} \\ &\quad = (375 + 301 + 313.7 + 301 + 313.6 + 282.3 + 283.7 \\ &\quad + 286.9 + 283.8 + 299.2 + 344.2 + 410.4 + 409.9 \\ &\quad + 314.3 + 367.7 + 300.1 + 296.2 + 282.4 + 364.4 \\ &\quad + 416.6 + 286.5 + 308.1 + 324.3 + 409.2 + 425.6 \\ &\quad + 336.2 + 329.6 + 298.6 + 292.6 + 273.4 + 277.7 \\ &\quad + 286.1 + 282.3 + 299.3 + 318 + 371.9)\ kWh \\ &\quad \div 36\ months \div 30\ days = 10.8\ kWh/day \end{aligned}$$

3 CONCEPT OF PV SYSTEM

3.1 Definition of a small-scale grid-connected PV system

According to the U.S. Energy Information Administration (EIA), a small-scale PV system is defined as the solar system with a power capacity of less than 1 MW, most of which are for residential use. (EIA, 2017)

Grid-connected PV systems represent the solar system connected with the local power grid; thus, when solar power generation is insufficient, electricity is imported from the grid; when the solar power generation is surplus, it can be fed back to the grid at an appropriate price.

3.2 Solar cell working principle

The core of solar panel power generation lies in the p-n junction of the semiconductor. By doping an intrinsic semiconductor with impurities of different elements to make it p-type semiconductor on one side and an n-type semiconductor on the other side, the contact area of two sides is called the p-n junction.

As illustrated in Figure 4, P-type semiconductors have many electron-holes and almost zero free electrons, while n-type semiconductors are the exact opposite. After the contact of two sides, the concentration difference in electron and electron-hole forces electron diffuse from the n-type area to the p-type area while electron-hole diffuse from the p-type area to the n-type area. As a result, the negatively charged impurity ions remaining in the p-type area and the positively charged impurity ions in the n-type area form an internal electric field from n to p at their contact area (Holmes, 2015).

However, due to drift current, the internal electric field force negatively charged ions like a free electron to move from the p-type are to the n-type area, which means the internal electric field blocks diffusion motion. Eventually, the electric field force and the diffusion of concentration difference balance each other to achieve dynamic equilibrium, so that a stable PN junction is obtained. (Holmes, 2015)

As the sun shines on the solar panel, the photons in the sunlight will provide energy to the electrons of silicon to get rid of the covalent bonds and form electron-hole pairs. After connecting the load to the solar panel, free electrons will move toward the n-type region in the electric field, thereby creating a current. Besides, the higher the solar radiation, the freer electrons, and the heavier the current. (Holmes, 2015)

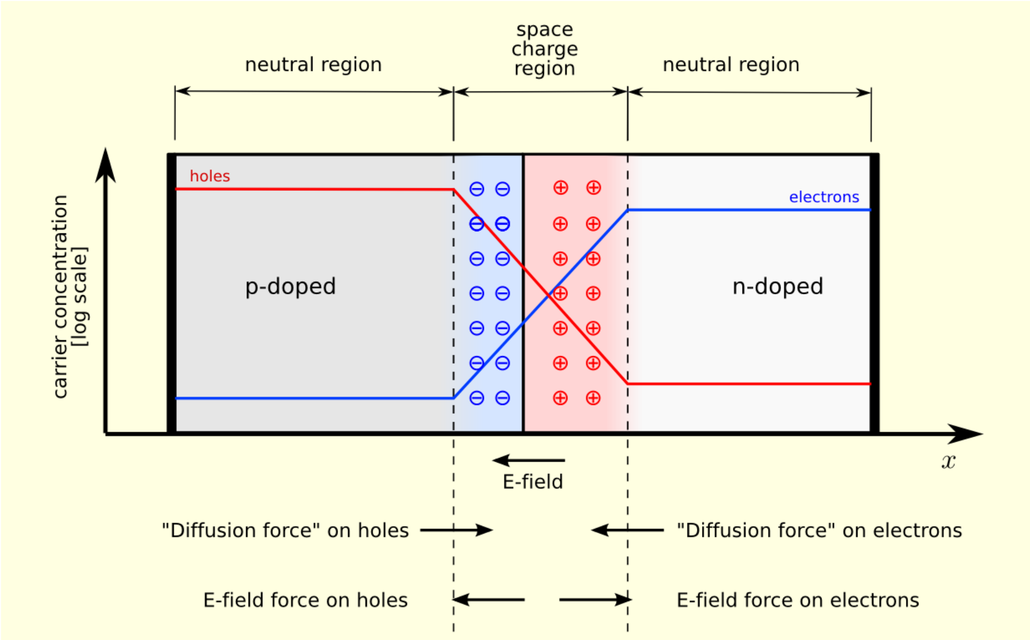

Figure 4. P-N junction in thermal equilibrium with a zero-bias voltage applied. (Mu301, 2020)

4 COMPONENTS OF PV SYSTEM

The selection criteria used for the solar system in this thesis project was to pursue cost performance while ensuring quality so that the world-leading companies were the preference for each component.

The battery is not a necessity in a grid-connected system, and the cost of energy storage systems often accounts for half the price of the entire system; thus, the battery is not a part of the system. The entire system is compatible with batteries, if the price of the battery drops in the future, the battery can be added to the system at any time.

The Grid-tied PV system designed in this project consists of a PV array, an inverter, a DC/AC disconnect, a power meter, a mounting rack, few cables, and a main service panel.

4.1 PV panel

The most common PV panels on the market can be classified into three types: Monocrystalline, polycrystalline, and thin-film panels. Despite the low price of a thin-film solar panel, it was still not considered here due to its poor performance and ample space required. The following paragraph will only compare the monocrystalline and polycrystalline solar panels.

4.1.1 Comparison of monocrystalline and polycrystalline panel

The monocrystalline solar panel is easy to be distinguished from the other solar cells due to its black color and as its name indicates, it is cut from a piece of high-purity crystalline silicon. Advantages of the monocrystalline panel are listed as follows:

- A monocrystalline solar panel has the best efficiency (15 to 20%) when compared to the others, which can output more power.
- Higher efficiency means less quantity required; a monocrystalline solar panel can offer a tremendous space-saving advantage.
- Besides, monocrystalline has a long lifetime, which is expected to be more than 25 years.

The disadvantages are listed as follows:

- It is a more expensive type of solar panels compared to the others, the average price of it is 0.105 USD/watt (EnergyTrend, 2020).
- It is easy to break down the circuit due to foreign bodies covering the surface of the panel.
- There is more waste, especially silicon waste, during the monocrystalline manufacturing process than the polycrystalline manufacturing process.

The polycrystalline solar panel is the most common solar panel on the market; its surface appears blue under the sunlight. The advantage of it is shown below:

- The average price of a polycrystalline solar cell on the market is 0.076 USD/watt, which is a bit lower than monocrystalline panel due to low manufacturing cost (EnergyTrend, 2020).
- The polycrystalline panel has better high-temperature tolerance and less shading occlusion effect.

The disadvantages are listed as follows:

- It has a lower efficiency (13 to 16%) compared to monocrystalline panels.
- It occupies more space on the roof than monocrystalline panels.

Considering the limited area on the roof of residential buildings and affordable prices, monocrystalline was the best choice for this study.

4.1.2 Sizing of solar panels

The output power of the solar panel marked by the merchant is usually based on its power output under the peak sunlight condition. Therefore,

to determine the size of solar panels, the first step is to calculate the time that panels have been working at rated power, which is called Peak Sunlight Hours. To be exact, a Peak Sunlight Hour is the irradiance solar panel received from the sun at around 1 kW/m^2 in one hour. As a result, Peak Sunlight Hours can be calculated based on average solar irradiance data in one day.

$$Peak\ Sunlight\ Hours = \frac{Average\ daily\ solar\ irradiance}{Peak\ sunlight}$$
$$= \frac{4.78\ kWh/m^2/day}{1\ kW/m^2} = 4.78\ hours/day$$

The second step is to calculate the power output required under ideal conditions, the solar system is designed to cover all the consumption, so the power output of the solar system should be higher than energy consumption. The energy bill clearly shows the average electricity per household consumed in a day, which is 10.8 kWh/day in San Francisco. After knowing energy demand and peak sunlight hours (working hours), the ideal power output required can be calculated as follows:

$$Ideal\ power\ required = \frac{Daily\ electricity\ use}{Peak\ sunlight\ hours}$$
$$= \frac{10.8\ kWh/day}{4.78\ hours/day} = 2.26\ kW$$

During the panel sizing process, there are many uncontrollable factors and variables should be considered, such as shading loss and performance loss, thus, sizing solar panel cannot be so accurate, the last step is to minimize these losses. Derate factor is used to represent all uncontrollable factors that affect the efficiency of solar panels; the default value of it is 0.77, as stated by NREL PVWatt Calculator (NREL, 2014). It means that the actual power output of a solar panel will only be 77% of the ideal value: wherefore the actual power output required, and the number of panels can be calculated as below:

$$Actual\ power\ required = \frac{Ideal\ power\ required}{Default\ derate\ factor}$$
$$= \frac{2.26\ kW}{0.77} = 2.935\ kW$$
$$Quantity\ of\ panels = \frac{Actual\ power\ required}{PV\ panel\ Rated\ power}$$
$$= \frac{2.935}{375} = 8\ pcs$$

4.1.3 Parameter

As Figure 5 shows, the selected PV panel was TSM-375W-DE14A(II) from Trina Solar, one of the world-leading PV panel suppliers, the efficiency of which can reach up to 19.3%. TSM-375W-DE14A(II) is a trustworthy solar

panel with a linear power warranty of 25 years, and it is certificated for most of the extreme conditions.

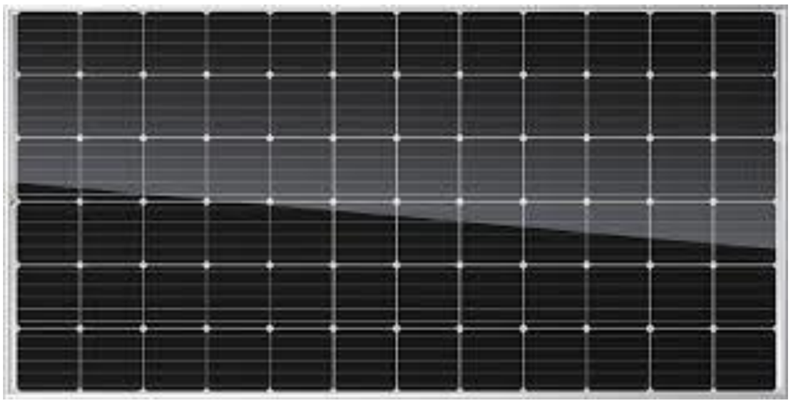

Figure 5. Trina Solar TSM-375W-DE14A(ll) (Solaris, 2020)

Table 3 illustrates the electrical and mechanical data of the PV panel under Standard Test Condition, which means 1000 W/m² in irradiance.

Table 2. Datasheet of PV panel under Irradiance of 1000 W/m² (TrinaSolar, 2017)

Module Dimensions	**1960 x 992 x 40 mm**
Footprint	1.94432 m^2
Solar Cell	Monocrystalline
Cell Quantity	72
Peak Power Watts-P_{MAX} (W_p)	375
Maximum Power Voltage-V_{MPP} (V)	40
Maximum Power Current-I_{MPP} (A)	9.37
Open Circuit Voltage-V_{OC} (V)	48.5
Short Circuit Current-I_{SC} (A)	9.88
Module Efficiency η_m (%)	19.3
Max Series Fuse Rating (A)	20
Maximum System Voltage (V_{DC})	1000
Nominal Operating Cell Tempera. (NOCT)	44°C (±2K)
Temperature Coefficient of I_{SC}	0.05%/K

In case the PV panel does not always work under ideal conditions, Figure 6 shows the power voltage curve under different irradiance, which helps to calculate the power output accurately in further simulation.

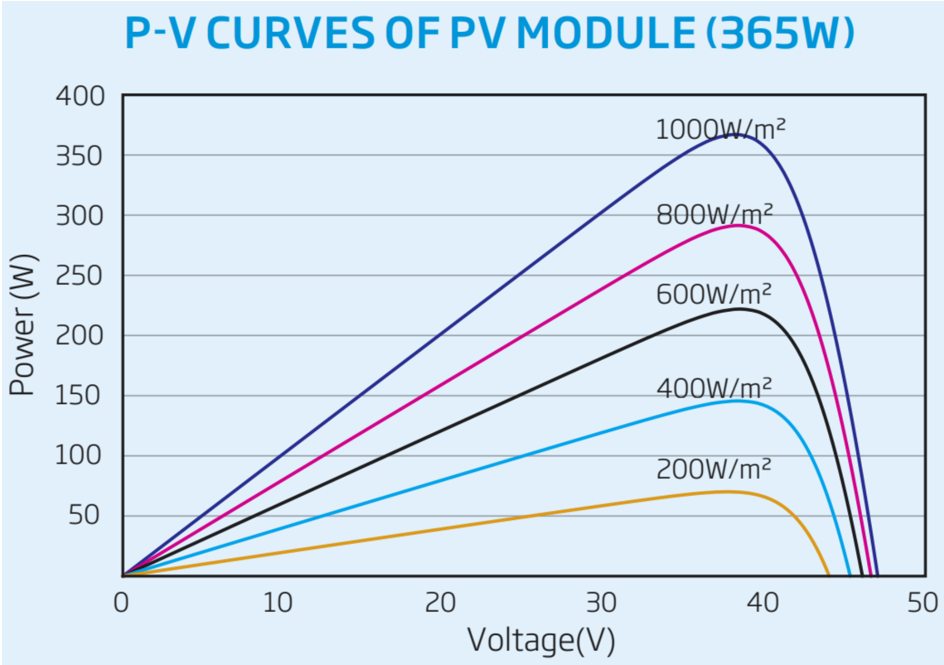

Figure 6. Power curve of panel (TrinaSolar, 2017)

4.2 **Inverter**

In the solar system, solar panels generate DC voltage while some of the domestic appliances and power grid require AC voltage, which makes the inverter an integral part. The traditional inverter is a box of circuitry to convert power from DC to AC; nonetheless, it is not suitable for the Grid-tied PV system. During the power grid outage, a traditional inverter that connected to the power grid will continue to feed electricity into the power grid, which is called the islanding phenomenon. The maintenance electrician may get an electric shock due to islanding; therefore, the solar inverter that integrated with anti-islanding protection is vital in the grid-tied PV system intending to keep electrician safe.

4.2.1 Centralized system and distributed system

Solar inverters can also be divided into two types by topology: Centralized and distributed. A centralized inverter system represents a single central inverter with immense load capacity for the whole solar array, while a distributed inverter system refers to multiple inverters distributed in a solar array.

A central inverter might be an excellent option for large scale commercial solar systems, but it is not ideal for residential building due to the features below:

- A centralized system is inexpensive and easy to install attributable to only one central inverter used, but it can only provide a system-level inspection.
- There are no individual inverters in different branches of the system, resulting in difficult troubleshooting.
- Relying solely on the central inverter will lead to enormous power loss during the maintenance of the central inverter.

A distributed inverter system is ideal for residential building since the following features:

- A distributed inverter system can implement detailed monitoring from panel-level or string-level.
- When the error occurred in one of the panels or inverters, the rest of the system can still work, and fault diagnosis will be simple and clear.

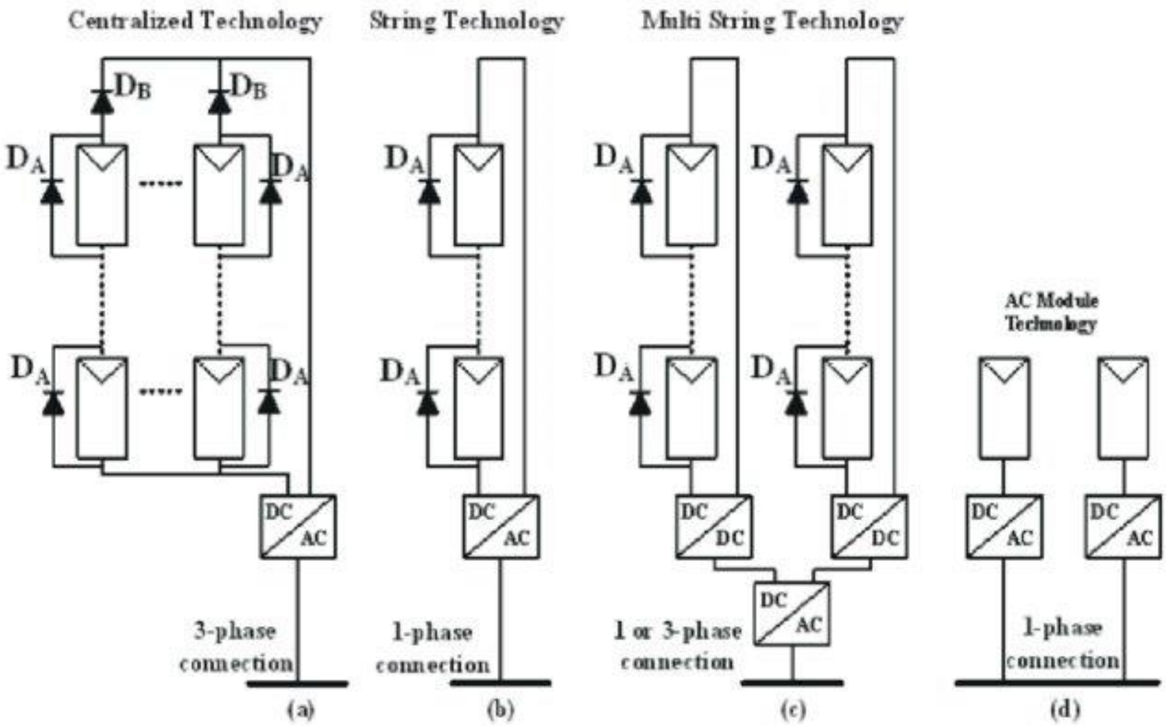

Figure 7. Topology of different types of inverter (Obeidat, 2017)

Figure 7 shows the three main options for distributed systems: string inverter, DC optimizer, and microinverter.

A solar system with string inverters is composed of several strings, and each string contains a group of solar panels and a string inverter in series wiring. Compared to microinverter and DC optimize, the efficiency of a string inverter is still not high enough, and this drawback is evident under the impact of the environment. It is usually inevitable to have dust or foreign matter on the PV panel, which leads to the loss of efficiency. For a

solar array that connected in series, once the efficiency of a panel decreased, the string inverter will output power at the lowest efficiency of the panel.

DC optimizer and microinverter systems are similarly efficient. On the one hand, the MPPT function helps both systems output at maximum power. On the other hand, DC optimizer and microinverter can effectively alleviate the power loss caused by the shadow since every solar panel in the system can work independently without interference.

In terms of price, the microinverter system is much higher for its quantity of inverter and installation difficulties, while only one central inverter required in the DC optimizer system. In terms of lifespan, both microinverter and DC optimizer has 25 years warranty but only 5 to 12 years for the central inverter (Energysage, 2019).

As a result, the DC optimizer system was an ideal option in this study.

4.2.2 Sizing of inverter and optimizer

From the perspective of safety and efficiency, the peak DC power output of the PV panel should not exceed the rated input DC power of the optimizer, and other electrical parameters like maximum voltage and current of the PV panel should be within the input range of power optimizer.

NEC 2017 stipulated that the inverter of a newly built system should conform to the standard of rapid shut down (Michael Johnston, 2017), which will be the measure of the inverter. Besides, the solar inverter is designed to convert power from DC to AC, so the prime concern should be DC power generated by the PV panels for inverter sizing.

Generally speaking, DC power under STC generated by PV arrays (P_{STC}) is recommended to match the maximum AC power output for safety; in other words, DC to AC ratio is 1. However, the power loss of PV panels is enormous since the influence of weather, PV panels will perform below the rated power output most of the time, and the efficiency is lower if DC to AC ratio is 1.

Oversizing of the inverter is a brilliant design concept nowadays, which increase the efficiency of the inverter in poor light condition by adding more solar panels than the maximum AC power of the inverter. As figure 8 shown, the ratio of DC to AC should not be too large; excess PV panels may lead to tremendous power losses or clipping losses under STC; according to FolsomLabs and Helioscope, the recommended range of DC to AC ratio is 1.0 to 1.35 (FOLSOMLABS, 2016). The rated AC power output of inverter should be within the range of 2222 W to 3000 W as the equation calculated below:

$$Inverter\ rated\ AC\ power\ output: P_{AC} = \frac{3000\ W}{1} = 3000\ W$$
$$P_{AC} = \frac{3000\ W}{1.35} = 2222\ W$$

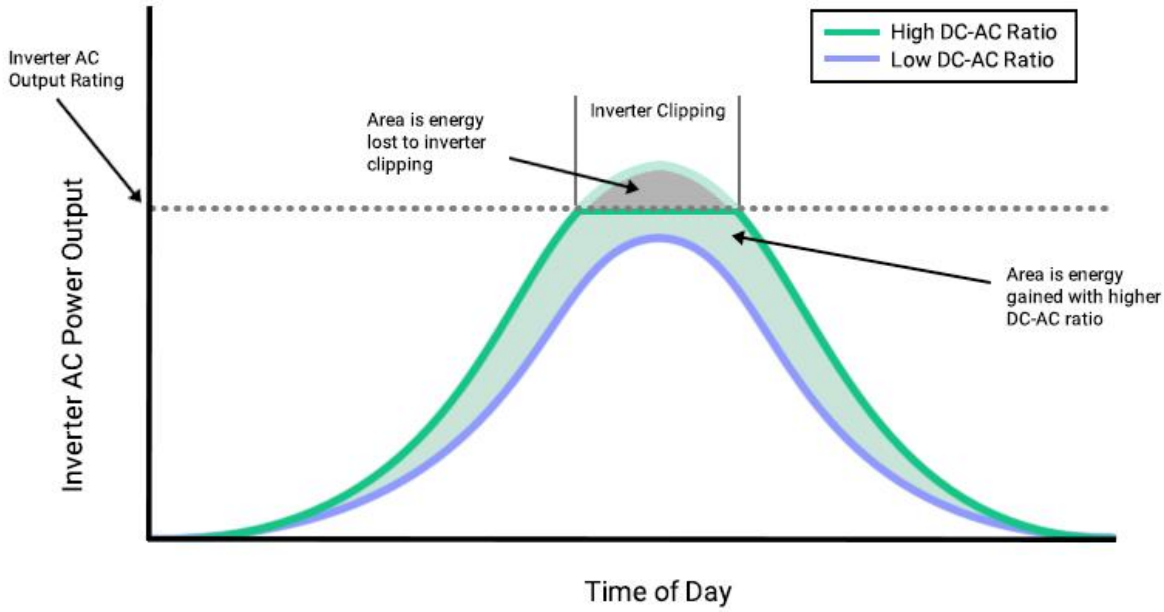

Figure 8. Inverter power output in different DC to AC ratio (Bromberg, 2017)

4.2.3 Parameter

SolarEdge company is a leading company that delicate to provide smart inverter solutions, of which the inverter system with power optimizer is the most popular one. The selected DC optimizer is the P401 model of SolarEdge; it provides panel-level monitoring and a 25 years warranty, table 3 below provides the detailed information of the DC optimizer.

Table 3. SolarEdge model P401 Datasheet (SolarEdge, 2020)

Rated input DC power (W)	**400**
Absolute maximum input voltage (Vdc)	60
Maximum short circuit current (Adc)	11.75
Maximum efficiency (%)	99.5
Weighted efficiency (%)	98.8
Maximum output current (Adc)	15
Maximum output voltage (Vdc)	60
Minimum string length	8
Operating temperature range (°C)	-40 to 85

SolarEdge power optimizers are designed to work with an inverter of the same brand. Since the minimum specifications of SolarEdge inverters are 3 kW, and the rest of the reliable inverters that meet US standards are not less than 3 kW, the selected model of the inverter is SolarEdge SE3000H-US.

SE3000H-US is a single-phase inverter that complies with NEC standards, and it provides a superior efficiency of up to 99%. Besides, SE3000H-US can work in conjunction with P401 to monitor and optimize the power output of the system through mobile devices. Some of the technical parameters of SE3000H-US inverter are illustrated in table 4:

Table 4. SolarEdge SE3000H-US inverter Datasheet (SolarEdge, 2020)

Rated and maximum AC power output (W)	**3000**
AC frequency (Hz)	59.3 - 60
Maximum continuous output current @240V (A)	12.5
Maximum DC power (W)	4650
Maximum input voltage (Vdc)	480
Nominal DC input voltage (Vdc)	380
Maximum input voltage (Adc)	8.5
Maximum input short circuit voltage (Adc)	45
Maximum efficiency (%)	99
CEC weighted efficiency (%)	99
DC input cable size (AWG range)	6-14
AC output cable size (AWG range)	6-14
Operating temperature range (°C)	-40 to 60

4.3 Cable

The cable serves as a conductor in solar systems to transmit power, and different wiring methods can vary the voltage and current inside of the cable. For the series wiring circuit, it requires more current carrying capacity in the cable. For the parallel wiring circuit, it requires cable to withstand more voltage. PV system in this thesis is in series wiring due to the installation requirement of power optimizer and inverter.

4.3.1 Sizing of DC cable

The essence of cable sizing is to determine the cross-sectional area of the cable, ensuring it allows ample enough current to pass through. Besides, all the components should be fully considered during the sizing, which means the wire must conform to all the requirements from system components. Current in the cable varies under different temperatures, the higher temperature it is, the lower current cable can carry, so it is vital to

consider temperature effect in the cable. According to NEC regulations, the sizing of the cable needs to be concerned with two aspects, continuous current and temperature aspects, and the one requires a larger current that determines the size of the cable (NEC, 2012). From the continuous current aspect, the cable should carry about 125% of the continuous output current from the electrical device. From the temperature aspect, the cable should carry enough current not exceeding the rating temperatures of the electrical device.

DC cable sizing and AC cable sizing are different since the output data and requirement from solar array and inverter are different.

In DC cable sizing, the continuous current from the solar array is 125% of the short circuit current, so the continuous current of the solar array is:

$$Isc \times 1.25 = 9.88 \times 1.25 = 12.35A$$

The rating current for the cable from the continuous current aspect is:

$$Continuous\ current \times 1.25 = 12.35 \times 1.25 = 15.44\ A$$

From the temperature aspect, TrinaSolar PV panel installation guide required to use the copper wire insulated for a minimum of 90°C (TrinaSolar, 2017), so the cable should carry the same amount of continuous current at 90 °C. The first step is to calculate the Isc at 90°C for solar panel, and it is 8.16 A as calculated below:

$$\begin{aligned} Isc_{(90℃)} &= (1 + Temperature\ of\ coefficient\ of\ Isc) \times Isc_{(NOCT)} \\ &\quad \times (90℃ - NOCT) \\ &= 1.05 \times 7.98 \times (90 - 44) = 8.16A \end{aligned}$$

Then the continuous current is:

$$Isc \times 1.25 = 8.16 \times 1.25 = 10.2\ A$$

According to Table 5, continuous current in the cable at 90°C is 29% of that at 30°C. Thus, the rating current for cable is:

$$\begin{aligned} Rating\ current &= \frac{Continuous\ current}{Temperature\ correction\ factor\ at\ 90℃} \\ &= 10.2\ \div 0.29 = 35.17\ A \end{aligned}$$

Ambient Temperature (°C)	Temperature Rating of Conductor			Ambient Temperature (°F)
	60°C	75°C	90°C	
10 or less	1.29	1.20	1.15	50 or less
11–15	1.22	1.15	1.12	51–59
16–20	1.15	1.11	1.08	60–68
21–25	1.08	1.05	1.04	69–77
26–30	1.00	1.00	1.00	78–86
31–35	0.91	0.94	0.96	87–95
36–40	0.82	0.88	0.91	96–104
41–45	0.71	0.82	0.87	105–113
46–50	0.58	0.75	0.82	114–122
51–55	0.41	0.67	0.76	123–131
56–60	—	0.58	0.71	132–140
61–65	—	0.47	0.65	141–149
66–70	—	0.33	0.58	150–158
71–75	—	—	0.50	159–167
76–80	—	—	0.41	168–176
81–85	—	—	0.29	177–185

Table 5. NEC Table 310.15 Ambient Temperature Correction Factors Based on 30°C (NEC, 2012)

The rating current is larger calculated from the temperature aspect, so the influence of temperature should determine the size of the cable. As Table 6 shown, 35.17A is within the range of AWG 10 cables with temperature resistance over 90°C; UL4703 is a standard PV cable, so AWG 10 UL4703 cable will be the DC cable.

Size	Temperature Rating of Conductor. [See Table 310.104(A).]					
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)
AWG or kcmil	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	Types TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	Types TW, UF	Types RH, RHW, THHW, THW, THWN, XHHW, USE	Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2
	Copper			**Aluminum or Copper-Clad Aluminum**		
18	—	—	14	—	—	—
16	—	—	18	—	—	—
14**	15	20	25	—	—	—
12**	20	25	30	15	20	25
10**	30	35	40	25	30	35
8	40	50	55	35	40	45

Table 6. NEC 110 .14 Ampacity allowance for different types of conductor at 30°C (NEC, 2012)

4.3.2 Sizing of AC cable

The continuous current output of the SE3000H-US inverter is 12.5 A, so the rating current of cable from the continuous current aspect is:

$$Continuous\ current \times 1.25 = 12.5 \times 1.25 = 15.525\ A$$

Datasheet of SE3000H-US indicated that the maximum operating temperature is 60°C, and the inverter can maintain its full power output until 50°C (SolarEdge, 2020). Thus, AC cable should have an insulation coat that can withstand a minimum temperature of 60°C. According to temperature derating data of the inverter (SolarEdge, 2019), the continuous output current is approximately 12A at 55°C, the temperature correction factor at 55°C is 0.41, so AC cable should carry current as calculated at 30°C below.

$$\frac{Continuous\ current}{Temperature\ correction\ factor\ at\ 55°\mathrm{C}} = 12 \div 0.41 = 29.27\ A$$

Temperature influences determine the cable since the current required by temperature is higher than 15.525A, the right AC cable is TW/UF AWG 10.

After size selection, it is essential to determine the wire length according to the data of the target building. In the standard solar system, except for the DC optimizer and solar panel placed on the roof, the rest of the components are installed on the wall. The height of the target building is 5 meters, so each DC wire length of the system is expected to be 8 meters to connect between the rooftop and the wall. The AC wire can be shorter than DC wire since the components on the wall are close to each other, 3 meters is an appropriate length for it. At last, communication cable CAT5E in the system is used in the system to enable remote monitoring.

4.3.3 Parameter

In conclusion, the PV system contained the following cables:

- 1 x 8m DC AWG 10 UL4703 positive cable for PV array-inverter
- 1 x 8m DC AWG 10 UL4703 negative cable for PV array-inverter
- 1 x 8m DC AWG 10 ground wire
- 1 x 3m AC AWG UF 10-4 for inverter-AC disconnect
- 1 x 3m AC AWG UF 10-4 for AC disconnect-power meter
- 1 x 3m AC AWG UF 10-4 for power meter-main service panel
- 1 x 15m Ethernet CAT5E cable with RJ45 connector

4.4 DC/AC Disconnect

According to NEC regulation (Michael Johnston, 2017), the disconnect device and Overcurrent Protection Device are necessary for the grid-tie system. In the conventional solar system, OCPD mainly refers to circuit breakers and fuses, which can effectively prevent overcurrent to ensure the safety of circuits and electrical devices in the PV system. DC and AC disconnect is the isolated switch theoretically, but DC and AC fused disconnect can also meet the need for OCP.

4.4.1 Sizing of disconnect

In this PV system, only AC disconnect needs to be concerned since SE3000H-US inverter has an integrated DC disconnect. As calculated in the cable sizing, the maximum ampacity in the AC cable can reach up to 29.27 A, the closest specification of the fuse is 30 A, so rated amps for AC disconnect box should be 30 A. In single-phase SE3000H-US inverter, there are four wires required for AC connect, L1, L2, neutral and grounding wires; thus, the AC disconnect should have two-poles and two 30 A fuses.

4.4.2 Parameter

Technical data of disconnect are listed in Table 7, its main parameter meet the requirements mentioned in previous chapter.

Table 7. Square Q D221NRB fused disconnect

Model	**D221NRB**
Line rated current	30
Fuse amps (A)	30
Rated AC power (VAC/W)	240
Number of poles	2

4.5 Bidirectional power meter

A bidirectional meter is a device used to measure the amount of electricity consumed by users and surplus electricity fed back to the grid. In a grid-connected solar system, it is compulsory to equip a bidirectional meter between the grid and the inverter. As the power generated by the PV system, the household load is the premier supply target; when the production is greater than the demand, the electricity will flow through the bidirectional meter measured as “kWh received” to the grid; when the demand is greater than the production, the power grid will supply the electricity through the bidirectional meter measured as “kWh delivered” to the household load.

The only consideration for bidirectional meter selection is whether it meets the requirements of the solar system and the local power grid, in this case, the specification of the bidirectional meter was single phase 240V 60Hz.

4.5.1 Parameter

Technical data of power meter are listed in Table 8, its main parameters meet the requirements of the U.S grid.

Table 8. Specification of Itron C2SODS smart meter (Itron, 2016)

Voltage Rating	**120 V, 240 V**
Frequency	60Hz
Operating Voltage	± 20% (60Hz)
Operating Range	± 3Hz
Battery Voltage	3.6 V nominal
Operating Temperature	-40 ℃ to +85 ℃
Accuracy	ANSI C12.20 0.5 accuracy class
Starting Current	20 mA (Class 200)

4.6 Mounting rack

Because the mounting rack is am extra in other components, the mounting brackets were used for solar panels here. The mounting rack is the frame used to fix the PV array, and it is mounted differently on different types of installation sites. In the solar system, the roof was flat in the target building; thus, the solar array needed to be mounted at a suitable angle of inclination.

The selection of the mounting rack mainly depends on whether it is in line with the size of the solar panel. Due to having only one string or row of solar panels in the system, the PV array should be placed vertically on the roof to save space. The width of each PV panel is 1 meter, and there wer eight panels in total for the PV array, which meant at least 8 meters required for the total length of the mounting rack. Besides, to place the PV panel perpendicularly to the solar incident, the mounting rack needed to be adjustable.

4.6.1 Parameter

The solar mounting rack was an adjustable design from Solar First, it could be adjusted freely within an angle of 10 ° to 60 °. The mounting system was customized according to the system power, so there were no specific dimension given.

Table 9. The product information of mounting rack

Installation Site	**Flat Roof**
Wind Load	60 m/s
Snow Load	1.4 kN/m2
Installation Angle	10-60
Material	Aluminum Alloy & Stainless Steel
Anti-corrosive	Anodized
Warranty	10 years guarantee and 20 years duration

5 DESIGN SCHEME OF PV SYSTEM

Figure 9 is the design scheme of the grid-tied PV system. For DC cable, the red line is positive wire; the black line is the negative wire; the green line is the ground wire. For AC cable, the red line is line 1; the orange line is line 2; the grey line is the neutral line. It is worth noting that the standard voltage of the American household is 120 V, and the power circuit is single-phase three-wire, so the voltage between L1/L2 and neutral is 120 V, and the voltage from line 1 to line 2 is 240 V.

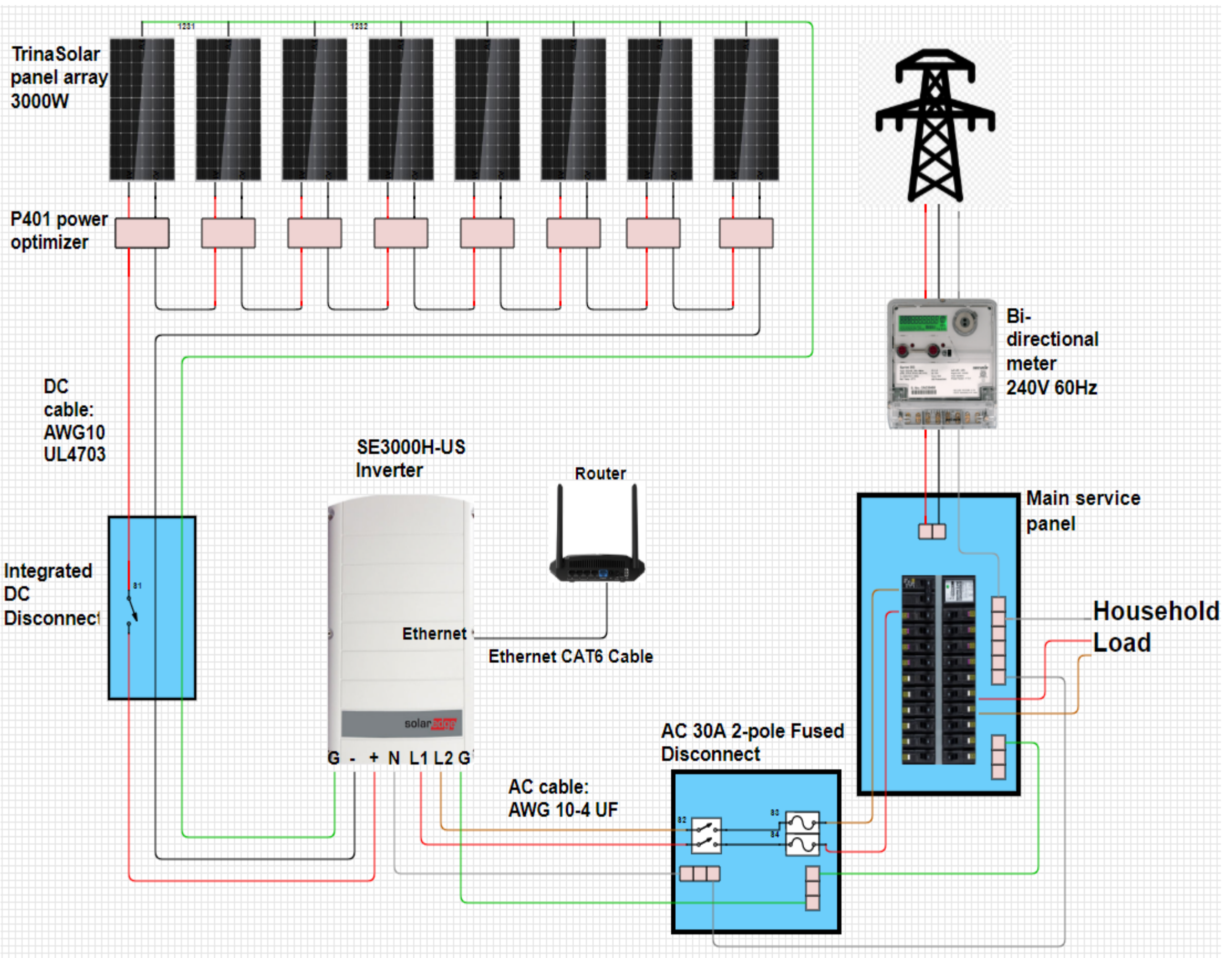

Figure 9. Wiring diagram of the PV system

6 OPTIMIZATION AND SAFETY OF PV SYSTEM

Since the house in the project was flat-roofed, it was quite flexible to place the solar array. A different tilt angle and orientation of the PV array varies the power output power of the system. The adjustment of these two parameters is to absorb the most solar irradiance on the PV panel; a proper tilt angle can ensure that the solar panel stays nearly perpendicular to the sun during the period of most substantial solar radiation, and a proper orientation can ensure that the solar panel faces the direction of the sun for a long time throughout the year. As a result, the optimization of the system focuses on finding an optimal tilt angle and orientation for the PV array.

6.1 Optimal tilt angle

The position of the sun determines the inclination angle of the solar panel, and the position of the sun changes with time. Since the selected solar mounting frame is adjustable, it is preferred to adjust the tilt angle of the solar panel according to the season, which has a higher power output than the fixed tilt angle throughout the year. Summer and winter are the two seasons with the most significant changes in the position of the sun; thus, the tilt angle of the solar panel should be adjusted based on these two seasons.

In different geographical locations, the position of the sun is also different, so the calculation of the tilt angle is based on the geographic latitude. The latitude of the project site was 37.3°. For sites with latitudes between 25°and 50°, the optimal inclination angle of the solar panel in summer is calculated as shown in the first equation (Landau, 2017):

$$Optimal\ tilt\ angle\ in\ summer: 0.92 \times latitute - 24.3 = 11°$$

In winter, the optimal tilt angle for the solar panel is:

$$Optimal\ tilt\ angle\ in\ winter: 0.89 \times latitute + 24.3 = 58°$$

6.2 Optimal orientation

The area with the most solar irradiance received on the earth is the equatorial area, so facing the equator to get more sunlight is a wise choice for the solar array. San Francisco is in the northern hemisphere, so the optimal orientation of the PV array should be south. Due to the declination between the magnetic south pole and the geographic south pole, the

south here refers to true south, not the magnetic south. The magnetic field still determines the direction in the real world, so it is necessary to calculate the magnetic angle of true south according to the magnetic declination. According to NOAA, magnetic declination in San Francisco is 13° East (NOAA, 2020), so the ideal magnetic direction is S13°E.

6.3 Safety Concern

Security is the primary factor that users consider. In this chapter, the security of the system is evaluated based on the following two aspects: the quality of the system and the rationality of the system design.

The components of this system are manufactured from leading companies in the industry, which have IEC certification and comply with NEC standards. In addition, the photovoltaic system component suppliers provide at least a 5-year warranty. Coupled with the regular maintenance of the system by users, the quality of the system is guaranteed.

The design of this system complies with NEC standards. In the system design, the impact of high temperature on solar panels and inverters was considered, ensuring that the wires could carry the peak current that the solar panels and inverters can reach. In addition, this PV system is equipped with OCPD (AC/DC disconnect) and a built-in surge protection inverter to protect the circuit.

Therefore, once the current is overloaded, the circuit is disconnected immediately. Even if it is affected by external influences such as fire hazards, firefighters can immediately disconnect the AC/DC isolating switch without a key.

7 SIMULATION AND CALCULATION OF THE PV SYSTEM

In this project, a simulator was used to simulate the influence of external factors on the photovoltaic system and to calculate the power output of the photovoltaic system, and eventually the economic benefits based on the results of the simulation were analysed.

7.1 Simulation of Grid-tied PV system

PVsyst was the simulation tool used in this project, it is one of the most commonly used photovoltaic system simulators. It can simulate near real solar system power output at selected locations according to the system selected by the user and then presents a detailed report.

Figure 10 illustrates the interface of PVsyst; the upper part is the solar radiation data and the geographic location of the target building, the lower part is the various variables of the photovoltaic system itself. The main parameters are the essential data required to run the simulation, which refers to the inclination and orientation of the solar panel and system components. With more optional parameter given by the user, the simulation result of PV system can be more precise.

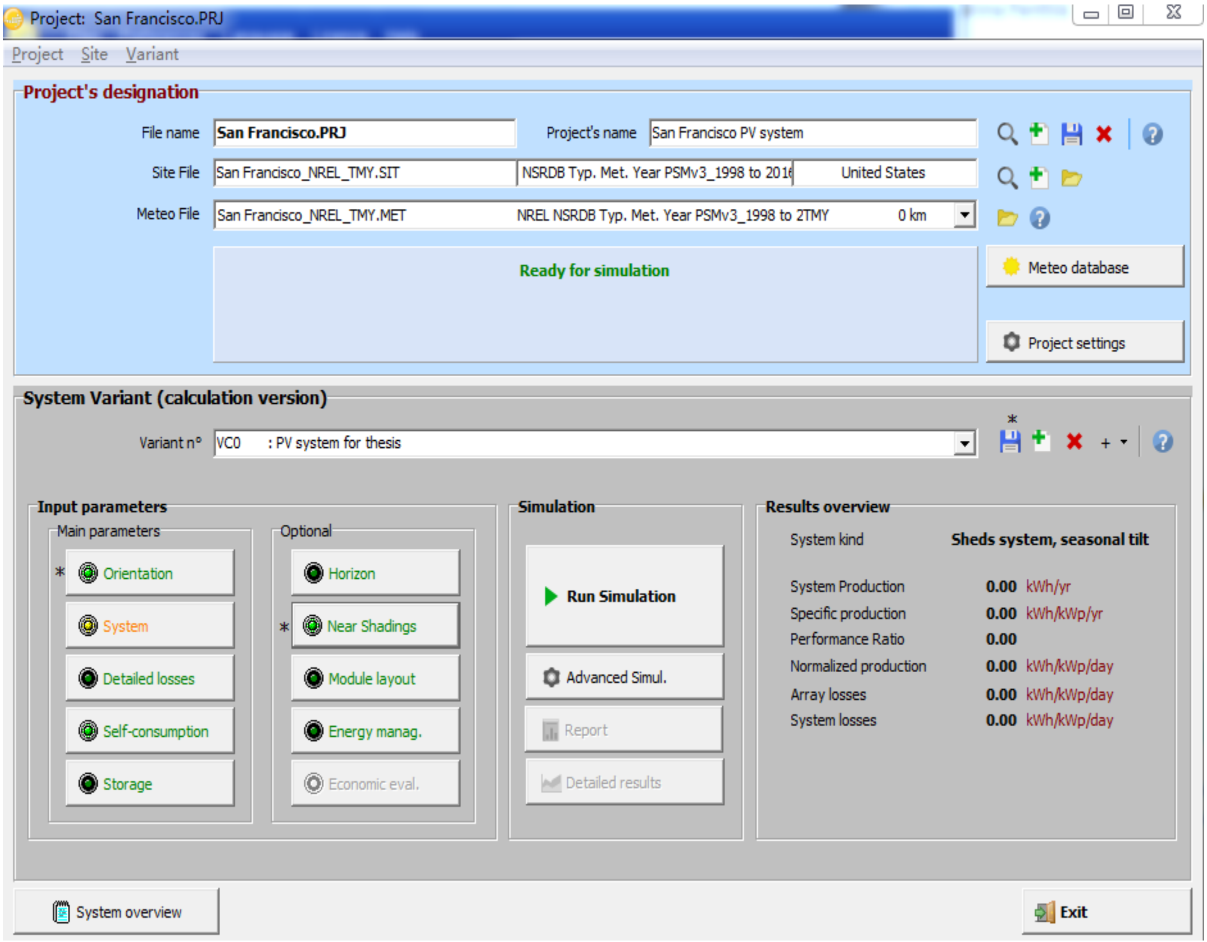

Figure 10. Interface of PVsyst

7.1.1 Site and meteo file

The first step of the simulation was to determine the geographic location and solar irradiance information of the photovoltaic system. By entering the geographic coordinates of the house in the site file, PVsyst's database generated its corresponding solar trajectory and solar irradiance data. For the accuracy of the data, the GHI data of Table 1 in the Meteo database was Imported to replace the original solar irradiance data.

7.1.2 Orientation bar

The second step of the simulation was to determine the inclination angle and orientation in the orientation bar. Entering the data into the orientation bar as Figure 11 shows, it is worth noting that azimuth here is the true south-based azimuths, so azimuth 0° means facing true south.

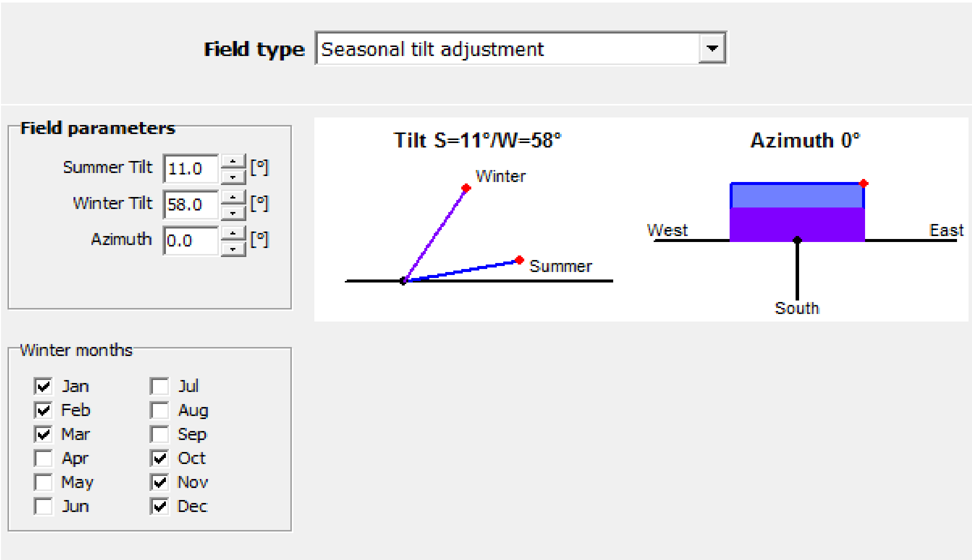

Figure 11. Orientation bar in PVsyst

7.1.3 System bar

The third step wass to determine the components of the PV system in the system bar. The database of PVsyst included models of the common solar suppliers on the market, with detailed parameters attached to each model, the required model and quantity were chosen from the database according to the component list. Figure 12 illustrates the final interface of the system bar in this project.

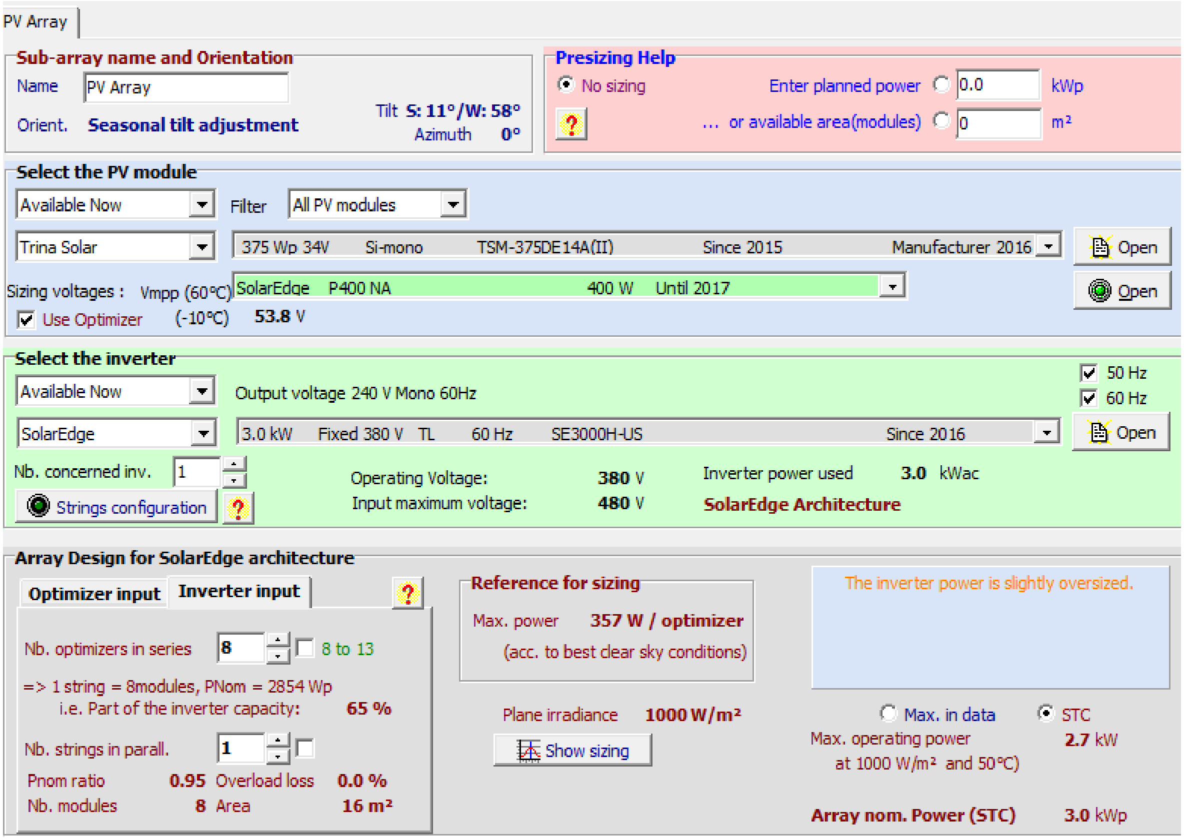

Figure 12. System overview in PVsyst

7.1.4 Self-consumption bar

The fourth step was to define the household electricity consumption in the self-consumption bar. The daily consumption data shown in Figure 13 used the consumption model in the database. After adjusting the power consumption of some appliances, the model matched the annual household power consumption data in Figure 3.

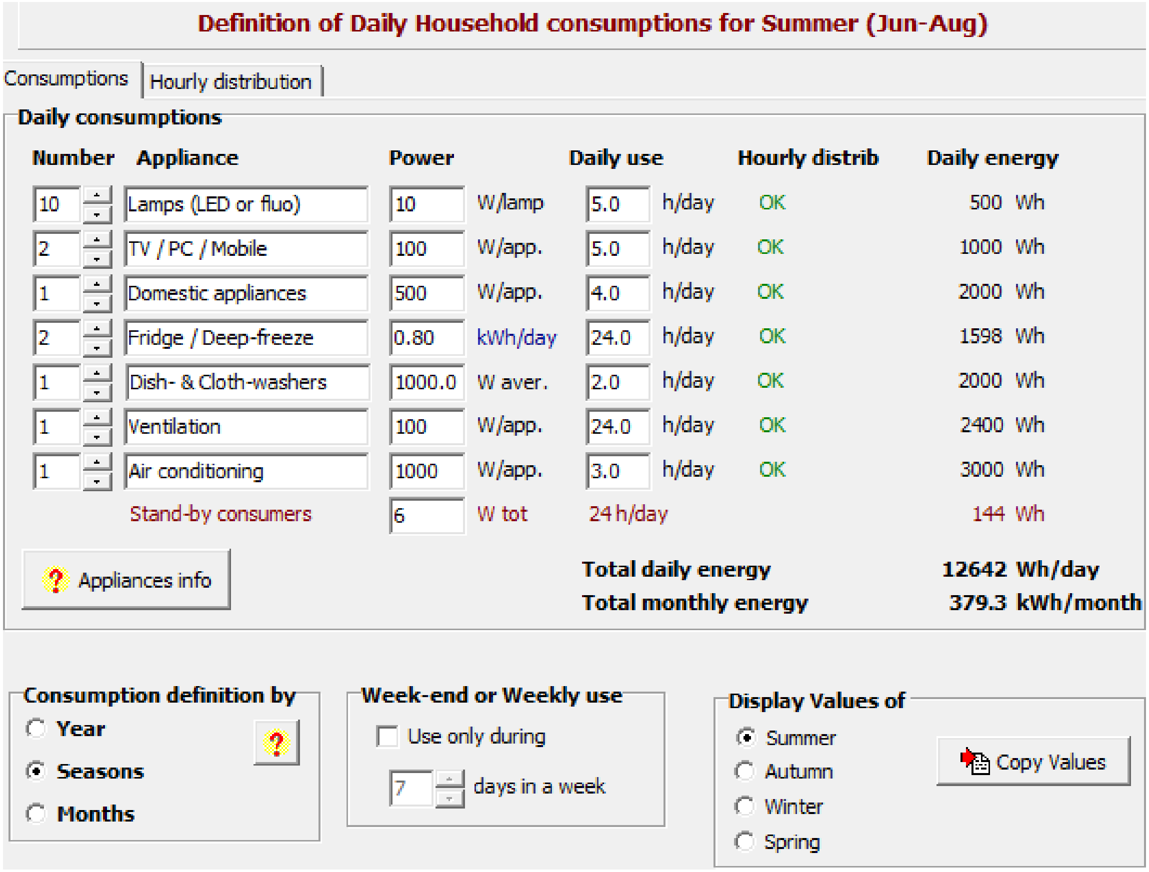

Figure 13. Household consumptions in the simulation

7.1.5 Horizon bar

The fifth step of the simulation was drawing the horizon line in the Horizon bar. Due to the software problem, it was not possible to import the horizon line from the integrated PVGIS service directly. Therefore, the only option is to select four representative points from the calculated PVGIS horizon data, to determine the horizon line shown in Figure 14.

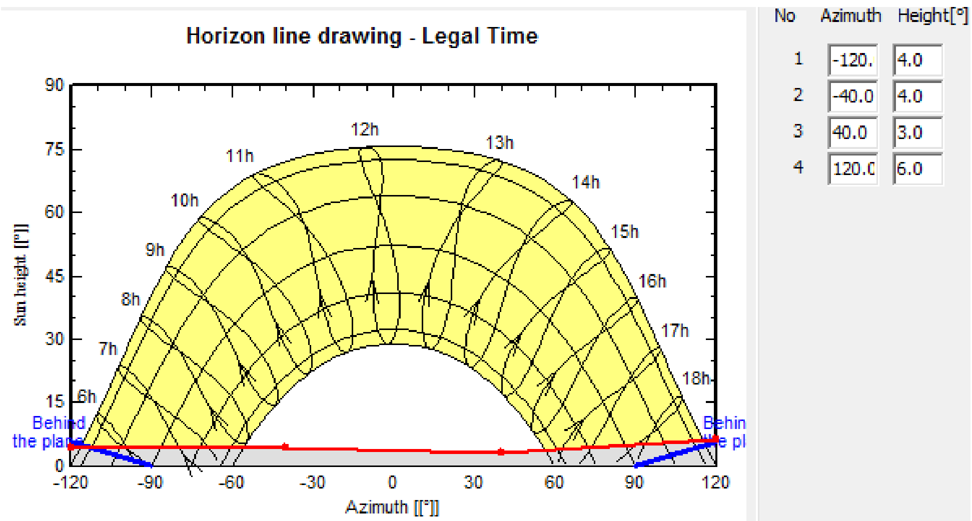

Figure 14. Horizon line of the simulation

7.1.6 Losses and near shadings

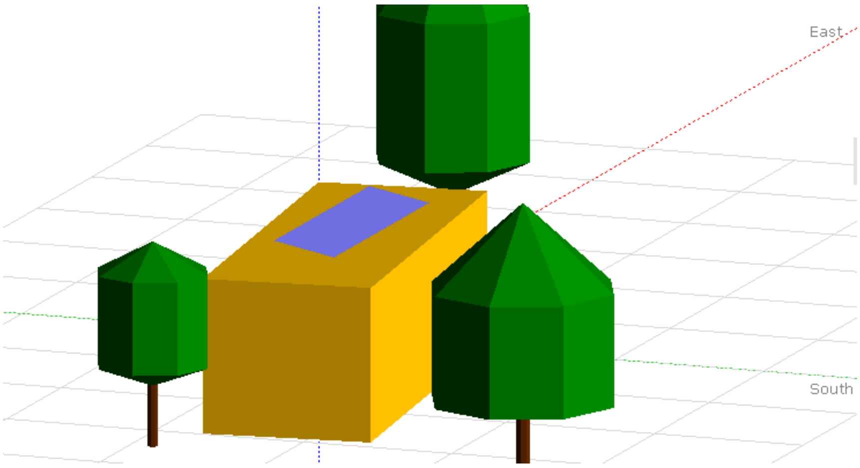

Figure 15. A simple model of the installation site

In the detailed losses bar, apart from the default values of some losses, the system automatically generated losses parameters such as aging according to the parameters of the selected component. Therefore, shading loss was the only loss that needed to be defined. In the near shading bar, PVsyst uses simple modeling to simulate the shadow of the surrounding environment in the photovoltaic system. Figure 15 illustrates the model created for the project, and figure 16 Illustrates the result of the beam shading factor.

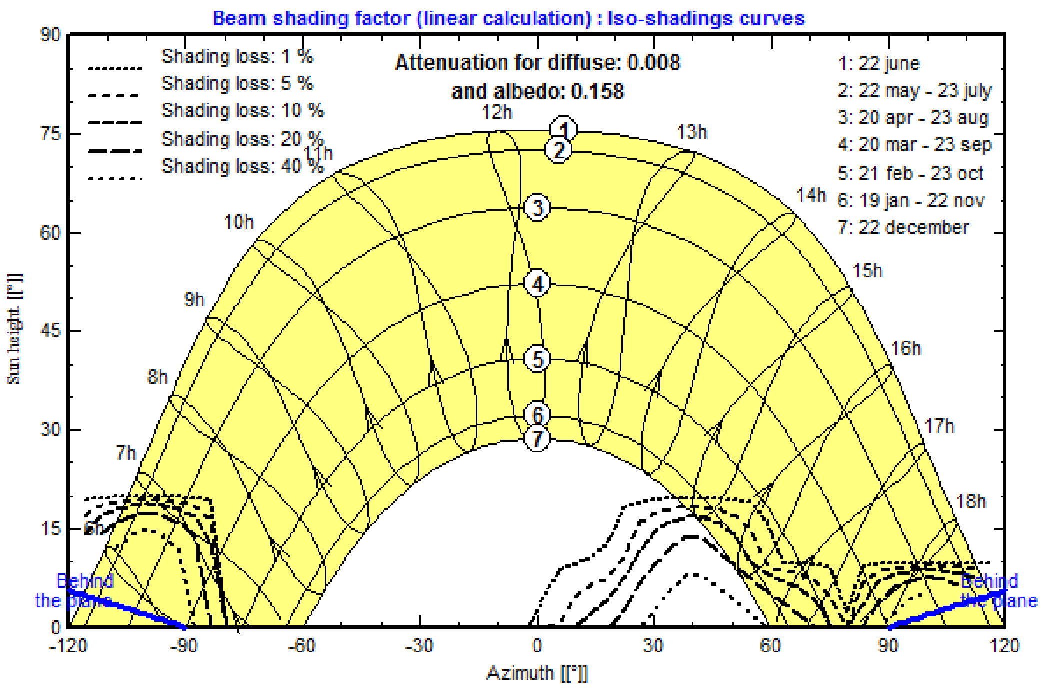

Figure 16. Beam shading factor of the project

7.2 System output simulation result

With enough data for calculation and analysis in simulation, Table 10 below shows the results of the PV system production. The main results of the simulation are listed by month and drawn from five factors: E_Array, E_User, E_Solar, E_Grid, and E_FrGrid.

Table 10. PV system output simulation result

	E_Array	E_User	E_Solar	E_Grid	E_FrGrid
	kWh	kWh	kWh	kWh	kWh
January	353.7	339.5	150.3	199.8	189.3
February	392.1	306.7	167.3	220.7	139.4
March	459	314.7	188	266.1	126.7
April	514.8	304.6	194.8	314.7	109.7
May	571.8	314.7	206.8	359.1	107.9
June	573.7	379.6	263.2	304.6	116.4
July	544.3	392.2	279.8	258.5	112.4
August	544.7	392.2	277.2	261.8	115
September	462.9	304.6	192.8	265.2	111.8
October	458.6	314.7	172.5	281.4	142.2
November	393	304.6	162.9	226	141.7
December	343.5	339.5	146.9	192.9	192.7
Year	5612	4007.5	2402.4	3150.7	1605

E_Array represents the direct power produced by the solar array, totaling 5612 kWh throughout the year. The solar radiation reaches its peak in summer, so the photovoltaic system maintains high power output from May to August; the solar radiation is relatively scarce in winter, resulting in the poor performance of the photovoltaic system during the winter.

As the name indicates, E_User is the total AC power consumed by the user in one year, which appears in the table as a reference to E_Array. In the simulation result, power consumption stays at the same level every month, totaling 4007.5 kWh in a year, meaning that the power generated by the PV system exceeds the user needs.

E_Solar is the power user consumed from the solar system; the annual consumption of it is 2402 kWh. Since the production of the PV system is higher than the user demand during the daytime, E_Grid is surplus power delivered to the grid, the annual amount of it is 3150.7 kWh. In theory, E_Array is the sum of E_Grid and E_Solar; nevertheless, the sum of that does not match the number of E_Array. The reason for the mismatch is the power loss during the conversion of the inverter.

Even though the output power of the PV system is tremendous, household electricity can not be entirely dependent on the production of the PV array. The solar system is unable to generate power during the night, but the

lighting demand from the household has surged. Especially in winter, with less solar radiation and high electricity demand, E_FrGird is much larger than that in summer. Therefore, E_FromGrid, the amount of electricity that needs to be transferred from the grid to users throughout the year, is 1605 kWh.

7.3 Economic benefits

As shown in table 7, the total expenditure on this residential PV system is 3838 USD, while the average cost for a 3kW PV system is 8880 USD (Matasci, 2020), which means the average cost in the market is 2.3 times the cost of this system. The reason for such a price difference may be the additional charges for design and installation by solar contractors, and the higher price of photovoltaic systems such as off-grid systems, which has increased the average market price.

Table 11. the total expenditure of the PV system

8 x TSM-375W-DE14A(II) PV panel	**1840 USD**
8 x P401 Power optimizer	640 USD
1 x SE3000H-US Inverter	995 USD
1 x Square D D221NRB Disconnect	60 USD
1 x Adjustable solar panel mounting kit	150 USD
1 x Itron C2SODS Bi-directional Meter	75 USD
2 x 8m AWG10 UL4703 wire with MC4 connectors	32 USD
3 x 3m AWG UF 10-4 cable	21 USD
1 x 15m AWG10 UL copper ground wire	20 USD
1 x 15m Ethernet CAT5E cable with RJ45 connector	5 USD
Total fee	3838 USD

In order to promote the development of residential solar power, the US government issued a solar energy incentive policy, called Solar Investment Tax Credit or ITC in short. ITC provides a waiver of taxes equivalent to 26% of the cost of solar systems for households installing solar systems in 2020; thus, the actual cost of the PV system is 2840 USD.

$$Actual\ cost: 3838 \times (1 - 26\%) = 2840 \text{ USD}$$

After investing in a photovoltaic system, the revenue generated by the photovoltaic system depends on the sale of surplus electricity. The local utility company will sign a Feed-in Tariff contract with the PV system installation households, stipulating that the surplus solar energy produced by the households will be purchased at a fixed price within the contract period. According to CPUC, the FIT incentive in California is 0.08923 USD /kWh for the PV system with a capacity below 3MW (CPUC, 2018). As mentioned in Table 6, the annual power delivered to the grid is 3150.7 kWh, so the annual revenue of selling surplus power is calculated as below:

$$Annual\ Revenue\ of\ E_{Grid} = FIT\ incentive \times E_{Grid}$$
$$= 0.08923 \times 3150.7 = 281\ \text{USD}$$

In addition to the sale of surplus electricity, the consumption of electricity produced by photovoltaic systems is essentially profitable. E_Solar in table 6 is 2402.4 kWh, which is equivalent to earning the same amount of electricity fee. The average residential electricity price in San Francisco has risen in recent years, with an average annual growth rate of 10%, the latest average electricity price is 0.23 USD/kWh (BLS, 2020); thus, the total electricity fee PV system save in the first year is 552 USD.

$$Saved\ Electricty\ Fee = E_{Solar} \times Electricity\ rate$$
$$= 2402.4 \times 0.23 \times (1 + 0.1)^0 = 552\ \text{USD}$$

Electricity expenses due to insufficient PV system capacity will not affect system revenue, the revenue generated by the photovoltaic system is derived from the sum of the electricity sold, and the savings in electricity costs. To extend the life of the system and maximize the capacity of the system, maintenance expenses are inevitable; the annual maintenance fee is assumed to be 60 $ for the system.

The equation below is the calculation of total profit in the first year.

$$Annual\ revenue = 281 + 2402.4 \times 0.23 \times (1 + 0.1)^0 - 60$$
$$= 773\ \text{USD}$$

Thus, assume that X is payback period, then it is calculated as the formula below:

$$Payback\ Period = \frac{Actual\ cost}{Annual\ revenue}$$

$$x = \frac{2840}{281 + 2402.4 \times 0.23 \times 1.1^{(x-1)} - 60x}$$

$$x = payback\ period = 3.4\ years$$

The following figure 19 shows the simulation results of the economic evaluation. Although the lifespan of the PV system is expected to be 25 years or more, the longer the working time of the photovoltaic system, the more unstable the production capacity. As a result, the simulation period is ten years in this project.

The payback period for the entire system is only 3.4 years, which is 2.6 years shorter than the average six-year payback period for systems on the California market. After the payback period, the profit brought by the photovoltaic system is a net profit, and the total profit can be as high as 7507 USD in ten years, which is equivalent to twice the total system cost.

Detailed economic results (USD)

Year	Sold energy	Run. costs	Deprec. allow.	Taxable income	Tax 0.00%	After-tax profit	Self-cons. saving	Cumul. profit	% amorti.
2021	281	60	384	0	0	221	552	773	27.2%
2022	281	60	384	0	0	221	607	1'602	56.4%
2023	281	60	384	0	0	221	663	2'485	87.5%
2024	281	60	384	0	0	221	718	3'424	120.6%
2025	281	60	384	0	0	221	773	4'418	155.6%
2026	281	60	384	0	0	221	828	5'468	192.5%
2027	281	60	384	0	0	221	883	6'572	231.4%
2028	281	60	384	0	0	221	939	7'732	272.3%
2029	281	60	384	0	0	221	994	8'947	315.0%
2030	281	60	384	0	0	221	1'049	10'217	359.8%
Total	2'810	600	3'838	0	0	2'210	8'007	10'217	359.8%

Figure 17. Detailed economics results of the simulation

8 CONCLUSION

The purpose of this project was to learn about photovoltaic systems to provide cost-effective photovoltaic system design solutions with a production capacity that would meet the daily electricity needs of a household in San Francisco.

The solar system was determined to be a 3 kW grid-connected PV system after analyzing the average household electricity consumption and energy loss. This prpject used PVsyst simulation software to analyze the system's revenue and power output, inferring that the system performed well in terms of economic benefits, safety, and power output.

In terms of economic benefits, the actual cost of the system is 2840 USD, compared with the average cost of the 3kw photovoltaic system, the average market price is 2.3 times that of the system. The payback period for this photovoltaic system is 3.4 years, which is 2.6 years less than the average payback period for the photovoltaic market in the California market. In long-term benefits, the ten-year net profit brought by the system is 7,507 USD.

In terms of safety, The design of this system complies with the NEC standards. The quality of the system is trustworthy and the system is equipped with OCPD to ensure the safety of the system. The system can effectively deal with disasters like fire hazard, thereby reducing losses.

In terms of power output, the estimated total power output of the system is 5612 kWh/year, which meets the power demand. However, because there is no energy storage equipment, residents cannot wholly rely on the solar system. As mentioned above, this is an economically based choice. In addition, the solar system faces true south and comes with an adjustable

mounting rack to maintain the optimal tilt angle, ensuring that the solar panel absorbs the maximum solar radiation in different seasons.

ITC policy subsidies in the U.S for residential photovoltaic systems have declined year by year until the policy will expire in 2022, so it can be predicted that the residential solar market in California will reach its peak within the next two years. The excellent development prospects of the solar energy industry have brought about fierce market competition, and the price of photovoltaic systems has been declining year by year. Under the influence of technological innovation and market competition, battery prices may also decrease year by year in the future. On the other hand, electricity costs are also increasing year by year, and grid-connected photovoltaic systems with batteries may become the mainstream of the civilian photovoltaic market.

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Grid-Connected System: Simulation parameters

Project :	**San Francisco PV system**			
Geographical Site	**San Francisco**		Country	**United States**
Situation	Latitude	37.77° N	Longitude	-122.42° W
Time defined as	Legal Time	Time zone UT-8	Altitude	29 m
	Albedo	0.20		
Meteo data:	**San Francisco**	NREL NSRDB Typ. Met. Year PSMv3_1998 to 2016 - TMY		

Simulation variant :	**PV system for thesis**			
	Simulation date	30/04/20 13h55		

Simulation parameters	System type	**Sheds system, seasonal tilt**		
Coll. plane: Seasonal tilt adjustment	Azimuth	0°	Winter season	O-N-D-J-F-M
	Summer Tilt	11°	Winter Tilt	58°
Models used	Transposition	Perez	Diffuse	Imported
Horizon	Average Height	4.0°		
Near Shadings	Linear shadings			
User's needs :	Daily household consumers	Seasonal modulation		
	average	11.0 kWh/Day		

PV Array Characteristics				
PV module Si-mono	Model	**TSM-375DE14A(II)**		
Custom parameters definition	Manufacturer	Trina Solar		
SolarEdge Power Optimizer	Model	**P400 NA**	Unit Nom. Power	400 W
PV modules on one Power Optimizer	in series	1	in parallel	1
Nb. of optimizers	In series	8	In parallel	1 strings
Total number of PV modules	Nb. modules	8	Unit Nom. Power	375 Wp
Array global power	Nominal (STC)	**3000 Wp**	At operating cond.	2705 Wp (50°C)
Output of optimizers	U oper	380 V	I at Poper	7.1 A
Total area	Module area	**15.5 m²**	Cell area	14.0 m²
Inverter	Model	**SE3000H-US**		
Custom parameters definition	Manufacturer	SolarEdge		
Characteristics	Operating Voltage	380 V	Unit Nom. Power	3.0 kWac
Inverter pack	Nb. of inverters	1 units	Total Power	3.0 kWac
			Pnom ratio	0.95

PV Array loss factors				
Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	722 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	-0.3 %
Module Mismatch Losses			Loss Fraction	0.0 % (fixed voltage)
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

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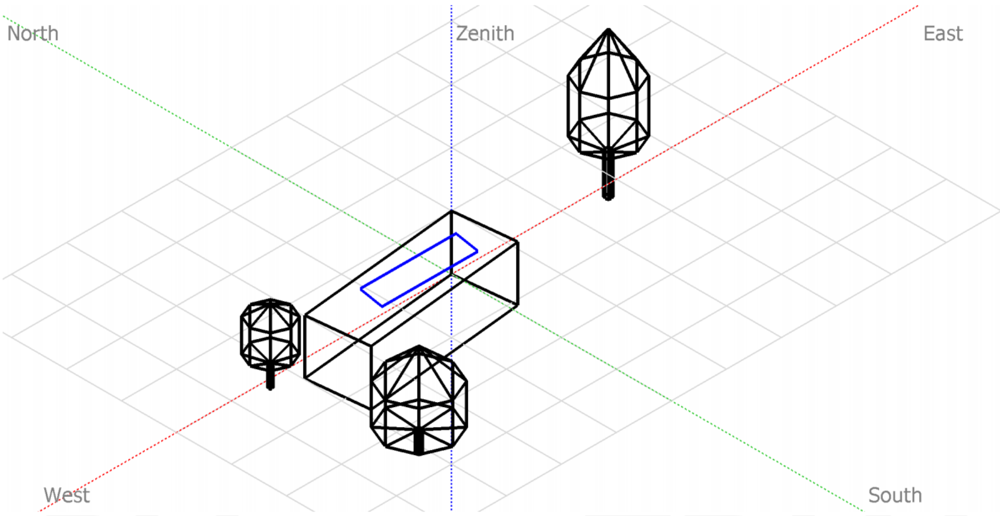
Grid-Connected System: Near shading definition

Project : **San Francisco PV system**

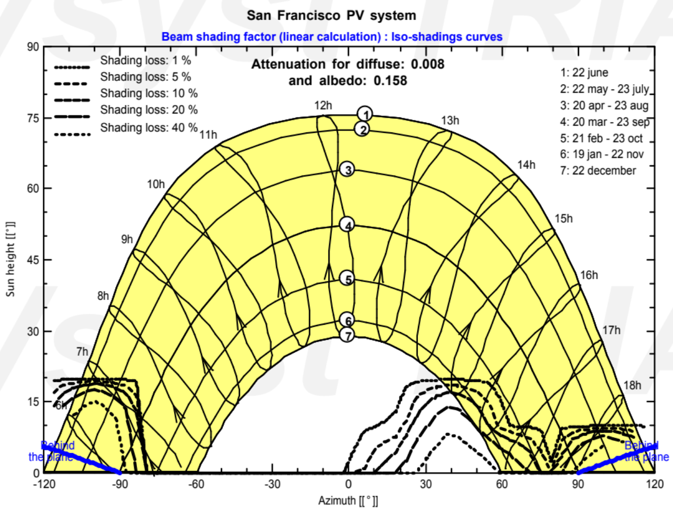
Simulation variant : **PV system for thesis**

Main system parameters	System type	**Sheds system, seasonal tilt**		
Horizon	Average Height	4.0 °		
Near Shadings	Linear shadings			
PV Field Orientation	Seasonal tilt: summer/winter	11 °/58 °	azimuth	0 °
PV modules	Model	TSM-375DE14A(II)	Pnom	375 Wp
PV Array	Nb. of modules	8	Pnom total	**3000 Wp**
Inverter	Model	SE3000H-US	Pnom	3000 W ac
User's needs	Daily household consumers	Seasonal modulation	Global	4004 kWh/year

Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram



Grid-Connected System: Detailed User's needs

Project : **San Francisco PV system**

Simulation variant : **PV system for thesis**

Main system parameters	System type	**Sheds system, seasonal tilt**		
Horizon	Average Height	4.0°		
Near Shadings	Linear shadings			
PV Field Orientation	Seasonal tilt: summer/winter	11°/58°	azimuth	0°
PV modules	Model	TSM-375DE14A(II)	Pnom	375 Wp
PV Array	Nb. of modules	8	Pnom total	**3000 Wp**
Inverter	Model	SE3000H-US	Pnom	3000 W ac
User's needs	Daily household consumers	Seasonal modulation	Global	4004 kWh/year

Daily household consumers, Seasonal modulation, average = 11.0 kWh/day

Summer (Jun-Aug)

	Number	Power	Use	Energy
Lamps (LED or fluo)	10	10 W/lamp	5 h/day	500 Wh/day
TV / PC / Mobile	2	100 W/app	5 h/day	1000 Wh/day
Domestic appliances	1	500 W/app	4 h/day	2000 Wh/day
Fridge / Deep-freeze	2		24 Wh/day	1598 Wh/day
Dish- & Cloth-washers	1		2 Wh/day	2000 Wh/day
Ventilation	1	100 W tot	24 h/day	2400 Wh/day
Air conditioning	1	1000 W tot	3 h/day	3000 Wh/day
Stand-by consumers			24 h/day	144 Wh/day
Total daily energy				12642 Wh/day

Autumn (Sep-Nov)

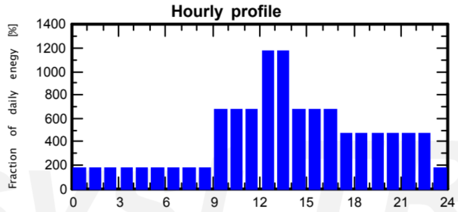
	Number	Power	Use	Energy
Lamps (LED or fluo)	10	10 W/lamp	5 h/day	500 Wh/day
TV / PC / Mobile	2	100 W/app	5 h/day	1000 Wh/day
Domestic appliances	1	500 W/app	5 h/day	2500 Wh/day
Fridge / Deep-freeze	2		24 Wh/day	1598 Wh/day
Dish- & Cloth-washers	1		2 Wh/day	2000 Wh/day
Ventilation	1	100 W tot	24 h/day	2400 Wh/day
Stand-by consumers			24 h/day	144 Wh/day
Total daily energy				10142 Wh/day

Winter (Dec-Feb)

	Number	Power	Use	Energy
Lamps (LED or fluo)	10	10 W/lamp	6 h/day	600 Wh/day
TV / PC / Mobile	2	100 W/app	6 h/day	1200 Wh/day
Domestic appliances	1	500 W/app	6 h/day	3000 Wh/day
Fridge / Deep-freeze	2		24 Wh/day	1598 Wh/day
Dish- & Cloth-washers	1		2 Wh/day	2000 Wh/day
Ventilation	1	100 W tot	24 h/day	2400 Wh/day
Stand-by consumers			24 h/day	144 Wh/day
Total daily energy				10942 Wh/day

Spring (Mar-May)

	Number	Power	Use	Energy
Lamps (LED or fluo)	10	10 W/lamp	5 h/day	500 Wh/day
TV / PC / Mobile	2	100 W/app	5 h/day	1000 Wh/day
Domestic appliances	1	500 W/app	5 h/day	2500 Wh/day
Fridge / Deep-freeze	2		24 Wh/day	1598 Wh/day
Dish- & Cloth-washers	1		2 Wh/day	2000 Wh/day
Ventilation	1	100 W tot	24 h/day	2400 Wh/day
Stand-by consumers			24 h/day	144 Wh/day
Total daily energy				10142 Wh/day



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Grid-Connected System: Main results

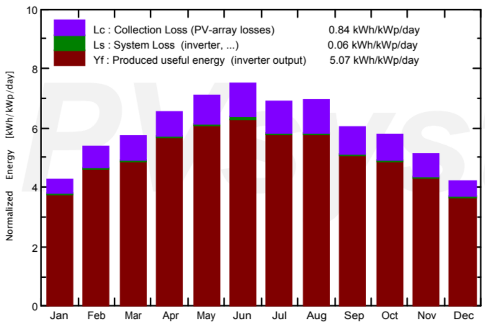
Project : **San Francisco PV system**

Simulation variant : **PV system for thesis**

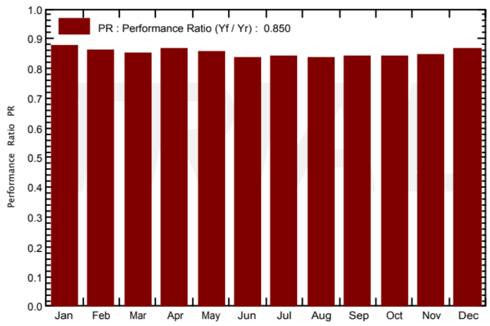
Main system parameters	System type	**Sheds system, seasonal tilt**		
Horizon	Average Height	4.0°		
Near Shadings	Linear shadings			
PV Field Orientation	Seasonal tilt: summer/winter	11°/58°	azimuth	0°
PV modules	Model	TSM-375DE14A(II)	Pnom	375 Wp
PV Array	Nb. of modules	8	Pnom total	**3000 Wp**
Inverter	Model	SE3000H-US	Pnom	3000 W ac
User's needs	Daily household consumers	Seasonal modulation	Global	4004 kWh/year

Main simulation results				
System Production	**Produced Energy**	**5.55 MWh/year**	Specific prod.	1850 kWh/kWp/year
	Performance Ratio PR	84.99 %	Solar Fraction SF	59.96 %

Normalized productions (per installed kWp): Nominal power 3000 Wp



Performance Ratio PR



PV system for thesis

Balances and main results

	GlobHor	DiffHor	T_Amb	GlobInc	GlobEff	EArray	E_User	E_Solar	E_Grid	EFrGrid
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	MWh	MWh	MWh	MWh	MWh
January	71.1	23.75	8.59	133.0	127.6	0.354	0.339	0.150	0.200	0.189
February	96.9	31.30	9.99	150.3	143.8	0.392	0.306	0.167	0.221	0.139
March	148.4	45.85	11.78	178.2	169.6	0.459	0.314	0.188	0.266	0.127
April	185.1	55.13	12.06	196.2	190.0	0.515	0.304	0.195	0.315	0.110
May	216.4	65.39	13.41	220.1	213.0	0.572	0.314	0.207	0.359	0.108
June	226.3	48.07	16.20	225.7	218.9	0.574	0.379	0.263	0.305	0.116
July	212.2	63.15	16.23	213.4	206.3	0.544	0.392	0.280	0.259	0.112
August	206.5	47.04	17.33	215.2	208.2	0.545	0.392	0.277	0.262	0.115
September	165.1	40.67	17.34	181.6	175.5	0.463	0.304	0.193	0.265	0.112
October	122.6	30.90	14.35	179.4	172.5	0.459	0.314	0.172	0.281	0.142
November	84.2	25.73	12.63	153.2	146.4	0.393	0.304	0.163	0.226	0.141
December	65.2	22.16	9.11	130.9	125.0	0.344	0.339	0.147	0.193	0.192
Year	1800.1	499.14	13.26	2177.2	2096.9	5.612	4.004	2.401	3.151	1.603

Legends:	GlobHor	Horizontal global irradiation	GlobEff	Effective Global, corr. for IAM and shadings
	DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
	T_Amb	T amb.	E_User	Energy supplied to the user
	GlobInc	Global incident in coll. plane	E_Solar	Energy from the sun
			E_Grid	Energy injected into grid
			EFrGrid	Energy from the grid

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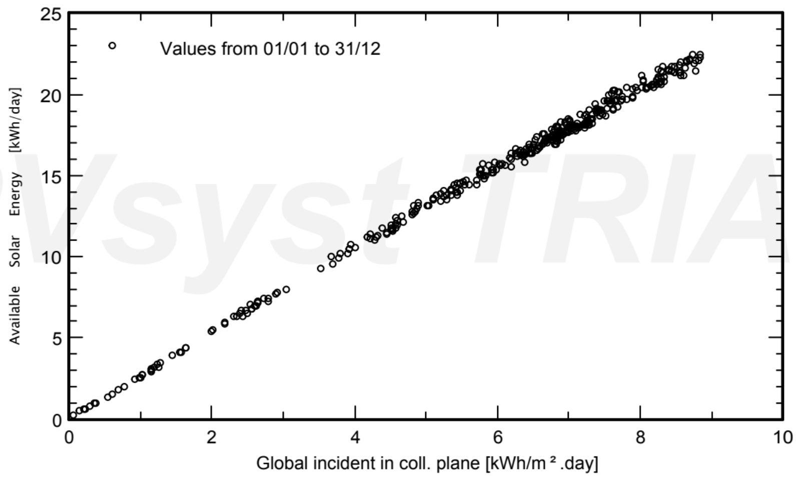
Grid-Connected System: Special graphs

Project : **San Francisco PV system**

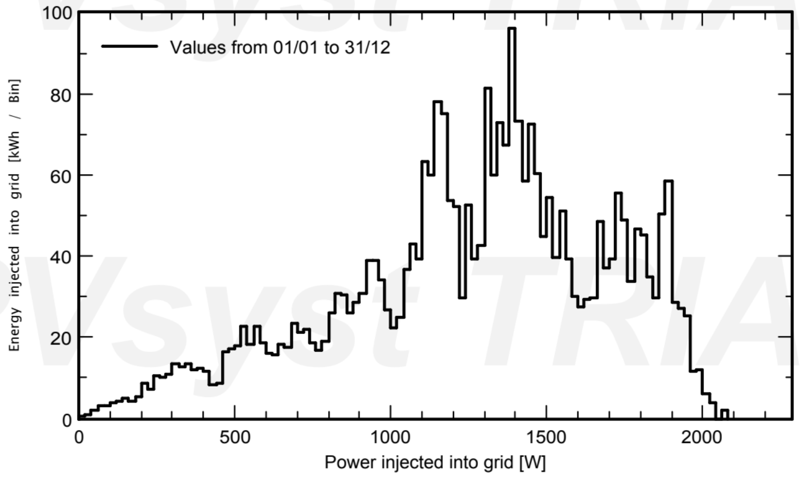
Simulation variant : **PV system for thesis**

Main system parameters	System type	**Sheds system, seasonal tilt**		
Horizon	Average Height	4.0°		
Near Shadings	Linear shadings			
PV Field Orientation	Seasonal tilt: summer/winter	11°/58°	azimuth	0°
PV modules	Model	TSM-375DE14A(II)	Pnom	375 Wp
PV Array	Nb. of modules	8	Pnom total	**3000 Wp**
Inverter	Model	SE3000H-US	Pnom	3000 W ac
User's needs	Daily household consumers	Seasonal modulation	Global	4004 kWh/year

Daily Input/Output diagram



System Output Power Distribution



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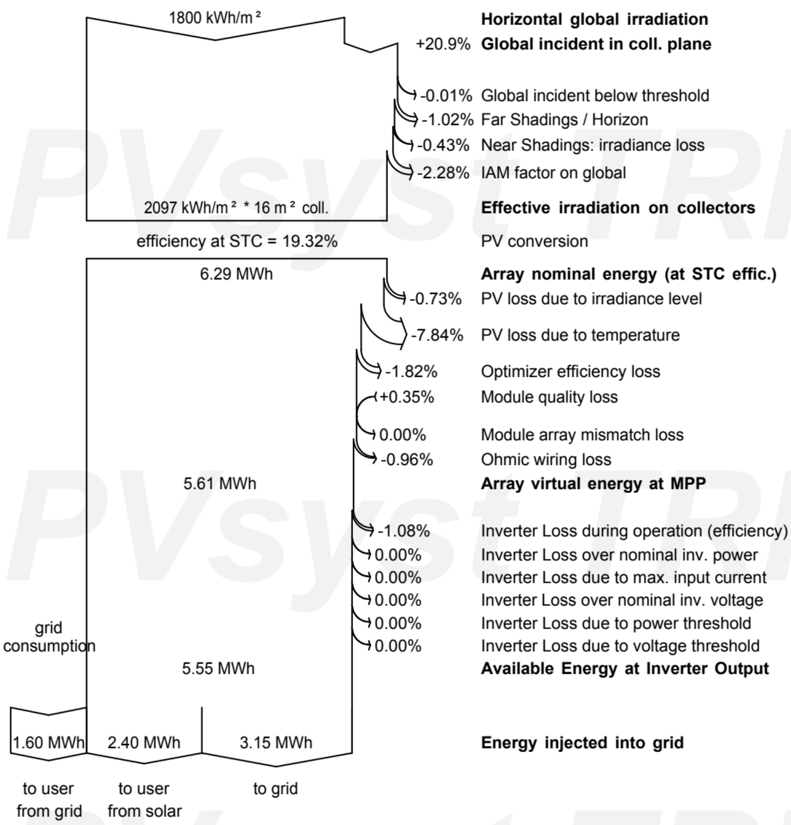
Grid-Connected System: Loss diagram

Project : **San Francisco PV system**

Simulation variant : **PV system for thesis**

Main system parameters	System type	**Sheds system, seasonal tilt**		
Horizon	Average Height	4.0°		
Near Shadings	Linear shadings			
PV Field Orientation	Seasonal tilt: summer/winter	11°/58°	azimuth	0°
PV modules	Model	TSM-375DE14A(II)	Pnom	375 Wp
PV Array	Nb. of modules	8	Pnom total	**3000 Wp**
Inverter	Model	SE3000H-US	Pnom	3000 W ac
User's needs	Daily household consumers	Seasonal modulation	Global	4004 kWh/year

Loss diagram over the whole year



Grid-Connected System: P50 - P90 evaluation

Project : **San Francisco PV system**

Simulation variant : **PV system for thesis**

Main system parameters	System type	**Sheds system, seasonal tilt**		
Horizon	Average Height	4.0°		
Near Shadings	Linear shadings			
PV Field Orientation	Seasonal tilt: summer/winter	11°/58°	azimuth	0°
PV modules	Model	TSM-375DE14A(II)	Pnom	375 Wp
PV Array	Nb. of modules	8	Pnom total	**3000 Wp**
Inverter	Model	SE3000H-US	Pnom	3000 W ac
User's needs	Daily household consumers	Seasonal modulation	Global	4004 kWh/year

Evaluation of the Production probability forecast

The probability distribution of the system production forecast for different years is mainly dependent on the meteo data used for the simulation, and depends on the following choices:

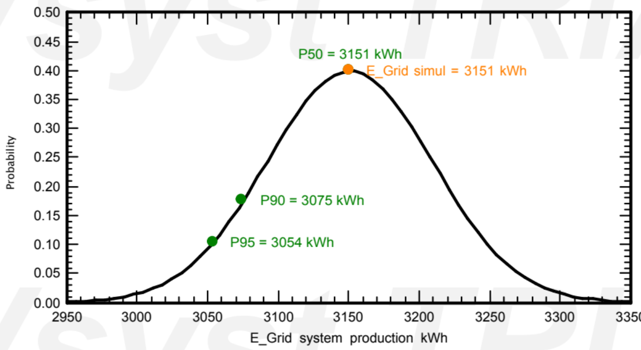
Meteo data source		NREL NSRDB Typ. Met. Year PSMv3_1998 to 2016		
Meteo data	Kind	Not defined	Year	1995
Specified Deviation	Year deviation from aver.	3 %		
Year-to-year variability	Variance	0.5 %		

The probability distribution variance is also depending on some system parameters uncertainties

Specified Deviation	PV module modelling/parameters	1.0 %	
	Inverter efficiency uncertainty	0.5 %	
	Soiling and mismatch uncertainties	1.0 %	
	Degradation uncertainty	1.0 %	
Global variability (meteo + system)	Variance	1.9 %	(quadratic sum)

Annual production probability	**Variability**	**0.06 MWh**
	P50	**3.15 MWh**
	P90	**3.08 MWh**
	P95	**3.05 MWh**

Probability distribution



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Grid-Connected System: CO2 Balance

Project : **San Francisco PV system**

Simulation variant : **PV system for thesis**

Main system parameters	System type	**Sheds system, seasonal tilt**		
Horizon	Average Height	4.0°		
Near Shadings	Linear shadings			
PV Field Orientation	Seasonal tilt: summer/winter	11°/58°	azimuth	0°
PV modules	Model	TSM-375DE14A(II)	Pnom	375 Wp
PV Array	Nb. of modules	8	Pnom total	**3000 Wp**
Inverter	Model	SE3000H-US	Pnom	3000 W ac
User's needs	Daily household consumers	Seasonal modulation	Global	4004 kWh/year

Produced Emissions	**Total:**	**5.42 tCO2**		
	Source:	Detailed calculation from table below		
Replaced Emissions	**Total:**	**87.9 tCO2**		
	System production:	5551.45 kWh/yr	Lifetime:	30 years
			Annual Degradation:	1.0 %
	Grid Lifecycle Emissions:	528 gCO2/kWh		
	Source:	IEA List	Country:	United States
CO2 Emission Balance	**Total:**	**70.9 tCO2**		

System Lifecycle Emissions Details:

Item	Modules	Supports
LCE	1713 kgCO2/kWp	3.52 kgCO2/kg
Quantity	3.00 kWp	80.0 kg
Subtotal [kgCO2]	5138	282