**University of New South Wales**

# Applied PV
# SOLA2540

*Stand Alone PV System Design*
*Final Report*
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# 1. Executive Summary

This report documents the preliminary design of a stand alone PV system to be installed for an agriculture processing plant located at 27° 28' 0.57"N, 86° 6' 38.88"E next to the Tama Koshi river in Nepal, East of Kathmandu. The area experiences five seasons: spring, summer, monsoon, autumn, and winter with moderate climate conditions (Climate of Nepal, 2020). The designed PV system must supply enough power to operate a grain mill and four lights at varying loads over the course of a year. This load requires 100.625 Ah per day at 48 V with 4 days of autonomy. Using an iterative system design process found in the Excel design tool described in Appendix A, components were selected to maximise cost efficiency and reliability while accounting for availability and maintenance. The selected PV system components consist of 12 Hyperion Diamond Modules connected in an array of 7 modules per string, 2 strings in parallel, with 2 Tesla Powerwall batteries are wired in parallel, and an MPPT charge controller.

# 2. Background and Objectives

This project aims to develop the optimal stand-alone PV array to power an agricultural processing plant. It will be located next to the Tama Koshi river in Nepal, east of Kathmandu. Its rural location reduces the feasibility of a grid connection due to lack of established infrastructure and poor reliability of the local connection. The PV system must be reliable, independent from the grid, require minimal maintenance, and provide low-emission energy. The loads of the agricultural plant will be analysed with solar data to determine the required type and scale of system components. The simple payback period and levelized cost of energy will be explored to determine the economic compatibility of the system with the needs of the users.

# 3. Load Assessment

The loads to be supplied consist of four lights and a grain mill. Their required wattage and hours are displayed in the following table. No AC power is needed as the appliances only require DC power.

*Table 1. Load table*

| Appliance | No | Power | Winter or dry season | | Summer or wet season | | Contribution to max demand |
|---|---|---|---|---|---|---|---|
| | | | Usage Time | Energy | Usage Time | Energy | |
| | | W | h | Wh | h | Wh | W |
| Light | 4 | 15 | 4 | 240 | 18 | 1080 | 60 |
| Grain Mill | 1 | 750 | 3 | 2250 | 5 | 3750 | 750 |
| **Daily Load Energy d.c. loads (Wh)** | | | | **2490** | | **4830** | |
| **Maximum d.c. demand (W)** | | | | | | | **810** |

The daily energy required for each appliance in watt-hours (Wh) is found by multiplying the power in watts with the daily usage time and the number of appliances. Since there are no AC components, the daily load energy is equal to the sum of each of the appliances' calculated daily energy requirement.

The maximum demand in watts (W) is equal to the sum of each of the appliances' wattage. Since the maximum daily load energy of 4830 Wh is above four kWh, a system voltage of 48 V is assumed according to the rule of thumb (Shrestha, 2020). This voltage will be maintained in both summer and winter since the infrastructure will be in place and a higher voltage is always ideal.

The daily load in ampere-hours (Ah) is equal to the daily load (Wh) divided by the system voltage of 48 V. In winter and summer, the daily load is estimated to be 51.875 Ah and 100.625 Ah respectively.

# 4. Battery Sizing

The days of autonomy are determined by counting the consecutive days in the solar data when the solar irradiance is below 4 $kW/m^2$ (S. Pfenninger, I. Staffell, 2020). The maximum consecutive days is assumed to be the number of days of autonomy required by the system. Four days of autonomy are required for the agricultural processing plant.

Considering days of autonomy and depth of discharge (DOD), the systems required capacity in ampere-hours is found with the following equation;

$$\text{System capacity} = \frac{\text{Daily load in amp hours} \times \text{Days of autonomy}}{\text{DOD}}$$

For the daily load, the larger summer value of 100.625 Ah is chosen since the system must be capable to function throughout the year. While the chosen battery is rated for 100% DOD, 90% has been chosen to ensure a robust system in case of any unforeseen problems during operation. With the decided four days of autonomy, the required battery capacity is calculated:

$$\begin{aligned} \text{System capacity} &= \frac{100.625\ \text{Ah} \times 4\ \text{Days}}{90\%} \\ &= 447.22\ \text{Ah} \end{aligned}$$

The chosen battery must have a capacity of at least 447.22 Ah.

The discharge rate of the battery is equal to the system capacity (Ah) divided by the average system current. The average system current is the daily load (Wh) divided by the system voltage and the number of daily operating hours, assuming appliances run simultaneously. This gives an average current of 12.969 A, and consequently a discharge rate of 34.48 hours.

If the discharge rate is too fast due to high current demands or the DOD is exceeded by drawing too much power, the batteries may be damaged. This can result in reduced capacity in the long-term. However, the chosen Tesla batteries are rated for 14.3 A of continuous current, with an individual capacity of 270 Ah. This equates to a discharge rate of 18.881 hours, significantly shorter than the estimated discharge rate so this will not damage the batteries. Furthermore, as the Tesla  batteries are rated for 100% DOD, the only issue is if too much power is consumed as the use of the appliances would be interrupted. Long term damage to battery capacity is not expected to become an issue in the system design.

Battery capacity also reduces while operating at low temperatures. This has been adjusted for in the battery capacity calculations with a temperature derating factor of 0.85.

# 5. Estimation of PV Array

The solar insolation data is required to estimate the PV array size. This information was sourced from  the website “Renewables.ninja” (S. Pfenninger, I. Staffell, 2020) data is provided on an hourly basis for the specific location of the facility.

## 5.1 Array Tilt Angle

The first step required to estimate the sizing of the PV array, is to optimize the panel tilt angle. The ratio between the average global insolation per day and the daily load is considered.

The average global insolation per day includes both the direct and the diffuse component of radiation. It is taken as an average throughout the month. The calculation is performed using a pivot table in Excel that aggregates the hourly value in the monthly range.

The daily load is determined by the load assessment for the facility and is equal to 2.49 kWh/day for winter and 4.83 kWh/day during summer. Table 2 displays the results of the calculations performed:

*Table 2. Tilt angle estimation*

| Month [kWh/m^2] | DNI [kWh/m^2] | DHI [kWh/m^2] | Total [kWh/m^2] | Number of days | Avg daily global insolation [kWh/m^2] | Daily load [kWh/day] | Insolation/ Load |
|---|---|---|---|---|---|---|---|
| 1 | 99848 | 30640 | 130 | 31 | 4.21 | 2.49 | 1.69 |
| 2 | 102237 | 34858 | 137 | 28 | 4.90 | 2.49 | 1.97 |
| 3 | 166067 | 33408 | 199 | 31 | 6.43 | 2.49 | 2.58 |
| 4 | 128016 | 73231 | 201 | 30 | 6.71 | 4.83 | 1.39 |
| 5 | 165168 | 74272 | 239 | 31 | 7.72 | 4.83 | 1.60 |
| 6 | 114361 | 91530 | 206 | 30 | 6.86 | 4.83 | 1.42 |
| 7 | 45613 | 103495 | 149 | 31 | 4.81 | 4.83 | 1.00 |
| 8 | 55143 | 102329 | 157 | 31 | 5.08 | 4.83 | 1.05 |
| 9 | 47388 | 81755 | 129 | 30 | 4.30 | 4.83 | 0.89 |
| 10 | 117595 | 43301 | 161 | 31 | 5.19 | 2.49 | 2.08 |
| 11 | 113321 | 26719 | 140 | 30 | 4.67 | 2.49 | 1.87 |
| 12 | 108404 | 21837 | 130 | 31 | 4.20 | 2.49 | 1.69 |

As highlighted in Table 2, September is calculated as the month with the worst insolation/load ratio. The 15th of september (258th day of the year) is used as the reference day for the optimization of the tilt angle.

The optimal tilt angle $\beta$ is calculated with the following procedure:

Declination angle ($\delta$)

$$\delta(d = 258) = 23.44 \cdot \sin\left((d - 81) \cdot \left(\frac{360}{365}\right)\right) = 2.25°$$

Altitude angle ($\alpha$)

$$\alpha = 90 - (\phi - \delta) = 64.78°$$

Tilt angle (□)

$$\beta = 90 - \alpha = 25.22°$$

## 5.2 Solar Insolation on the Panels

The global radiation ($G_B$) on the panel is calculated as the sum of the direct ($S_B$) and diffuse component ($D_B$) :

$$G_B = S_B + D_B$$

The direct component is calculated with the following:

$$S_B = DNI \cdot \left( \sin\delta \sin\Phi \cos\beta - [sign(\Phi)] \cdot \sin\delta \cos\Phi \sin\beta \cos\psi + \cos\delta \cos\Phi \cos\beta \cos HRA \right.$$
$$\left. + [sign(\Phi) \cos\delta \sin\Phi \sin\beta \cos\Psi \cos HRA + \cos\delta \sin\beta \sin\psi \sin HRA \right)$$

The diffuse component is found with:

$$D_B = \frac{D_H(180 - \beta)}{180}$$

$G_B$, $S_B$, and $D_B$ are all calculated on an hourly basis. They are then summed together over 24 hour periods to calculate the average daily global radiation each day of the year.

## 5.3 Ah Generated by the Array

Once the average global radiation is determined, the load generated by the PV array is calculated. As a general procedure, the peak array current must be estimated according to the rule of thumb:

$$Peak\ array\ current = 5 \cdot Load\ Current$$

Using the previous equation, the peak array current is estimated as 64.85 A. This value will be updated at the end of the array sizing procedure to meet the battery and system requirements.

The load generated is calculated as:

$$AH_{generated} = I_{peak} \cdot G_B \cdot (1 - \eta_{dust}) \cdot (1 - \eta_{mismatch}) \cdot (\eta_{battery}) \cdot \frac{C_{Pmax}}{100} (1 + (T - T_{std}))$$

The derating factors on the right hand side of the equation are considered:

- Dust factor ($\eta_{dust}$ = 5%)
- Manufacturing tolerance (0%)
- Mismatch losses ($\eta_{mismatch}$ = 2%)
- Battery efficiency ($\eta_{battery}$ = 85%)
- Temperature derating coefficient ($C_{p(max)}$ = -0.45%/°C.)
- Cell temperature ( $T$ = 45°C)
- Standard condition temperature ( $T_{std}$ =25°C)

The generated Ah by the array is updated when the value of peak current $I_{peak}$ is adjusted.

## 5.4 Ah Load

The daily load is calculated taking into account the cable losses and the battery's self discharge rate according to the equation:

$$AH\ load = \frac{Load \cdot 1000 \cdot \left(1 + \eta_{cable\ loss}\right)}{V} + Battery\ capacity \cdot \left(\frac{\eta_{self\ discharge}}{n\ days}\right)$$

The derating factor from the previous equation are estimated as following:
- Cable loss factor ($\eta_{cable\ loss}$ = 2.5%)
- Battery self discharge ($\eta_{self\ discharge}$ = 2%.)

## 5.5 Battery SOC

The battery's State Of Charge (SOC) is calculated based upon the energy generated and the energy consumed as following:

$$Battery\ SOC = \frac{Capacity\ at\ beginning\ of\ the\ day + Daily\ energy\ generated - Daily\ load}{Battery\ capacity}$$

It is assumed at the system start-up that the battery is fully charged (100% SOC).

The calculation of the aforementioned parameters has been completed with a time frame of 2 years to allow the battery to reach 100% after the winter period when the sun's contribution is at its minimum. The battery can be discharged up to 100% (Tesla, 2016). As the battery DOD is assumed to be 90% to provide a safety factor, the required minimum SOC is 10%. To make sure the SOC of the battery doesn't fall below the minimum limit, the PV array system must be sized accordingly. This is accomplished by optimizing the peak array current previously estimated. Microsoft Excel's Goal Seek function is applied to optimize the peak array current by setting the minimum SOC to 10%.
As a result, the optimized peak array current is estimated to be 52.86 A.

Once the peak array current is updated, the variation of the battery SOC over the two year modeling period is visualized as following:

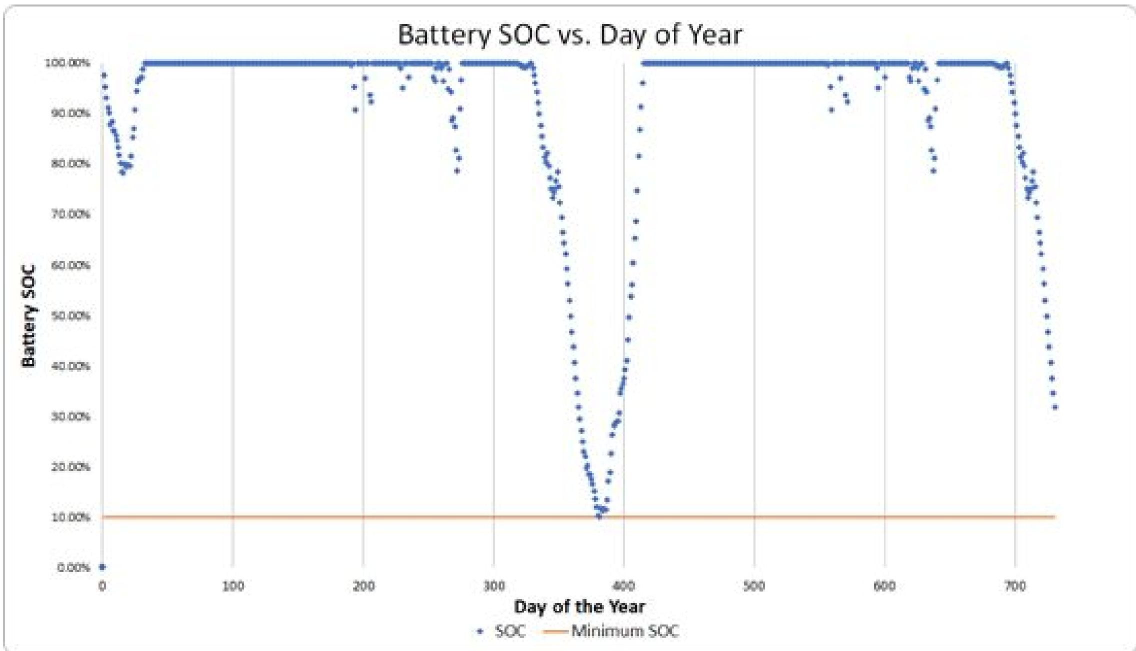


*Figure 1. Battery SOC*

In Figure 1., the minimum SOC never falls below 10%. The selection of the PV modules can now be pursued.

# 6. Selection of PV System Components

The PV system components including the PV module, battery and the battery charge controller are selected to meet the system requirements. These selections were justified on the basis of cost, reliability, availability and maintenance requirements. An DC/AC inverter is not required as the system only operates DC loads. The datasheets for each selected component are in Appendix B.

## 6.1 Batteries

The Tesla Powerwall 2 is deemed the most suitable battery for the system. It is marketed as a DC battery system for residential and light commercial use. As a rechargeable lithium-ion battery, it can provide energy storage for solar self-consumption, load shifting and backup power. Its compact design allows for high energy density and ease of installation.

A total of two Tesla Powerwall 2's connected in parallel meet the specific requirements of the system, including the:

- Maximum amp-hour load, which occurs in summer at 100.625 Ah/day,
- Battery capacity of at least 559.03 Ah, and
- Discharge rate of 34.48 hrs.

The Tesla batteries have a rated 10 year lifetime. 4 batteries are required during the 20 year project lifetime. Four Powerwall 2's cost $26,000, hence costing $1,300 per year.

The battery cost to meet the system requirements over the course of the project lifetime is compared to other batteries. Batteries considered are another lithium ion type, lead acid, carbon lead, and AGM. The Tesla Powerwall 2 is the most cost-effective battery to meet the requirements of our system.

*Table 3: Tesla Powerwall 2, Specifications (Tesla, 2016)*

| No. of Batteries Required | DC Voltage (V) | Efficiency (%) | Operating Temp. (℃) | Dimensions (mm) | Total Cost ($) |
|---|---|---|---|---|---|
| 4 | 50 | 91.8 | -20 to 50 | 1150 x 755 x 155 | 26,000 |

## 6.2 PV Modules

14 Hyperion Diamond modules by Phono Solar are selected for the system due to their competitive cost and efficiency while meeting the system requirements. They will be

connected in an array of 2 modules per string and 7 strings in parallel. To select the module type, the requirements of a system voltage ($V_{sys}$) of 48V and a peak current ($I_{peak}$) of 52.86A are considered.

Three modules were considered for the system: the Hyperion Diamond, the JAM60D09, and the JAM72D10. The total cost of implementation of each module model was calculated and compared for selection. To determine the total cost, each module was evaluated on the number of modules required using a standard PWM regulator and an MPPT regulator. The panels required for each regulator type were multiplied with the cost per module to determine the total cost of each module type and regulator type pair. Next, a module type was selected for the PWM and MPPT charge controller according to the cost to implement the modules alone.

The module types selected for the PWM and the MPPT regulators were used to determine the total cost of implementation for two PWM and three MPPT charge controller options. The most cost effective module-charge controller combination was selected for the system. The most cost effective combination of PV modules and a charge controller is the Hyperion Diamond modules paired with a PWM charge controller.

The Hyperion Diamond modules have a 25 year performance warranty to 80.7% efficiency, which easily meets the project lifetime of 20 years.

To determine the array layout when using a PWM charge controller, the following calculations were performed.

No. of panels in series = $V_{sys}/V_{mp}$ = 48/31.76 = 2

No. of panels in parallel = $I_{peak}$ * Oversupply Coefficient / $I_{mp}$ = 52.86*1.05/8.66 = 7

*Table 4: Hyperion Diamond by Phono Solar, Specifications (Sumec, 2020)*

| **No. of Modules Required** | **Rated Power (W)** | **Efficiency (%)** | **Operating Temp. (℃)** | **Dimensions (mm)** | **Total Cost ($)** |
|---|---|---|---|---|---|
| 14 | 275 | 80.7 | -40 to 85 | 1640 x 992 | 1420.44 |

## 6.3 Charge Controller

The East-Sun ESC series PWM Charge Controller was found to be the most cost-effective charge controller whilst also meeting the system requirements. The cost of the selected charge controller is $320.

Five different charge controllers were compared against their total cost to implement for selection. They included the East-Sun ESC (PWM), the Solar Talker (PWM), the Turbo Light (MPPT), the FLEXmax 60 (MPPT), and the BlueSolar 150/100 (MPPT). As previously stated, the most cost effective combination of PV modules and a charge controller is the Hyperion Diamond modules paired with a PWM charge controller.

A PWM charge controller operates within voltage and current rating specified by the manufacturer. The following calculations determined the required ratings if a PWM regulator was utilised:

Voltage Rating = $V_{oc(cell)}*(1+V_{derating(cell)}*(T_{min(cell)} - T_{STC})) = 42.12$ V

Current Rating = $I_{sc(cell)}*(1+I_{derating(cell)}*(T_{min(cell)} - T_{STC})) = 80.44$ A

The East Sun PWM Charge Controller has a 96 V rated voltage, a 120 A rated current, and a rated efficiency above 90%. It is suitable for the system, and in comparison to alternatives, the most cost effective charge controller. The working temperature range is between -20℃ and 50℃. This fits well within the minimum -1.706°C and maximum 29.977°C temperatures at the processing plant location in Nepal.

*Table 5: East-Sun ESC series PWM Charge Controller, Specifications (Focus Technology Co., 2020)*

| Rated DC Voltage (V) | Rated Current (A) | Efficiency (%) | Operating Temp. (℃) | Dimensions (mm) | Total Cost ($) |
|---|---|---|---|---|---|
| 96 | 120 | 90 | -20 to 50 | 370 x 330 x 195 | 320 |

# 7. System Layout

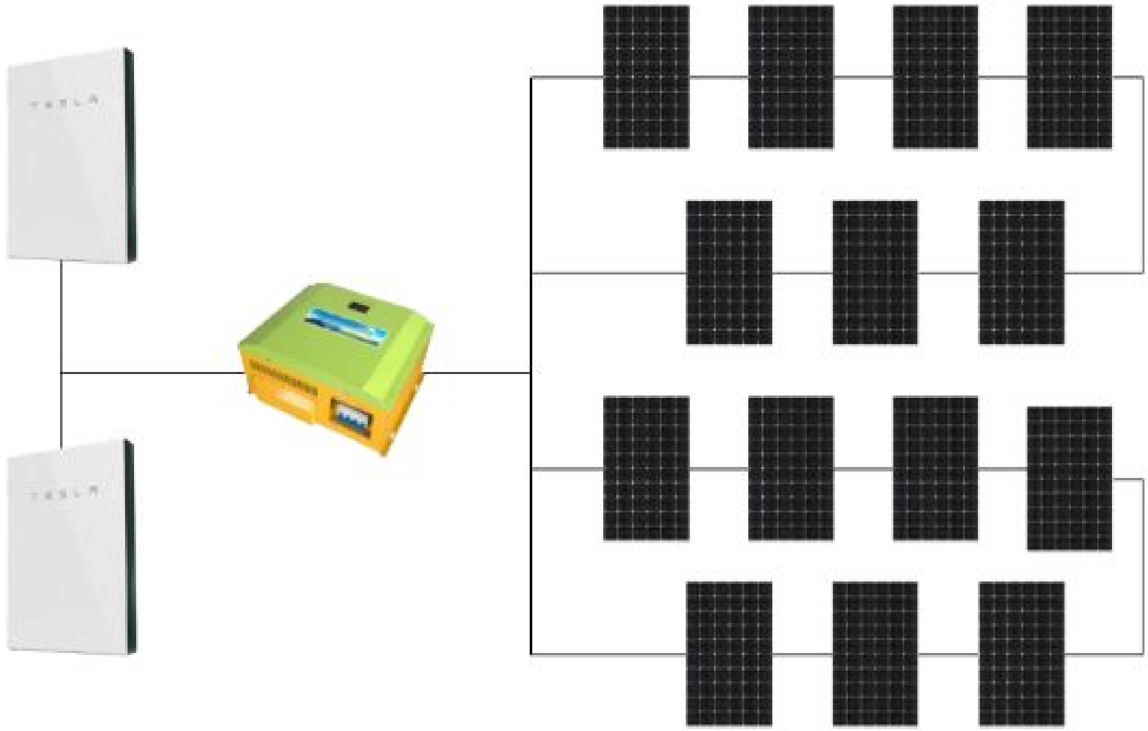

*Figure 2. System Layout*

# 8. Performance and Economic Analysis

## 8.1 Performance Ratio

The performance ratio (PR) is dependent on all inefficiencies in the stand-alone system. This includes losses due to high temperatures, modules, mismatch, soiling, and subsystems. Table 6 reports each factor, its loss, efficiency, and justification.

*Table 6: System Deratings and Inefficiencies*

| Factor | Loss factor | Efficiency | Justification |
|---|---|---|---|
| Temperature | 12.3% | 87.7% | Determined with the selected module power temperature derating (-0.41 %/°C) (Sumec, 2020), maximum operating temperature (54.98°C) (S. Pfenninger, 2020), and STC temperature (25 °C) |
| Module manufacturing | 19.3% | 80.7% | Determined with the performance warranty of the selected module (Sumec, 2020). |
| Mismatch | 0.4% | 99.6% | Based on an approximation for modeling PV systems (EcoSmart, 2019). |
| Soiling | 0.5% | 99.5% | Based on an approximation for modeling PV systems (EcoSmart, 2019). |
| Subsystems | 12.2% | 87.8% | Accounts for efficiency of the selected charge controller (90%) (Focus Technology Co., 2020) and the system wiring (97.5%) (Santosh 2020). |

The PR is the product of the efficiencies of the factors. It is calculated as 0.616.

## 8.2 Simple Payback Period

The capital costs of the PV system include the system components, the installation, and our company margin. They are displayed below in Table 7.

*Table 7: System costs*

| Item | Cost (USD) | Justification |
|---|---|---|
| Battery | $26,000.00 | Four Powerwall batteries are required through the 20 year lifetime of the system (Tesla, 2016). |
| Module | $1420.44 | Fourteen Hyperion |

| | | |
|---|---|---|
| | | Diamond modules are required in the system (Sumec, 2020). |
| Charge Controller | $320.00 | (Focus Technology Co., 2020) |
| Installation | $400.00 | System will take 20 hours to install, with a rate of $20/hr (Santosh ,2020) |
| Company Margin | $5570.77 | 20% profit of capital costs |
| Total | $33,768.53 | Sum of all system costs |

$4038.48 USD of government funding is subtracted from the capital costs. This aligns with the Nepal Renewable Energy Subsidy policy (Government of Nepal, 2018).

The maintenance cost of the system is due to regular cleaning of the PV panels. Our model assumes the system owner performs cleaning. Costs are for the cleaning brush ($300 USD) and soap ($30 USD) (HomeAdvisor, 2020). These costs are assumed over the project lifetime of 20 years to be $16.50 USD each year.

In comparison, if electricity comes from the local grid, it would cost $0.11 USD per kWh. An extra connection fee of $1.63 USD per month is added on. From Table 1, the energy consumed in summer and winter is 881.5 kWh and 454.4 kWh respectively. The total energy consumed over the course of a year is 1335.9 kWh. The following equation calculates the cost of electricity per year.

$$G = EC * 0.11 + 1.63 * 12$$

The cost of grid electricity per year (*G)* is $166.51 USD.

The simple payback period (*SPB*) is calculated using the following equation to be 198 years.

$$SPB = C/(G - M)$$

Where *C* is the capital costs of the system and *M* is the maintenance cost of the system per year.

## 8.3 Levelized Cost of Energy (LCOE)

### Energy Generation

To determine the system-generated energy per year, the solar data, array size, PR, and system degradation factor are used.

The global average determined during the PV Array Sizing for each day of the year is multiplied with the number of modules in the system and the area of each module. Daily values are summed together to determine the energy generated before any inefficiencies. To take into account the system inefficiencies, this sum is multiplied with the PR. Next, to determine the energy generated each year, the value is multiplied with a degradation factor of 1-0.5%**n* where *n* is the year. The system degradation rate is assumed to be 0.5% per year to account for changes in system performance over time not taken into account in the PR (B. Stahley, 2019).

Energy generation is reported in Table 8 below.

*Table 8: Energy generation during project lifetime*

| Year | Energy Generated |
|---|---|
| 1 | 13011.27 kWh |
| 2 | 12945.89 kWh |
| 3 | 12880.51 kWh |
| 4 | 12815.13 kWh |
| 5 | 12749.74 kWh |
| 6 | 12684.36 kWh |
| 7 | 12618.98 kWh |
| 8 | 12553.59 kWh |
| 9 | 12488.21 kWh |
| 10 | 12422.83 kWh |
| 11 | 12357.44 kWh |
| 12 | 12292.06 kWh |
| 13 | 12226.68 kWh |
| 14 | 12161.29 kWh |
| 15 | 12095.91 kWh |
| 16 | 12030.53 kWh |
| 17 | 11965.14 kWh |
| 18 | 11899.76 kWh |
| 19 | 11834.38 kWh |
| 20 | 11768.99 kWh |
| **Total** | **247802.71 kWh** |

## Discounted Operation & Maintenance Costs

The cleaning fee of $16.50 USD per year is discounted at a rate of 6.9% (Trading Economics, 2020). The discounted cost of maintenance (*DO&M*) in year *n* is determined with the following equation.

$$\frac{DF_{n-1}}{1+f} * 16.50 = DO\&M$$

Yearly costs are reported in Table 9.

*Table 9: Yearly Maintenance Costs*

| Year | Maintenance Cost |
|---|---|
| 1 | $15.64 USD |
| 2 | $14.44 USD |
| 3 | $13.51 USD |
| 4 | $12.63 USD |
| 5 | $11.82 USD |
| 6 | $11.06 USD |
| 7 | $10.34 USD |
| 8 | $9.68 USD |
| 9 | $9.05 USD |
| 10 | $8.47 USD |
| 11 | $7.92 USD |
| 12 | $7.41 USD |
| 13 | $6.93 USD |
| 14 | $6.48 USD |
| 15 | $6.06 USD |
| 16 | $5.67 USD |
| 17 | $5.31 USD |
| 18 | $4.96 USD |
| 19 | $4.64 USD |
| 20 | $4.34 USD |
| **Total** | **$176.17 USD** |

### LCOE Calculation

The LCOE is calculated using the following equation.

$$\frac{C+DO\&M}{EG} = LCOE$$

Where *EG* is the energy generated over the lifetime of the project (Table 8).
If the government subsidy is used to offset the capital cost, the LCOE is $0.12 USD per kWh. Without the funding, the LCOE is $0.14 USD per kWh.

The cost of electricity from the grid is estimated to be $0.12 USD per kWh including the monthly connection fee (at the system's average monthly load). The system's LCOE including the subsidy is comparable to grid electricity. Without government funding, the LCOE is too high to deem the PV system economically competitive.

# 9. Conclusion

The stand-alone PV array will reliably power the agricultural processing plant for the twenty year project lifetime. The system is designed to supply the facility's demand without

withdrawing electricity from the grid. The system components must be sized in such a way that the demand is covered at all times without any cut-offs.
The components consist of 2 Tesla Powerwall batteries wired in parallel, an East-Sun ESC series MPPT charge controller, and 14 Hyperion Diamond Modules connected in an array of 7 modules per string, 2 strings in parallel. This results in a total capital cost of $33,768.53 including the system components, installation, and the company margin. The cleaning and maintenance of the system will cost $16.50 per year. The system provides energy at a LCOE of $0.12 USD per kWh.This is comparable to the local grid energy cost and is therefore a viable approach. As the local grid connection is unreliable and the grid connection infrastructure would be costly due to the remote location, the stand-alone PV array is a reasonable alternative. However, the PV system's payback period is 198 years. Therefore alternative options and/or additional funding may need to be considered. A lower payback time could be achieved if the system was running under different circumstances. For instance, if the local grid electricity was more expensive, the system would lead to higher savings, resulting in lower payback time. Although the work presented highlights the cost barrier to renewable energy, it has value as it outlines the viability of renewable energy as a reliable power source.

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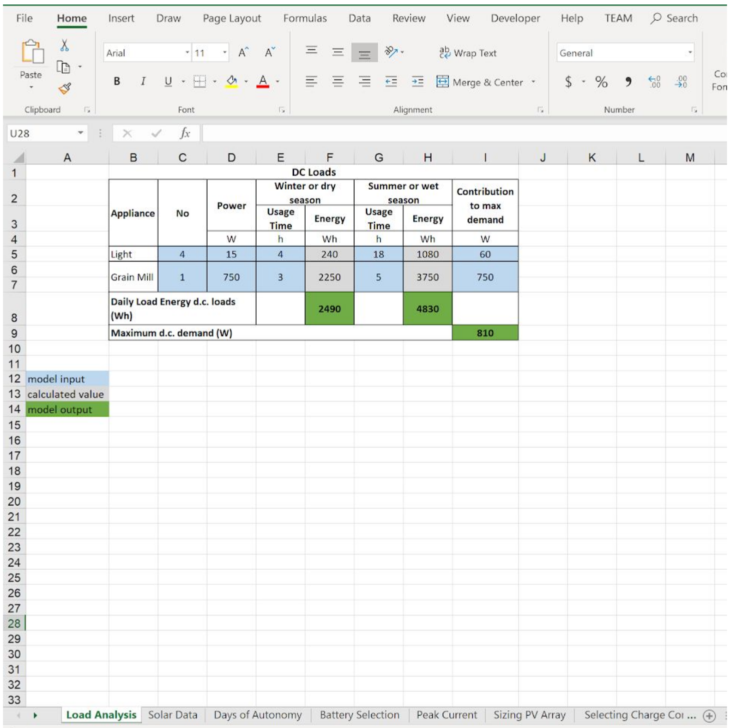
# Appendix A: Excel PV System Design Tool Description

Excel was utilized to design the PV system to the load requirements and available solar energy. Below is a description of how the software is designed for easy user input to determine optimized stand-alone PV system designs.

The first sheet contains the load analysis:



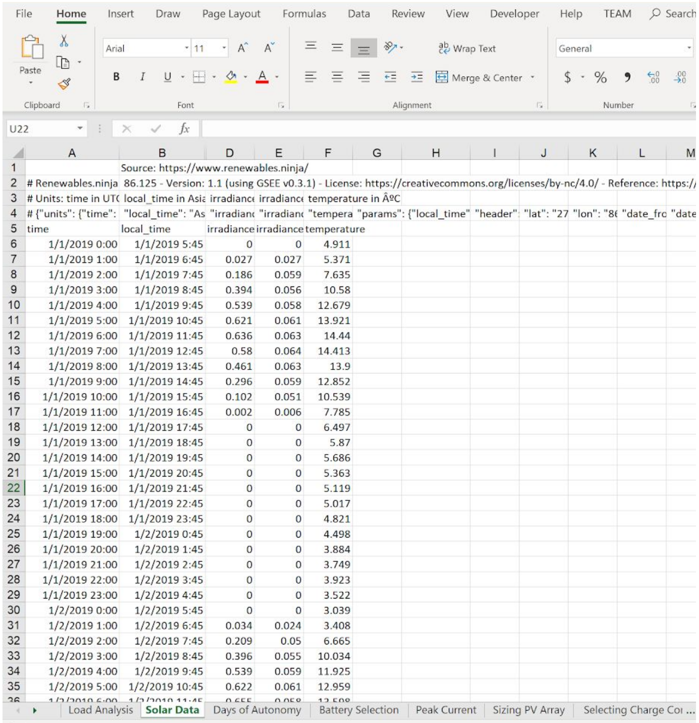
| DC Loads | | | | | | | |
|---|---|---|---|---|---|---|---|
| Appliance | No | Power | Winter or dry season | | Summer or wet season | | Contribution to max demand |
| | | | Usage Time | Energy | Usage Time | Energy | |
| | | W | h | Wh | h | Wh | W |
| Light | 4 | 15 | 4 | 240 | 18 | 1080 | 60 |
| Grain Mill | 1 | 750 | 3 | 2250 | 5 | 3750 | 750 |
| Daily Load Energy d.c. loads (Wh) | | | | 2490 | | 4830 | |
| Maximum d.c. demand (W) | | | | | | | 810 |

model input
calculated value
model output



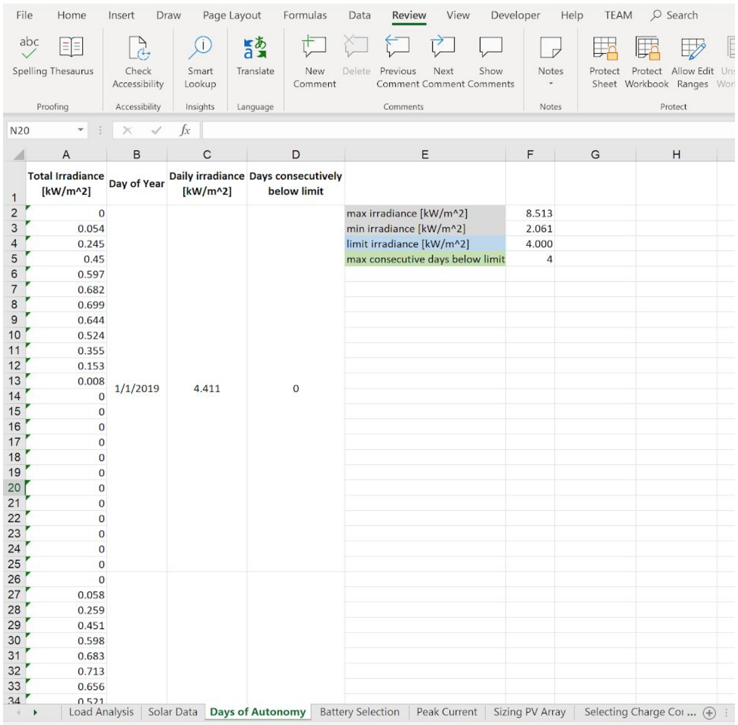
Throughout the model, user inputs are highlighted in blue. Grey and green highlighted cells are calculated values and model outputs respectively.

The second sheet allows the user to input 1 year of hourly solar data:



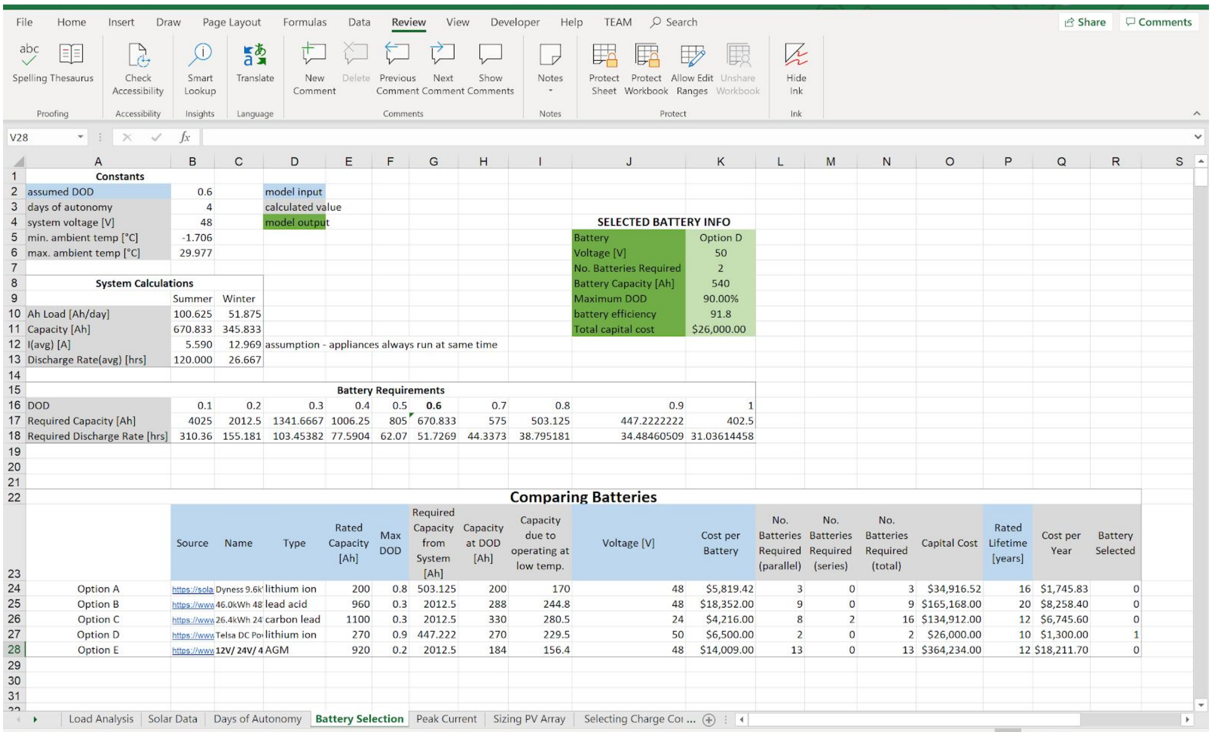
| | A | B | D | E | F |
|---|---|---|---|---|---|
| 1 | | Source: https://www.renewables.ninja/ | | | |
| 2 | # Renewables.ninja | 86.125 - Version: 1.1 (using GSEE v0.3.1) - License: https://creativecommons.org/licenses/by-nc/4.0/ - Reference: https:/ | | | |
| 3 | # Units: time in UTC | local_time in Asia | irradiance | irradiance | temperature in ÂºC |
| 4 | # {"units": {"time": | "local_time": "As | "irradianc | "irradianc | "tempera |
| 5 | time | local_time | irradiance | irradiance | temperature |
| 6 | 1/1/2019 0:00 | 1/1/2019 5:45 | 0 | 0 | 4.911 |
| 7 | 1/1/2019 1:00 | 1/1/2019 6:45 | 0.027 | 0.027 | 5.371 |
| 8 | 1/1/2019 2:00 | 1/1/2019 7:45 | 0.186 | 0.059 | 7.635 |
| 9 | 1/1/2019 3:00 | 1/1/2019 8:45 | 0.394 | 0.056 | 10.58 |
| 10 | 1/1/2019 4:00 | 1/1/2019 9:45 | 0.539 | 0.058 | 12.679 |
| 11 | 1/1/2019 5:00 | 1/1/2019 10:45 | 0.621 | 0.061 | 13.921 |
| 12 | 1/1/2019 6:00 | 1/1/2019 11:45 | 0.636 | 0.063 | 14.44 |
| 13 | 1/1/2019 7:00 | 1/1/2019 12:45 | 0.58 | 0.064 | 14.413 |
| 14 | 1/1/2019 8:00 | 1/1/2019 13:45 | 0.461 | 0.063 | 13.9 |
| 15 | 1/1/2019 9:00 | 1/1/2019 14:45 | 0.296 | 0.059 | 12.852 |
| 16 | 1/1/2019 10:00 | 1/1/2019 15:45 | 0.102 | 0.051 | 10.539 |
| 17 | 1/1/2019 11:00 | 1/1/2019 16:45 | 0.002 | 0.006 | 7.785 |
| 18 | 1/1/2019 12:00 | 1/1/2019 17:45 | 0 | 0 | 6.497 |
| 19 | 1/1/2019 13:00 | 1/1/2019 18:45 | 0 | 0 | 5.87 |
| 20 | 1/1/2019 14:00 | 1/1/2019 19:45 | 0 | 0 | 5.686 |
| 21 | 1/1/2019 15:00 | 1/1/2019 20:45 | 0 | 0 | 5.363 |
| 22 | 1/1/2019 16:00 | 1/1/2019 21:45 | 0 | 0 | 5.119 |
| 23 | 1/1/2019 17:00 | 1/1/2019 22:45 | 0 | 0 | 5.017 |
| 24 | 1/1/2019 18:00 | 1/1/2019 23:45 | 0 | 0 | 4.821 |
| 25 | 1/1/2019 19:00 | 1/2/2019 0:45 | 0 | 0 | 4.498 |
| 26 | 1/1/2019 20:00 | 1/2/2019 1:45 | 0 | 0 | 3.884 |
| 27 | 1/1/2019 21:00 | 1/2/2019 2:45 | 0 | 0 | 3.749 |
| 28 | 1/1/2019 22:00 | 1/2/2019 3:45 | 0 | 0 | 3.923 |
| 29 | 1/1/2019 23:00 | 1/2/2019 4:45 | 0 | 0 | 3.522 |
| 30 | 1/2/2019 0:00 | 1/2/2019 5:45 | 0 | 0 | 3.039 |
| 31 | 1/2/2019 1:00 | 1/2/2019 6:45 | 0.034 | 0.024 | 3.408 |
| 32 | 1/2/2019 2:00 | 1/2/2019 7:45 | 0.209 | 0.05 | 6.665 |
| 33 | 1/2/2019 3:00 | 1/2/2019 8:45 | 0.396 | 0.055 | 10.034 |
| 34 | 1/2/2019 4:00 | 1/2/2019 9:45 | 0.539 | 0.059 | 11.925 |
| 35 | 1/2/2019 5:00 | 1/2/2019 10:45 | 0.622 | 0.061 | 12.959 |

In the third sheet, the days of autonomy are determined:



| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | Total Irradiance [kW/m^2] | Day of Year | Daily irradiance [kW/m^2] | Days consecutively below limit | | |
| 2 | 0 | | | | max irradiance [kW/m^2] | 8.513 |
| 3 | 0.054 | | | | min irradiance [kW/m^2] | 2.061 |
| 4 | 0.245 | | | | limit irradiance [kW/m^2] | 4.000 |
| 5 | 0.45 | | | | max consecutive days below limit | 4 |
| 6 | 0.597 | | | | | |
| 7 | 0.682 | | | | | |
| 8 | 0.699 | | | | | |
| 9 | 0.644 | | | | | |
| 10 | 0.524 | | | | | |
| 11 | 0.355 | | | | | |
| 12 | 0.153 | | | | | |
| 13 | 0.008 | 1/1/2019 | 4.411 | 0 | | |
| 14 | 0 | | | | | |
| 15 | 0 | | | | | |
| 16 | 0 | | | | | |
| 17 | 0 | | | | | |
| 18 | 0 | | | | | |
| 19 | 0 | | | | | |
| 20 | 0 | | | | | |
| 21 | 0 | | | | | |
| 22 | 0 | | | | | |
| 23 | 0 | | | | | |
| 24 | 0 | | | | | |
| 25 | 0 | | | | | |
| 26 | 0 | | | | | |
| 27 | 0.058 | | | | | |
| 28 | 0.259 | | | | | |
| 29 | 0.451 | | | | | |
| 30 | 0.598 | | | | | |
| 31 | 0.683 | | | | | |
| 32 | 0.713 | | | | | |
| 33 | 0.656 | | | | | |

The battery selection sheet allows users to compare up to five different batteries for their system design:



| Constants | |
|---|---|
| assumed DOD | 0.6 |
| days of autonomy | 4 |
| system voltage [V] | 48 |
| min. ambient temp [°C] | -1.706 |
| max. ambient temp [°C] | 29.977 |

model input
calculated value
model output

| SELECTED BATTERY INFO | |
|---|---|
| Battery | Option D |
| Voltage [V] | 50 |
| No. Batteries Required | 2 |
| Battery Capacity [Ah] | 540 |
| Maximum DOD | 90.00% |
| battery efficiency | 91.8 |
| Total capital cost | $26,000.00 |

| System Calculations | Summer | Winter |
|---|---|---|
| Ah Load [Ah/day] | 100.625 | 51.875 |
| Capacity [Ah] | 670.833 | 345.833 |
| I(avg) [A] | 5.590 | 12.969 |
| Discharge Rate(avg) [hrs] | 120.000 | 26.667 |

assumption - appliances always run at same time

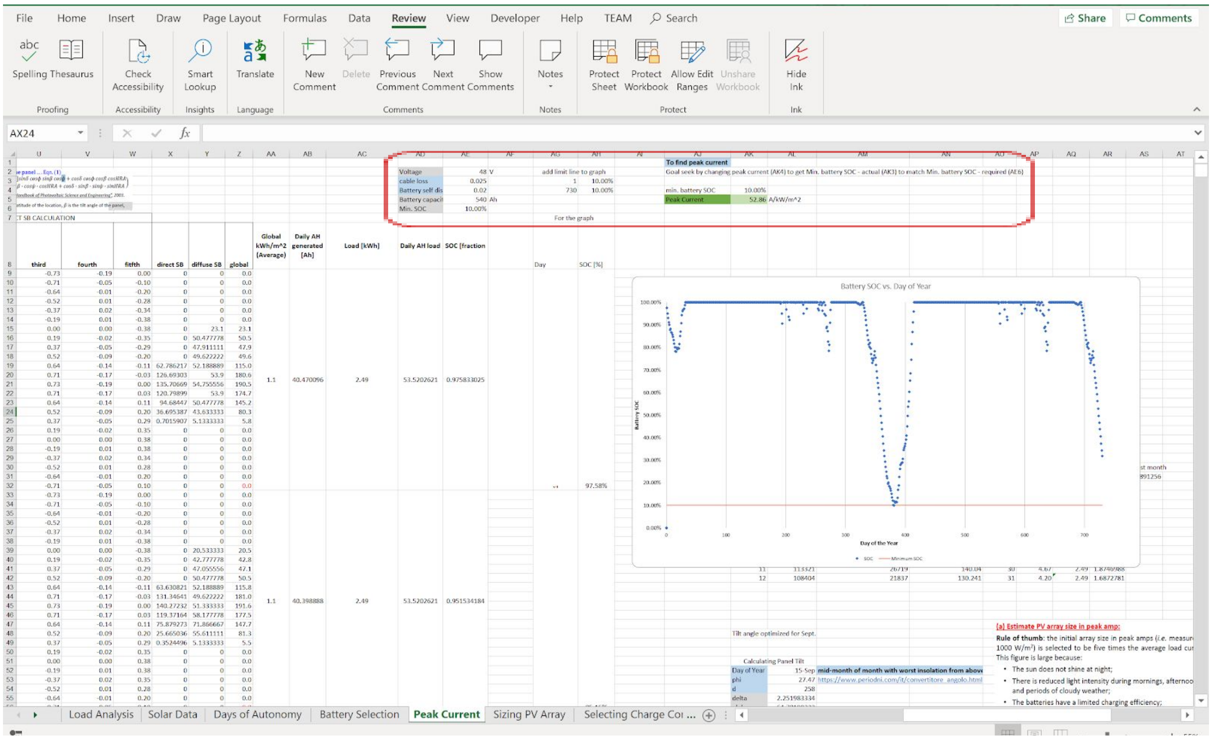
| Battery Requirements | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| DOD | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | **0.6** | 0.7 | 0.8 | 0.9 | 1 |
| Required Capacity [Ah] | 4025 | 2012.5 | 1341.6667 | 1006.25 | 805 | 670.833 | 575 | 503.125 | 447.2222222 | 402.5 |
| Required Discharge Rate [hrs] | 310.36 | 155.181 | 103.45382 | 77.5904 | 62.07 | 51.7269 | 44.3373 | 38.795181 | 34.48460509 | 31.03614458 |

**Comparing Batteries**

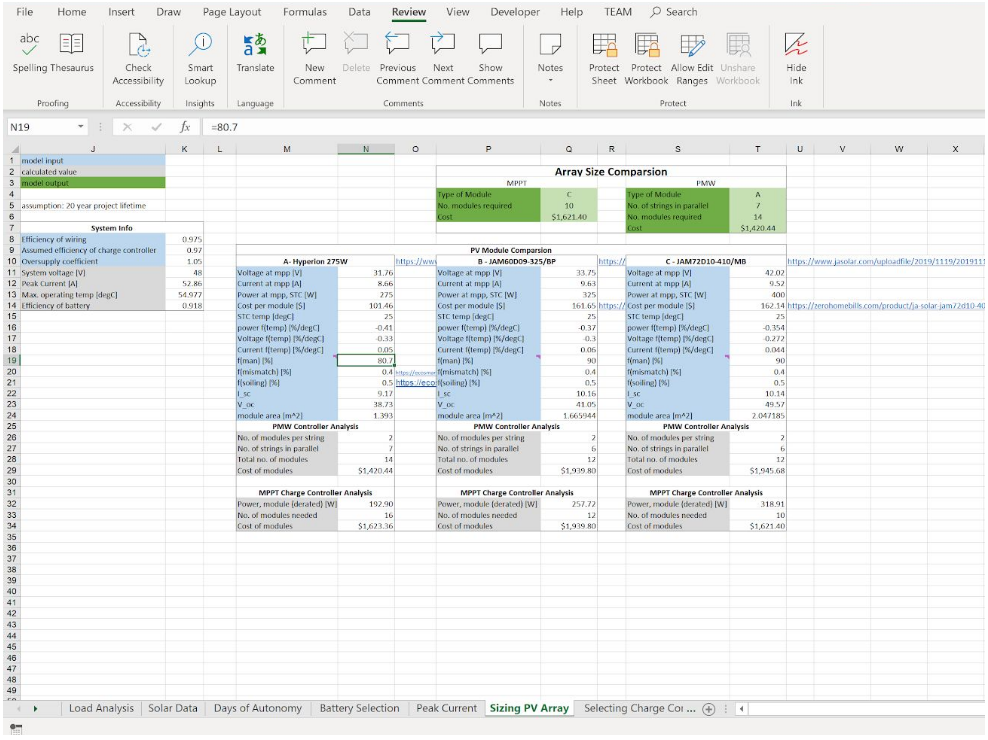
| | Source | Name | Type | Rated Capacity [Ah] | Max DOD | Required Capacity from System [Ah] | Capacity at DOD [Ah] | Capacity due to operating at low temp. | Voltage [V] | Cost per Battery | No. Batteries Required (parallel) | No. Batteries Required (series) | No. Batteries Required (total) | Capital Cost | Rated Lifetime [years] | Cost per Year | Battery Selected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Option A | https://sola | Dyness 9.6k | lithium ion | 200 | 0.8 | 503.125 | 200 | 170 | 48 | $5,819.42 | 3 | 0 | 3 | $34,916.52 | 16 | $1,745.83 | 0 |
| Option B | https://www | 46.0kWh 48 | lead acid | 960 | 0.3 | 2012.5 | 288 | 244.8 | 48 | $18,352.00 | 9 | 0 | 9 | $165,168.00 | 20 | $8,258.40 | 0 |
| Option C | https://www | 26.4kWh 24 | carbon lead | 1100 | 0.3 | 2012.5 | 330 | 280.5 | 24 | $4,216.00 | 8 | 2 | 16 | $134,912.00 | 12 | $6,745.60 | 0 |
| Option D | https://www | Telsa DC Po | lithium ion | 270 | 0.9 | 447.222 | 270 | 229.5 | 50 | $6,500.00 | 2 | 0 | 2 | $26,000.00 | 10 | $1,300.00 | 1 |
| Option E | https://www | 12V/ 24V/ 4 | AGM | 920 | 0.2 | 2012.5 | 184 | 156.4 | 48 | $14,009.00 | 13 | 0 | 13 | $364,234.00 | 12 | $18,211.70 | 0 |

If the user chooses to import new solar data, the optimized tilt angle will need to be recalculated using a pivot table in the Peak Current sheet as described earlier in the report.

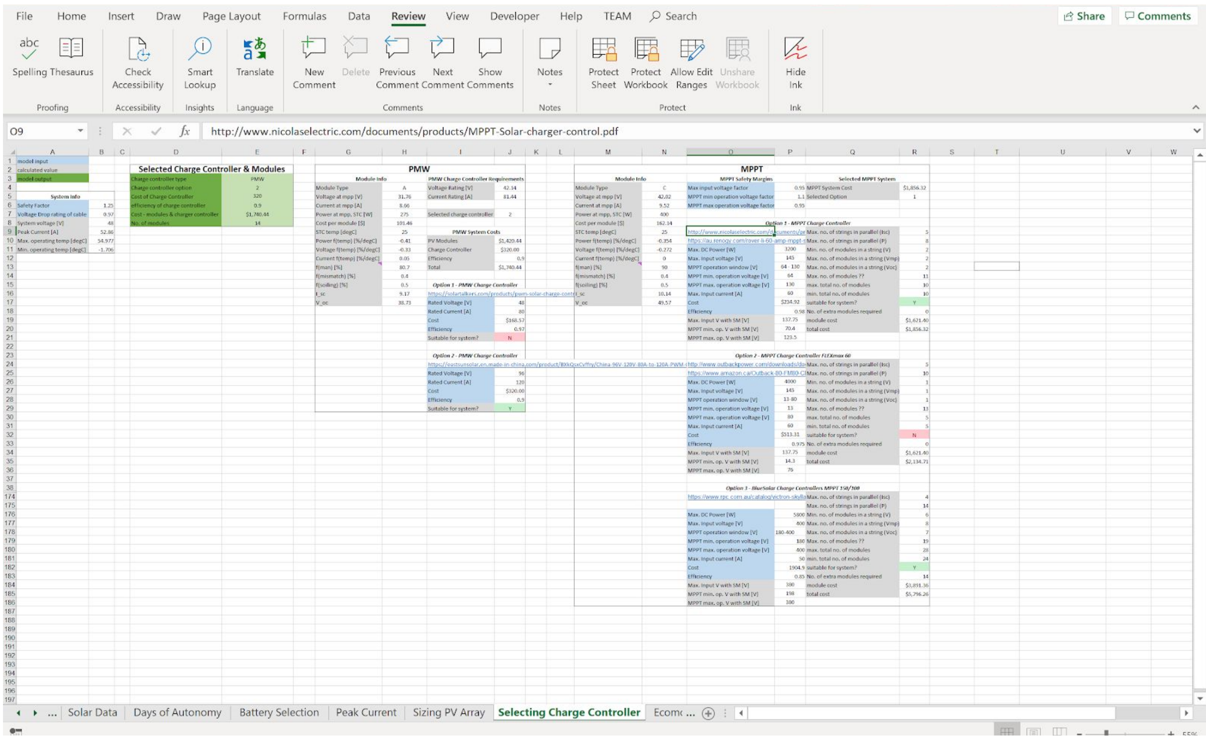
The optimized peak array for the system is not automatically calculated by Excel. Users apply the Goal Seek function as highlighted in the red square in the screenshot below. The graph will update and the user can verify the battery’s SOC does not drop below the minimum SOC requirement.



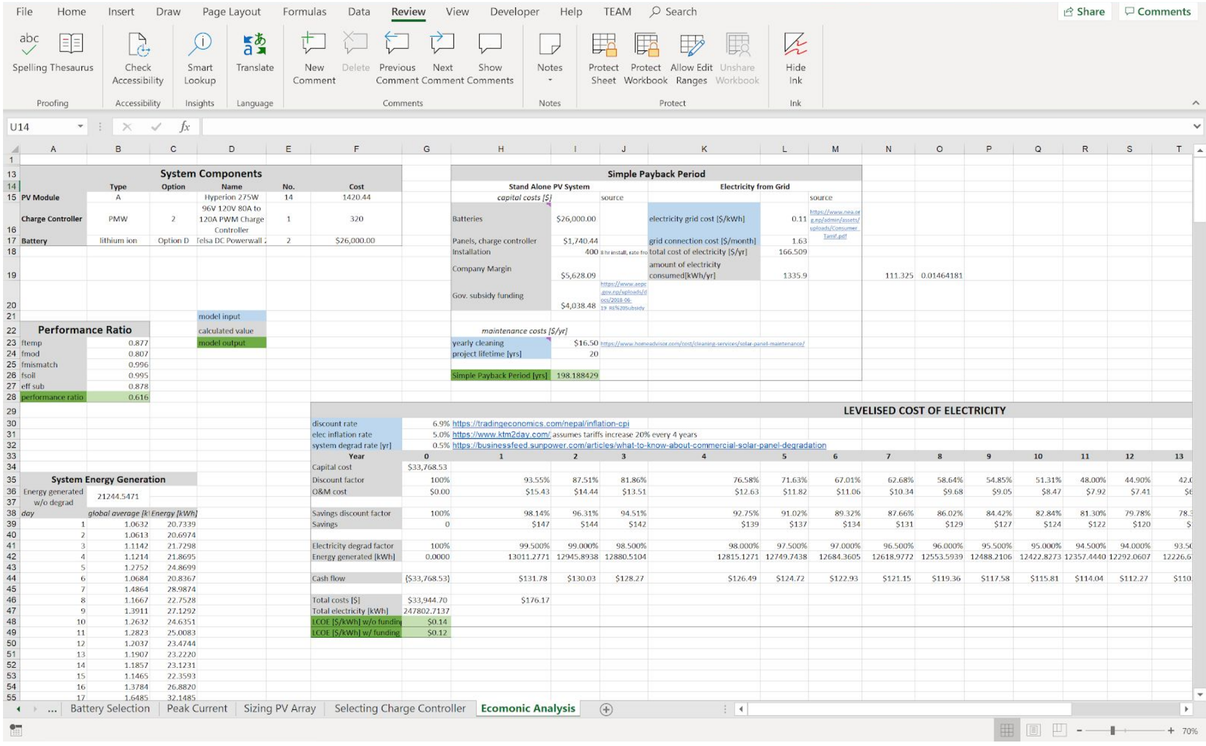
Inputs for up to three types of PV modules are entered for comparison in the sixth sheet.




Up to two models of PWM and three models of MPPT charge controllers can be compared on the seventh sheet. The Excel program is designed to check if the charge controllers meet the system requirements.



Finally, the model performs the economic calculations according to the selected system components. It reports the PR, the SPB, and the LCOE:



# Appendix B: PV System Components Datasheets


## POWERWALL 2 DC

The Tesla Powerwall is a DC battery system for residential or light commercial use. Its rechargeable lithium-ion battery pack provides energy storage for solar self-consumption, load shifting and backup power.

Powerwall's electrical interface is provided by an internal isolated bi-directional DC/DC converter that controls the charge and discharge of the battery for integration with grid-tied solar inverters. Its revolutionary compact design achieves market-leading energy density and is easy to install, enabling owners to quickly realize the benefits of reliable, clean power.

### PERFORMANCE SPECIFICATIONS

| | |
|---|---|
| DC Energy[1] | 13.5 kWh |
| Power, continuous | 5 kW (charge and discharge) |
| Power, peak (10 s) | 7 kW (discharge only) |
| DC Voltage Range | 350–550 V |
| DC Current, continuous | 14.3 A |
| DC Current, peak (10 s) | 20 A |
| Depth of Discharge | 100% |
| Internal Battery DC Voltage | 50 V |
| Round Trip Efficiency[1,2] | 91.8% |
| Warranty | 10 years |

[1] Values provided for 25°C (77°F), 3.3 kW charge/discharge power.
[2] DC to battery to DC, at beginning of life.

### INTERFACE SPECIFICATIONS

| | |
|---|---|
| Communication Protocols | Modbus (RS485), CAN |
| Modularity | Multi-Powerwall capability with compatible inverters |
| User Interface | Tesla App |

### ENVIRONMENTAL SPECIFICATIONS

| | |
|---|---|
| Operating Temperature | –20°C to 50°C (–4°F to 122°F) |
| Storage Temperature | –30°C to 60°C (–22°F to 140°F) |
| Operating Humidity (RH) | Up to 100%, condensing |
| Maximum Altitude | 3000 m (9843 ft) |
| Environment | Indoor and outdoor rated |
| Enclosure Type | NEMA 3R |
| Ingress Rating | IP67 (Battery & Power Electronics)<br>IP56 (Wiring) |
| Noise Level @ 1m | <40 dBA at 30°C (86°F) |

### MECHANICAL SPECIFICATIONS

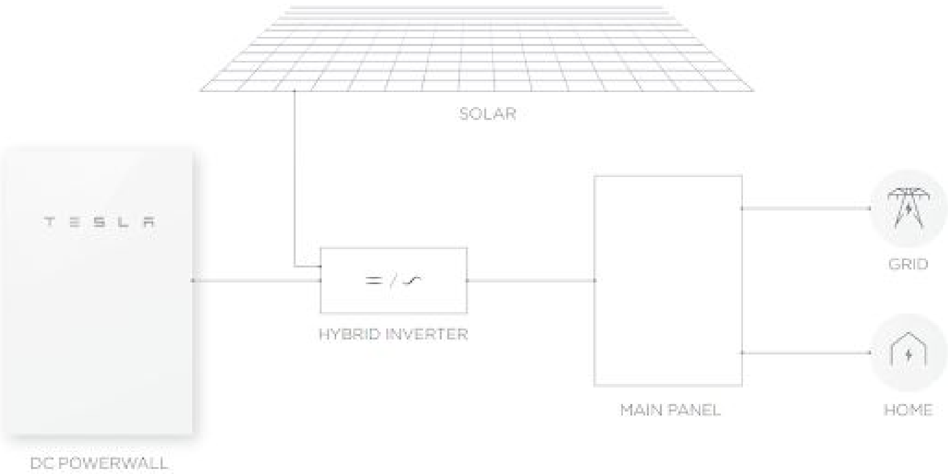
| | |
|---|---|
| Dimensions | 1150 mm x 755 mm x 155 mm (45.3 in x 29.7 in x 6.1 in) |
| Weight | 120 kg (264.5 lbs) |
| Mounting options | Floor or wall mount |

### COMPLIANCE INFORMATION

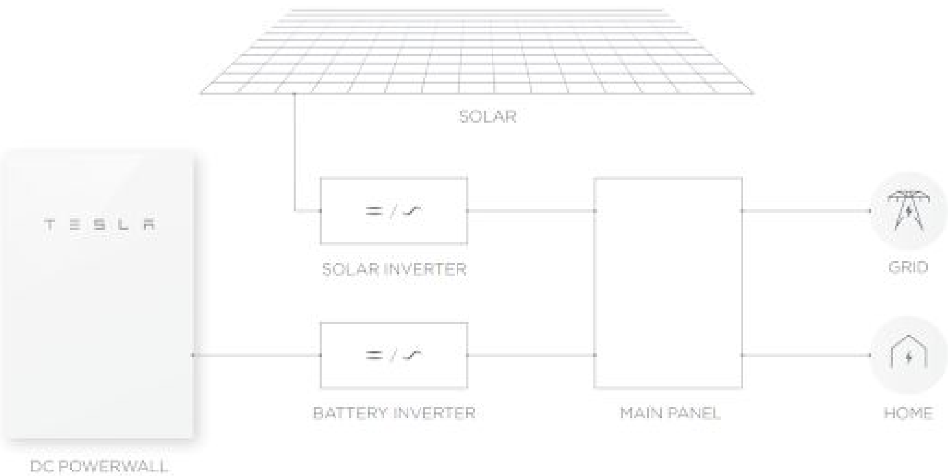
| | |
|---|---|
| Safety | UL 1642, UL 1741, UL 1973, UL 9540, UN 38.3, IEC 62109-1, IEC 62619, CSA C22.2.107.1 |
| Emissions | FCC Part 15 Class B, ICES 003, EN 61000 Class B |
| Environmental | RoHS Directive 2011/65/EU, WEEE Directive 2012/19/EU, 2006/66/EC |
| Seismic | AC156, IEEE 693-2005 (high) |

# TYPICAL SYSTEM LAYOUTS

## DC-COUPLED POWERWALL SYSTEM WITH SOLAR




## AC-COUPLED POWERWALL SYSTEM WITH SOLAR




SUMEC
Phono Solar
AUSTRALIA
15 YEAR DIAMOND DEALER PRODUCT WARRANTY
275W
HIGH PERFORMANCE POLYCRYSTALLINE MODULE
HYPERION™ DIAMOND
Hyperion Diamond Cells absorb more sunlight!
4 C'S OF HYPERION DIAMOND TECHNOLOGY
1. CELL - Hyperion™ Nano Structure Rebuilding (NSR) Technology
2. CUT - Latest diamond cell cutting technology
3. COLOUR - Consistent dark blue cell colouration
4. CONSISTENCY - Hyperion™ manufactured in Phono Solar's own 2.5GW cell facility
Standard Polycrystalline
Hyperion™ Inverted Pyramid
Hyperion™ Diamond
CAPTURING MORE SUN
TIER 1 Bloomberg
BLOOMBERG TIER 1 BRAND
OWNED BY FORTUNE 500 GLOBAL COMPANY
DNV·GL
TOP PERFORMING PANEL
AUSTRALIAN OFFICE AND REPRESENTATION
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Phono Solar
AUSTRALIA
BLUE™ CHIP Solar Panel
SUMEC PHONO SOLAR AUSTRALIA
Level 35, Tower One, 100 Barangaroo Ave, Sydney, AUSTRALIA
TEL: 02 8114 4516 www.phonosolar.com.au
PHONO SOLAR INTERNATIONAL (SUMEC)
No. 1 Xinghuo Rd., Nanjing Hi-tech Zone, Nanjing, CHINA
www.phonosolar.com
• 15-year product warranty
• 25-year linear performance warranty to 80.7 %
1. In compliance with our warranty terms and conditions.
NOTE: This datasheet is not legally binding. Phono Solar reserves the right to make specifications changes without notice. Further information can be found on our website: www.phonosolar.com

SUMEC Phono Solar AUSTRALIA

15 YEAR DIAMOND DEALER PRODUCT WARRANTY

BLUE CHIP Solar Panel

# Hyperion™ Diamond Module

**275W**

## ELECTRICAL TYPICAL VALUES

| Model | PS275P-20/U<br>PS275PH-20/U |
|---|---|
| Type | 60 x Polycrystalline, 6 inch x 6 inch cells |
| Rated Power (Pmpp)[2] | **275W** |
| Tolerance | 0~+5 |
| Rated Current (Impp) | 8.66 |
| Rated Voltage (Vmpp) | 31.76 |
| Short Circuit Current (Isc) | 9.17 |
| Open Circuit Voltage (Voc) | 38.73 |
| Module Efficiency (%) | 16.90 |
| NOCT (Nominal Operating Cell Temperature) | 45°C ± 2°C |
| Voltage Temperature Coefficient | -0.33%/°C |
| Current Temperature Coefficient | +0.05%/°C |
| Power Temperature Coefficient | -0.41%/°C |

## MECHANICAL CHARACTERISTICS

| | |
|---|---|
| Dimensions | Length: 1640mm, Width: 992mm<br>Height: 35mm |
| Weight | 18kg |
| Front Glass | 3.2mm toughened glass |
| Frame | Anodized aluminium alloy |
| Cable | 4mm2 (IEC), 900mm |
| Junction Box | IP 68 rated |
| Connectors | MC4 (1000Vdc) / EVO2 (1500Vdc) |

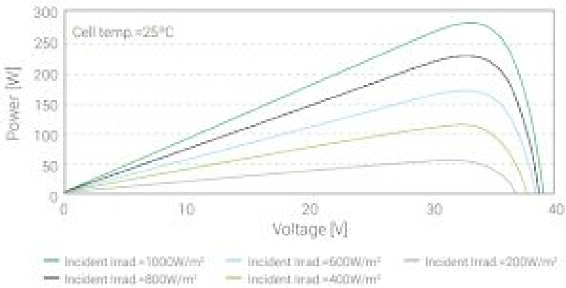
## PACKING CONFIGURATION

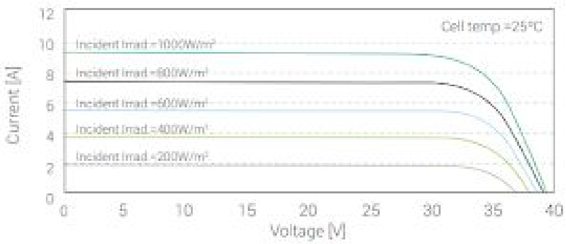
| Container | 20'GP | 40' HQ |
|---|---|---|
| Pieces per container | 312 | 896 |

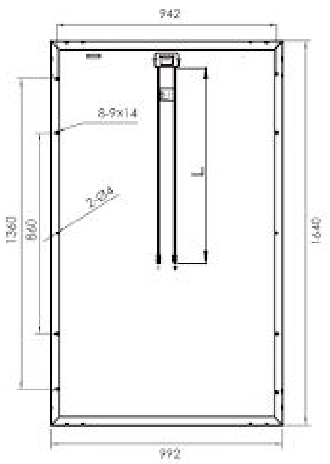
## ABSOLUTE MAXIMUM RATING

| Parameter | Values |
|---|---|
| Operating Temperature | From -40 to +85°C |
| Hail Diameter @ 80km/h | Up to 25mm |
| Surface Maximum Load Capacity | Up to 5400Pa |
| Maximum Series Fuse Rating | 20A |
| Application Class & Safety Class | II |
| Fire Rating (IEC61730) | C |
| Module Fire Performance (UL1703) | Type 1 |
| Maximum System Voltage | DC 1000V/1500V<br>(IEC/ETL) |

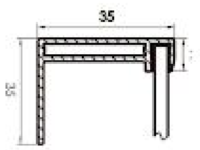
## WEAK LIGHT PERFORMANCE




[2] Measurement conditions under irradiance level of Standard Test Conditions (STC): Rated Power (Pmpp), 1000W/m2, Air mass 1.5 Spectrum, cell temperature of 25°C.




Note: mm

SUMEC Phono Solar AUSTRALIA

15 YEAR DIAMOND DEALER PRODUCT WARRANTY

BLUE CHIP Solar Panel

SCAN CODE TO WATCH VIDEO

Sumec Phono Solar modules are proudly manufactured in China

Basic Info | **Product Description** | Customer Question & Answer

ESC series solar Charge Controller is designed for PV off-grid power generation system, it can control the charge and discharge of multichannel solar array phalanx. It automatically control solar array phalanx connected or disconnected on the basis of the pulse width according to the changes of the battery voltage. It tracks PV array to deliver the available current for charging batteries. When charging, the controller regulates battery voltage and output current based on the amount of energy available from the PV array and state-of-charge of the battery.

1. High efficiency PWM charging technology.
2. LED display make running status at a glance.
3. Simple structure, function stable and reliable.
4. It controls multiple solar battery array charging and discharging function.
5. Protection: overcharge, short circuit, over discharge, connection reverse.

| 12VDC-48VDC | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Model | 12V 30A | 12V 40A | 12V 50A | 12V 60A | 12V 70A | 24V 30A | 24V 40A | 24V 50A | 24V 60A | 24V 70A | 48V 30A | 48V 40A | 48V 50A | 48V 60A | 48V 70A |
| Rated charging current(A) | 30 | 40 | 50 | 60 | 70 | 30 | 40 | 50 | 60 | 70 | 30 | 40 | 50 | 60 | 70 |
| Numbers of batteries(pieces) | 1 | | | | | 2 | | | | | 4 | | | | |
| Rated DC voltage(V) | 12 | | | | | 24 | | | | | 48 | | | | |
| Overcharge protected voltage(V) | 15 | | | | | 30 | | | | | 60 | | | | |
| Overcharge of recovered voltage(V) | 13.7 | | | | | 28 | | | | | 55 | | | | |
| Floating voltage(V) | 13.7 | | | | | 27 | | | | | 54 | | | | |
| Solar maximum input voltage(V) | 30 | | | | | 48 | | | | | 96 | | | | |
| Size | 290*210*190 | | | | | | | | | | | | | | |

| 96VD-120VDC | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Model | 96V 30A | 96V 40A | 96V 50A | 96V 60A | 96V 70A | 96V 80A | 96V 90A | 96V 100A | 96V 110A | 96V 120A | 120V 80A | 120V 90A | 120V 100A | 120V 110A | 120V 120A |
| Rated charging current(A) | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 80 | 90 | 100 | 110 | 120 |
| Numbers of batteries(pieces) | 8 | | | | | 8 | | | | | 10 | | | | |
| Rated DC voltage(V) | 96 | | | | | 96 | | | | | 120 | | | | |
| Overcharge protected voltage(V) | 120 | | | | | 120 | | | | | 150 | | | | |
| Overcharge of recovered voltage(V) | 110 | | | | | 110 | | | | | 140 | | | | |
| Floating voltage(V) | 108 | | | | | 108 | | | | | 135 | | | | |
| Solar maximum input voltage(V) | 180 | | | | | 180 | | | | | 192 | | | | |
| Size | 290*210*190 | | | | | 370*330*195 | | | | | | | | | |
| 220VDC-384VDC | | | | | | | | | | | | | | | |
| Model | 220V 80A | 220V 90A | 220V 100A | 220V 110A | 220V 120A | 240V 80A | 240V 90A | 240V 100A | 240V 110A | 240V 120A | 384V 80A | 384V 90A | 384V 100A | 384V 110A | 384V 120A |
| Rated charging current(A) | 80 | 90 | 100 | 110 | 120 | 80 | 90 | 100 | 110 | 120 | 80 | 90 | 100 | 110 | 120 |
| Numbers of batteries(pieces) | 18 | | | | | 20 | | | | | 32 | | | | |
| Rated DC voltage(V) | 220 | | | | | 240 | | | | | 384 | | | | |
| Overcharge protected voltage(V) | 270 | | | | | 300 | | | | | 480 | | | | |
| Overcharge of recovered voltage(V) | 260 | | | | | 290 | | | | | 470 | | | | |
| Floating voltage(V) | 243 | | | | | 270 | | | | | 432 | | | | |
| Solar maximum input voltage(V) | 330 | | | | | 360 | | | | | 576 | | | | |
| Size | 370*330*195 | | | | | | | | | | | | | | |
| Common parameter | | | | | | | | | | | | | | | |
| Control mode | PWM | | | | | | | | | | | | | | |
| Working temperature | "-20ºC~50ºC" | | | | | | | | | | | | | | |
| Humidity | 85% | | | | | | | | | | | | | | |