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NEW SOUTH WALES**



**SCHOOL OF PHOTOVOLTAIC AND RENEWABLE ENERGY
ENGINEERING**

**Design of a PV-genset-battery hybrid system to supply the
electricity demand of Lucma mine.**

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Literature review: Design of a PV-genset-battery hybrid system to supply the electricity demand of the mining company Lucma.

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Literature review: Design of a PV-genset-battery hybrid system to supply the electricity demand of the mining company Lucma.

Abstract

Development of an economic analysis and design of a hybrid photovoltaic-genset-battery system for an off-grid Peruvian mine named Lucma. Several programs were analysed to model the best mix of generators being HOMER the chosen to model this Peruvian minigrid. Furthermore, in order to choose the base solar data, it was developed a comparison between the different solar resources available in the region. The load needs of the mine were gathered, and different PV technologies were modelled in different scenarios finding the best scenarios for the high technology PV modules and facing the reality that the smallest LCOE is not the smallest payback period.

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To my sister who has supported me all the way of the master

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List of abbreviations

Diffuse Horizontal Irradiance (DHI)

Direct Normal Irradiance (DNI)

Generator set (genset)

Global Horizontal Irradiance (GHI)

Hybrid Optimization Model for Electric Renewable (HOMER)

Levelized cost of electricity (LCOE)

Mean Bias Error (MBE)

Mixed-integer linear programming (MILP)

National Aeronautics and Space Administration Langley Research Center (NASA LaRC)

National Aeronautics and Space Administration Prediction Of Worldwide Energy Resources (NASA POWER)

National Renewable Energy Lab (NREL)

National Solar Radiation Data Base (NSRDB)

Open energy modelling framework (Oemof)

Open source energy modelling system (OSeMOSYS)

Photovoltaic (PV)

Root Mean Error Square (RMES)

Surface meteorology and Solar Energy (SSE)

United State Agency for International Development (USAID)

Variable Renewable Energy (VRE)

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1. Literature review

1.1 Problem

The aim of this research is to prove that PV systems can provide enough electricity to operate mines allocated off the Peruvian network. The project desires to create a viable solution for middle size off the grid load.

The specific research question can be synthesised as: What is the economic and sustainability opportunity of a hybrid PV-genset-battery system to supply electricity to a mine located in the Peruvian Andes mountain range?

The installation of a PV-genset-battery hybrid system for electricity supply to an off the grid small mine (530 kW_p) in Peru is a very good opportunity. Because it can reduce the cost of electricity of the mine by shifting from mainly diesel generators to a hybrid system. It can reduce the emissions of CO₂. In addition, it can increase the reliability of the electricity supply since it will reduce the operation time of the genset. i.e. more time available for maintenance.

Using a hybrid system should reduce the levelized cost of electricity (LCOE) of the mine. It has been producing electricity with diesel generators since its set up in 2012, the cost of the gensets maintenance is very low hence the cost of operation is mainly due to the fuel cost of 3.35 S/L and its transportation to the mine 164.3 km from the city of Trujillo. The LCOE of a PV utility is 51 €/MWh roughly 189 S/MWh [1] (Zappa 2019, p. 1033) while the LCOE of a genset is 294.84 AU\$/MWh (AEMO) roughly 695.82 S/MWh. The LCOE of a hybrid system must be between 189 – 695.82 S/MWh, all in all cheaper than the genset alone.

The hybrid systems must reduce the GHG emission of the mine. One of the main advantages of using photovoltaic panels is its zero emissions of GHG during its usage phase. On the other hand, a reciprocating engine emits 500 kg of CO₂/MWh thus, depending on how much electricity is supplied by the PV panels the CO₂ emissions of the hybrid systems should be substantially smaller than the produced by a genset.

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1.2 Background

The photovoltaics has experienced a massive increase during the last decade, and it is expected to increase further within the common applications like residential; centralized utilities; water pumping systems; space; telecommunications; lighting; remote monitoring; solar cars and new applications.

Peru is located in the east site of South America. It is bordered by Chile in the south, Brazil and Bolivia in the west and Ecuador and Colombia in the north. Peru has a population of 31,800,000 inhabitants (October 2017). The majority of mines are ubicated in the Andean mountain range, minerals and precious gems represent more than 30% of peruvian exports. In La Libertad state the main electrical network extends along the cost and the mountain range remain mainly isolated from the grid, this deter the development of the mines and the growth of the country. The isolation is handled by producing electricity with diesel generators which are both expensive, due to the cost of the fuel and the transportation cost; and pollutive.

Due to the bad access to good quality petrol in the Peruvian Andean mountain range there is an extra price for the transportation and storage of the fuel used by the diesel generator.

One of the main challenges of the analysed area is the lack of grid connection and the high cost of diesel generator thus a hybrid stand-alone system is proposed to meet the load of the local mine of Lucma, Peru.

The mine has good insolation and naked hills hence there is a lot of albedo in the area that will increase the capacity factor of the PV system. It has been producing electricity with diesel generator since its set up in 2012, the cost of the gensets is very low so the cost of operation is mainly the fuel cost of 3.35 S/L and its transportation to the mine 164.3 km from the city of Trujillo. The peak demand of the mine is 650kW.

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Figure 1 Aerial photograph of the site

1.3 Justification

Renewable energy represents an alternative to the grid electrification for rural areas because grid electrification is often expensive and uneconomic in low demand and isolated areas due to the geographical reasons [2]. Furthermore, renewable energies are a sustainable way to produce energy for all and assure the supply of electricity for economic development. So, using Renewable Energy is a cost-effective solution to this type of loads that are necessary for the development of a country and due to their location are difficult to connect to the grid.

1.4 Prior work

Hybrid projects around the world have been using HOMER (Hybrid Optimization Model for Electric Renewable) software since 2012 and algorithms until 2012 to estimate the LCOE (levelized cost of electricity), now a days there are other models being used like PLEXOS modelling package and SAM software.

Muh assess the electricity cost and emissions of nine hybrid systems in order to address the lack of electricity access of isolated villages in southern Cameroon. The cost of electricity is divided in operating cost and capital cost. The comparative analysis is done with HOMER by analysing nine hybrid systems based on PV module, wind turbine, microhydro turbine, diesel generator, battery, charge controller, and inverters. Each system consists of different capacities of the mentioned parts. Muh's approach also considers an estimation of the electric load; solar radiation and wind resource,

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obtained from NASA Surface Meteorology and Solar Energy website; the diesel fuel price and interest rate [2].

Bearing in mind the many difficulties in the operation of south Algeria power plant Khelif investigates the feasibility of hybridization of AFRA power plant. The power plant consists of diesel generators and it is intended to work alone with PV modules. To estimate the performance Khelif has created a program based on electrical models, that considers the temperature. “This program is able to calculate voltage, current, battery state of charge, fuel consumption and power of the hybrid system every hour, as well as the economic assessment” [3]. The cost of the project is analysed with different diesel fuel price.

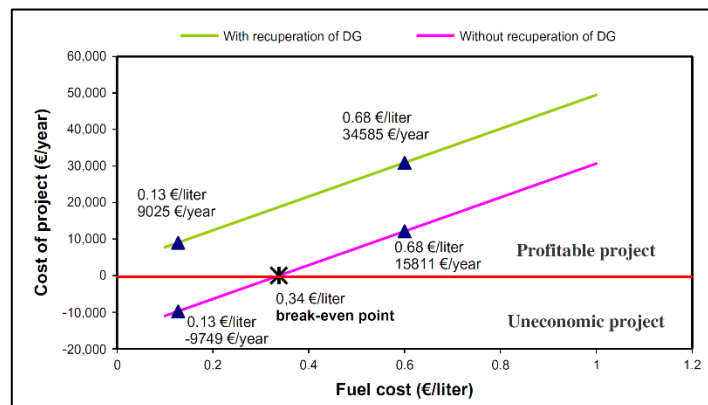


Figure 2 Annual cost of the project [4]

Kusakana have develop a program based on current flow to find the optimal size and operation control of a hybrid system, this tailored design model is not able to deliver the amount of emissions or the cost of electricity and it was limited to the development of a mathematical model [4].

1.5 Analysis of the experimental techniques

Khelif concluded that the profitability of the hybridise AFRA power plant depends on the fossil fuel cost. He states that “in order to find out the best option it is necessary to take into account several issues, for instance fuel saving, battery lifetime, investment cost, and the total annual cost of the project” (Khelif 2012, p. 552) [3]. Khelif research was done based on South Algeria Climates conditions thus, the feasibility analysed might be completely different for Peruvian conditions.

While Khelif result shows that a PV-genset hybrid system is the cheapest solution for the AFRA power plant in South Algeria, Muh results shows that the best scenario for Southern Cameroon

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off-grid area is a mix of PV/diesel/small hydro/battery system (Muh 2019, p. 53) [2]. This difference highlights the effect of Renewable Energy resources on the generator mix in different regions when the levelized cost of electricity is considered.

1.6 The proposed work

Some of the steps of the project are finding solar data, selecting the modelling software, model the system with 3 different PV technologies and evaluate the levelized cost of electricity for the actual fuel price.

In order to optimize the cost of capital and operation it is necessary to model the system base in the constraints of the site, which are defined as: technology characteristic, technology cost, resource potential, and load.

1.7 Concepts

1.7.1 Measurement of cost-effectiveness of electrification

As state by USAID in order to find the best approach for electrification, that are mainly: grid extension; mini grids; solar home systems, developers need to consider electricity services needed, projected load profile and costs [5].

Mini-grids are usually cost-effective in mid-density communities far from the grid that are placed in areas of renewable energy resources. USAID comments that “mini grids are most cost-effective for applications that require mid-level amounts of electricity”. A mid-level amount of electricity is considered between 10 kW- 10 MW [6].

Extending the national grid is more suitable for large or dense communities that are close to the national grid, “where electricity costs are low and /or where large quantities of electricity are required”. On the other hand, Stand-alone power systems are better for sparse homes that are far from the grid, require small amount of electricity and have certain amount of sunlight.

The cost effectiveness of a mini grid could be found by determining the energy needs and gathering capital costs for renewable energy, storage components and dispatchable generators. Then, programs like HOMER can calculate the LCOE of the mini grid and this should be compared to the LCOE of usual generation plus the levelized cost of grid extension.

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1.7.2 Renewable energy

Renewable energy is any source that is replenish faster than it is consume. Within the renewable energy there are many options like wind turbines that use the wind resource; photovoltaics that use the sun light; and hydro turbines that can use the energy potential of a dam or the flow of a river. These generators run intermittently depending on the variability of their respective source (i.e., the variability of the weather), creating patterns of generation so wind can create long periods of electricity production while photovoltaics in a sunny day usually has a peak at solar noon and hydro depends on the water level that is replenish faster on the wet season. As can be seen any of the renewable energies require energy storage. The best option therefore for off-grid loads are hybrid systems.

Hybrid systems combine variable renewable energy sources with diesel generators and may also include energy storage in order to meet the load of electricity demand at any time by using each sore in and optimize way and storing excess energy for times of deficit resources, variable renewable energy resources [4].

1.7.3 PV system

PV systems are arrays of Photovoltaic panels that absorb sunlight to produce electricity. There is not a classification of the PV system by size but the national renewable energy laboratory classified them as residential (3-10 kW) commercial (10 kW-2 MW) and Utility-scale (2MW) [7]. In order to analyse the potential of this source the correct analysis of the data is essential.

1.7.3.1 Solar Data

Accessible data is fundamental for assessing the potential of solar technologies and quantify energy output. For the latitude and longitude of the Peruvian territory there are two sources of open solar data: the National Solar Radiation Data Base (NSRDB) developed and updated by the National Renewable Energy Lab (NREL) [8] and the NASA Prediction Of Worldwide Energy Resources (POWER) developed by the NASA Langley Research Center (LaRC) [9].

NSRDB

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The NSRDB is ancillary data for solar deployment and sizing applications. It was released in 1982 providing 30 years of data from 1961 to 1990. This data set was created with measured and modelled solar radiation. During the nineties the dataset migrated from a manual system to full-sky cloud observation to the ASOS, which derive cloud cover from laser ceilometer observation at the zenith. [10](U.S. Department of Energy 2012, p. pag33).

In the most recent update, the NSRDB changed from using mainly empirical modelling and data collected at stations to using a physics-based modelling approach that provides solar radiation data for the entire United States in gridded segments ($0.038^\circ \times 0.038^\circ$) using geostationary satellites. This is the same for the rest of the Americas that extend between longitudes 25° W on the east and 175° on the west, and by latitudes -20° S on the south and 60° N on the north.

The current version provides solar and meteorological data recorded every 30 minutes.

The NSRDB validation has been done by all the research with data of the United States. The National Renewable energy laboratory has proven that for clear sky conditions the daily measurements of GHI %RMES could go up to 9% and the MBE until 5% while under cloudy days the %RMSE can go up to 20% and the MBE down to -16%, in few cases the MBE is smaller for cloudy days (National Renewable Energy Laboratory 2017, p. 21) [11]. If the all sky daily average is evaluated the %RMES of GHI can reach 13.90% while the MBE reach -4.44% (National Renewable Energy Laboratory 2017, p. 21) [11].

Sengupta et al. show that under clear sky conditions the correlation between ground-measured data and satellite data is higher than in cloudy days, under clear sky conditions the correlation is closer to 1:1. Furthermore, the GHI has smaller deviation than DNI under cloudy-sky conditions (Sengupta et al, 2015, p. 3) [12]. Sengupta mentioned experiment is based on measurements of GHI and DNI at zenith angles above 75° .

In another publication based on US data Sengupta et al. calculate the bias of the GHI as 5% and calculates that the %RMSE of the hourly-averaged GHI and DNI can reach up to 20% and 40% respectively, both statistics compare surface-based measurements with satellite data. (Sengupta 2018, p. 55) [13].

The NSRDB is very useful for locations in the Americas that mainly have clear sky conditions and is especially suitable for the modelling of PV systems.

NASA POWER

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The Surface meteorology and Solar Energy (SSE) project was created to improve the use of NASA's data. SSE is a global and continuous in time data and it is useful for the renewable energy industry. It was released in 1997, 1999, 2000, 2003, 2005 and 2008. The POWER project is an outgrowth of SSE and it was release on 2003. Further to the Renewable energy dataset it supplies datasets for Sustainable Buildings and Agro-climatology industries.

The parameter in POWER released-8 are in a resolution of $0.5^\circ \times 0.5^\circ$ and they are obtained from satellite observations and meteorological data, the former is obtained from NASA GEWEX/SRB the latter is provided by the assimilation model: MERRA-2 and GEOS 5.12.4. The parameters are tailored for three different communities – solar and renewable energy, energy efficiency and sustainable buildings, and agricultural- are calculated from the same solar and meteorological values. The units of the values are specific for each community.

The validation method for NASA POWER is performed with data from around the world. The solar data is available in annual, monthly, and daily average. The uncertainty of the POWER data set is evaluated in Longwave and Shortwave Radiative Fluxes. If the data from 2008 to 2016 is compared with ground measure data for shortwave the RMSE% varies from 17.66 to 41.59 while the longwave RMSE% varies from 5.73 to 13.44 and the MBE% can reach down to -6.94%. In the case of clear sky conditions, the RMES% decreases to 7.04% (POWER Release 8.0.1 2018, p. 14) [14]. Stackhouse shows in previous publication that for the United States under all sky conditions the monthly GHI average has a MBE of 4% while the RMSE is 7% (Stackhouse et al) [15].

Data quality assessment

The data quality assessment recommended consist of applying flags to outlying values, missing data and duplicates. Furthermore, it is recommended to apply the solar specific test closure approach. Since the flags are assign to the values outside the parameters, the flagged data must not be use in the calculations.

Outlying values consist of determining the first and third quarter of the data and applying the following criteria: If the data is bigger than $Q3 + 1.5 \times IQR$ the data is wrong. In addition, if the data is smaller than $Q1 - 1.5 \times IQR$ the data is wrong. IQR is the inter quartile range, i.e. $IQR = Q3 - Q1$.

Missing data is data that the satellite has not recorded, and duplicates are two subsequence data that are the same. In both these scenarios a flag is applied.

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The closure approach mainly consists of applying the relation between the direct and diffuse irradiance with the global horizontal irradiance.

$$GHI = DNI \cos\theta_z + DHI$$

Where

GHI is global horizontal irradiance

DNI is direct normal irradiance

DHI is Diffuse horizontal irradiance

Θ_z is the zenith angle, angle of the sunlight with respect the vertical from the ground

Zenith angle

$$\theta_z = 90^\circ + \alpha_s$$

Where

Θ_z is the zenith angle

α is the altitude angle, angle of the sunlight with respect to the horizon

$$\alpha = \sin^{-1}[\sin \delta \sin \phi + \cos \delta \cos \phi \cos HRA]$$

Where

α is the altitude

δ is the declination

ϕ is the latitude

HRA is the hour angle

$$\delta = \varepsilon \sin \left[(d - 81) \frac{360}{365} \right]$$

Where

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δ is the declination

ε tilt of the earth's axis

d is the day of the year base on the 365 days of a year

$$HRA = \omega = (hour - 12) \cdot 15^\circ$$

HRA ω is the hour angle

Hour is the local solar time

$$LST = LCT + \frac{(L - LSTM) \times 4 + EoT + DS}{60}$$

LST is the local solar time

LCT is the local clock time

L is the latitude

LSTM is the local solar time meridian $LSTM = 15^\circ \times \Delta T_{GMT}$ (ΔT_{GMT} is the difference between the LCT and the Greenwich Mean Time (GMT) in hours. ($15^\circ = 1$ hour))

EoT is the equation of time

DS is the daylight saving in minute

$$EoT = 9.87 \sin 2\Omega - 7.53 \cos \Omega - 1.5 \sin \Omega$$

EoT is the equation of time

$$\Omega = (360/365) \times (d - 81)$$

Some of the requirements for a hybrid system are performance, safety and fire protection, generators and intelligent management system.

1.7.3.2 Performance

The hybrid system must assure a high performance of all its component. A PV system could use two-axis tracking, single-axis tracking and fixed tilt. The first and second used to be an important solution for expensive PV modules but cheaper modules can be use in fixed tilt systems. Ball summarize the design and operation factors that influence system efficiency as:

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Table 1 Design and operation factors impacting performance [16]

Factor	Feature or impact	Considerations
Array orientation	Two-axis tracking	Energy capture is maximized by keeping the plane of array normal to the direct beam of the sun through the day and seasonally. Energy yield is as high as 40% over fixed tilt systems. High structural, space, and cost requirements.
	Single-axis tracking (N-S) axis	Energy capture is enhanced as much as 25% over fixed tilt systems. Simpler and less expensive than two-axis tracking systems. Typical tracker rotation range is 45 degrees East and West. "Backtracking" arrays away from low sun angles in the morning and night limit shading from adjacent rows of trackers.
	Fixed tilt systems	Least cost balance of system approach. Ideal tilt for annual production is the site azimuth angle (determined by latitude) $\pm 15-20$ degrees. Practical considerations such as row-to-row shading, available space, and wind loading tend to favour tilts less than azimuth angle.
Array shading	Row to row shading	Shading of one row of modules by another, influenced by the tilt angle and space between rows. Cost and performance trade-off involve consideration of available space, structure costs, annual energy lost from shading. 3-5% shading loss typical.
	Object shading	Shading of modules by trees, structures, roof objects or features, chimneys, etc. Shading a portion of the array causes disproportionately high losses on series and parallel connected DC strings. Designing to minimize shading by objects can have a significant impact on annual production.
	Horizon shading	Shade crated by landscape features such as hills, distant tree lines, terrain slopes. Accurate accounting for these losses is important for determining project economies.
Electrical losses	Wiring losses	Resistive losses in potentially very long DC conductors, create voltage drop. Array designs have lower loss targets (0.5-1.5% on DC side, 1% or less on AC side) than typical AC industrial wiring (2-5%). Lower losses achieved by increasing conductor sizes.
	Array voltage	Wiring and inverter losses are impacted by the array voltage as determined by the number of modules connected in series per string. Losses occur if the maximum array voltage is outside the inverter's maximum power tracking range. Higher voltages reduce wiring resistive losses on a per Watt basis, offset somewhat by larger switching losses in the inverter. Lower voltages create higher wiring resistive losses on a per Watt basis.
	Inverter efficiency	Inverter DC-AC conversion efficiency is a significant competitive factor for manufacturers. Typical range is 94-98% and expressed in terms of peak and

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		weighted output efficiency. Inverter maximum power point tracking (MPPT) efficiency typically can result in additional 0.5-1% loss.
	Transformer losses	Additional external transformers are sometimes required to interconnect with utility distribution or transmission systems. Losses on an annual basis typically in range of 0.5-15%.
Soiling		Modules soiled by dirt, dust, and other particulates can cause annual energy production losses between 1-10% or more. Periodic cleaning in operations phase can be justified depending on cost, safe access, etc.
Mismatch		Mismatch losses occur as a result of variations in module nameplate current and voltage ratings when connected in series and parallel strings, variations in the array plane angles, and non-uniform shading, soiling, age-related degradation. Impact ranges from less than 0.5% in well-designed ground mount systems to 5% on systems with significant object shading.

Bearing in mind that the PV cost is very low the production could be increase by installing more PV modules even if this generates more shading. Another production/cost-driven decision is installing a bigger DC/AC ratio in this way the power install capacity is higher than the capacity of the inverter. When the power reaches the limit, the inverter *clip* and move the operation point away of the maximum power point. Figure 3 shows that the electricity production is higher with a bigger DC/AC ratio than normal because the inverter produces more energy from off-peak sun hours.

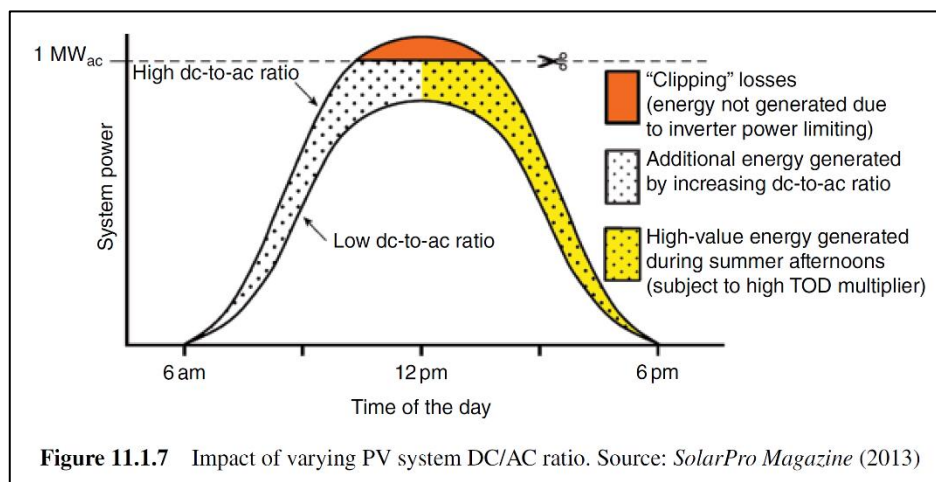


Figure 3 Impact of varying PV system DC/AC ratio.

Since the mine is in a very isolated place and there is no specialist in the area the PV system must avoid at all cost shadings so it should be optimised for high efficiency instead of boosting system

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production. Furthermore, it should be optimized to produce a leveled output during the year, so the inverter works near its peak. Increasing the DC/AC ratio should be considered if the space allowed it.

1.7.3.3 Safety and fire protection

The wide use of PV system in rooftops, carports, fences and so on make the safety an important issue of the PV systems. As explained by Ball who site (Reil *et al.*, 2011; Ball *et al.*, 2013) fault protection -the basis for fire protection- is a set of measures to prevent and/or mitigate unintended currents and voltages on conductors and equipment, such as short-circuits [16]. Here it will be explained:

- Short circuits between DC circuits
- Short circuits between DC circuits and ground
- Arcing faults.

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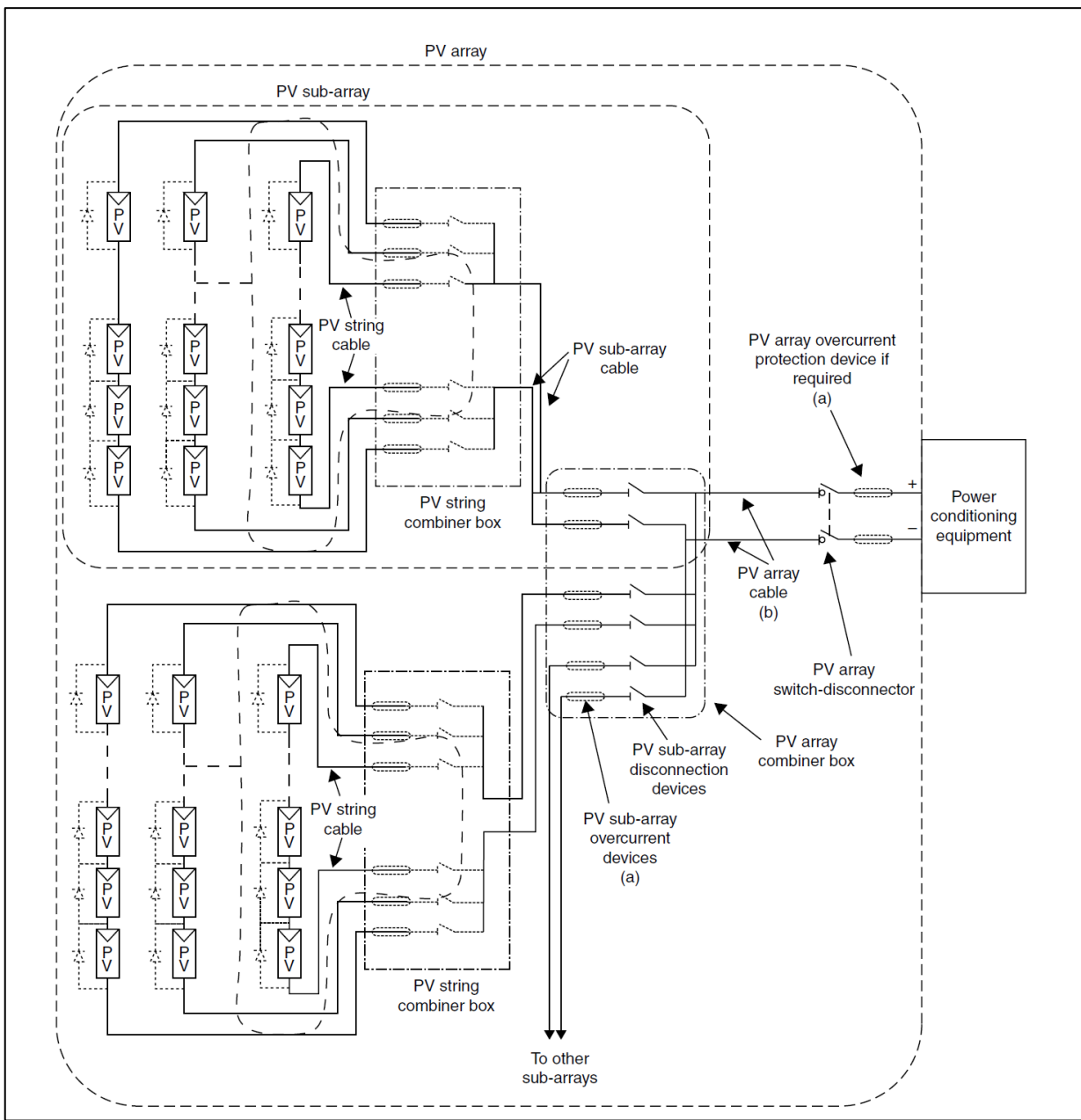


Figure 4 Electrical circuit diagram for large PV system. Source: (IEC TS 62548, ed. 1.0)

Overcurrent Protection

Overcurrent protection as explained by Ball “measures use fuses, circuit breakers, and other devices to limit currents to safe and appropriate levels and interrupt short circuits” [16]. The variable characteristic of the electricity generation by a PV module make difficult the selection of a fuse for a PV string. The short circuit current of a module is just 10% higher than its maximum power point current (I_{mpp}) and the light generated current varies with the intensity of the light.

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If there are few strings high fault current can only come from the utility through the inverter. On the other hand, when there are several strings the current flows in an opposite way from the good string to the faulted string. Thus, the fault current is limited by the number of strings in parallel. A Higher fault current ensure a rapid function of the protection fuse (or circuit breaker).

A fuse should not trip at high light intensity and low temperatures. The string cable are connected in parallel and joint in combiner box subsequently the PV subarray cables are combined in a PV array combiner box. In each box before been connected the cables are protected by fuses of different size. Due to the variability of the electricity produce fuses, size to the upper limits, are not very effective. Thus, reverse current detection is recommended, they disconnect the circuit in case of any reverse current beside noise and leakage.

Grounding and Ground Fault Protection

Ball defines Ground faults as “They are short circuits between a live conductor and a grounded conductive surface, such as metallic enclosures, cable conduits or trays, module frames, mounting structures, etc. They occur when a conductor’s insulation is damaged or nicked, and the exposed wire makes contact with the metal object” [16]. Ground faults can generate large fault current due to the voltage different between source and ground and they can impose the conductor voltage on a metal object.

PV system grounding is the connection of one of the polarities of the circuit to the ground, which is different to equipment grounding, connecting metal object and parts to the ground to ensure they touch-safe. There are three main system grounding methods Ungrounded, grounded and AC reference grounded.

Arc Fault Protection

An arc is formed between two metal when the current jump through the gap and “it is maintain by the continuous ionization of the air in the path” [16]. Arc fault’s high temperature can damage components. In PV systems arc faults occur in the connection; connection between modules, connection of strings, connection in the module junction box and terminals in the combiner boxes.

Loose connection is a high resistance that transform power into heat that damage the insulation until the point that the current can jump the air gap. This arc faults are called series arc because they are the result of series resistance in the normal path of the current. They can be detected by measuring high frequency spectrum and they can be stop by simply turning off the inverter that

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stop the current flow. The arc fault protection is successful in string level protection other areas require further research.

Arc fault can also be detected by the reverse current, residual ground current, low conductor resistivity to the ground, arc fault signature, etc. This could be stop by opening contactors, they can be located at any level of the PV system.

1.7.3.4 Intelligent energy management system

A core element in a hybrid system is the intelligent energy management systems, it make sure high efficiency and reliability and reduction of maintenance [16] (Reinders et al. 2017, p.542). During very low RE sources it can use auxiliary power generation to supply the demand.

The energy produces during a day must be equal to the consumption and the State Of Charge (SOC) of the battery should be bigger than the healthy benchmark of the it SOC_{min} . This is applied dividing a day in several term equal to $t_2 - t_1$.

Reinders et al defines and optimization criteria for a hybrid system as follows:

Optimization Criteria 1

$$\int_{t_1}^{t_2} P_{residual} dt = \int_{t_1}^{t_2} (P_{load} - P_{PV} - P_{wind}) dt \rightarrow minimum$$

Equation 1 Optimization Criteria 1

$P_{residual}$ (in W) represents the actual net load as a difference between the actual load P_{load} (in W) and the actual PV power P_{PV} (in W) and the actual wind power P_{wind} (in W).

Boundary conditions

$$\int_{t=0h}^{t=24h} P_{el,generated} dt \approx \int_{t=0h}^{t=24h} P_{el,consumed} dt$$

Equation 2 Boundary condition

$$SOC_{Battery} \geq SOC_{min}$$

Equation 3 Boundary condition

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$P_{el,generated}$ represents the power of all connected power generators and $P_{el,consumed}$ represents the power of all connected loads. $SOC_{Battery}$ is the state of charge of the battery and SOC_{min} the allowed minimal state of charge value of the battery.

If both boundary conditions have to be fulfilled in a single time interval (t_1 to t_2) or in certain critical applications, even at each single time step, the residual load is covered by the auxiliary generator and/or the battery:

$$\int_{t_1}^{t_2} P_{residual} dt = \int_{t_1}^{t_2} P_{aux,generator} dt + \int_{t_1}^{t_2} P_{battery} dt$$

Equation 4 Residual load covering

$P_{residual}$ (in W) represents the actual net load, $P_{aux,generator}$ (in W) represents the actual power of the auxiliary generator and $P_{battery}$ (in W) represents the actual power of the battery system. The auxiliary generator is replacing the fuel cell that reinders use in Photovoltaic solar energy because the mine has already bought a diesel gensets.

If the auxiliary generator is switch off, only the battery covers the residual load as long as the state of charge is above its absolute limit:

$$P_{battery} = P_{residual}, \text{ if } P_{battery} \leq P_{battery,discharge,max} \text{ and } SOC \geq SOC_{min}$$

Equation 5 Battery discharging

$P_{battery}$ (in W) represents the actual power of the battery system, $P_{residual}$ (in W) represents the actual net load, $P_{battery,discharge,max}$ (in W) represents the maximum discharge power of the battery system, SOC is the actual state of charge of the battery system and SOC_{min} represents the minimum allowed state of charge value of the battery system.

If the residual load is negative, meaning that PV and wind generation exceed the actual load, the battery is charged:

$$P_{battery} = P_{residual}, \text{ if } |P_{battery}| \leq P_{battery,charge,max} \text{ and } SOC \leq 1$$

Equation 6 Battery charging

Whereas $P_{battery,charge,max}$ represents the maximum allowed charge power, which is also dependent on the actual state of charge (SOC) of the battery [16].

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Reinders et al also defines the specifications for a micro grid of less than 10% of electricity produce by VRE, they should have at least one diesel generator operating all the time to be the grid-forming unit and their PV inverters works in parallel mode and are only feeding in [16].

To further increase the penetration that will consequently reduce the LCOE Reinders et al recommend integrating additional control measures, this are call “fuel saver” and they fulfil the following tasks:

- Optimized control of the diesel engine;
- Reduction of PV inverter output to ensure minimum diesel generator power, which has to be typically above 30% of the nominal power.

In order to match the demand and the operational requirements of the diesel generator the maximum power point tracker (MPPT) could be switch off and the inverter control follows the supervisory control algorithm of the fuel saver. For the purpose of a hybrid system with storage it must be add to that MPPT must be switch off if the battery reaches 100% SOC.

1.7.4 Economics

Levelized cost of electricity

Since the hybrid systems use different kind of generators to produce electricity it is advisable to use a common metric for the price. The levelized cost of electricity (LCOE) is a common metric for generators. It gives an average cost of electricity for all the life of the generator and it is used to compare prices between different generators and in the case of variable renewable energies to also compare generators with different technologies i.e., wind farms in different weather conditions.

The calculation for the LCOE is the net present value of the total life-cycle costs of the PV project divided by the quantity of energy produced over the system’s life:

$$LCOE = \frac{\textit{Total Life Cycle Cost}}{\textit{Total Lifetime Energy Production}}$$

The above LCOE equation can be disaggregated for solar generation as follows:

$$LCOE = \frac{Int\ Inv - \sum_{n=1}^N \frac{Depreciation}{(1 + Discount\ Rate)^n} \times (Tax) + \sum_{n=1}^N \frac{Annual\ Costs}{(1 + Discount\ Rate)^n} \times (1 - Tax\ Rate) - \frac{Residual\ Value}{(1 + Discount\ Rate)^n}}{\sum_{n=1}^N \frac{Initial\ \frac{kWh}{kWp} \times (1 - System\ Degradation\ Rate)^n}{(1 + Discount\ Rate)^n}}$$

Equation 7 LCOE

The costs include the initial capital investment and the lifetime operating expenses, less the end-of-life value discounted into the present value. The lifetime costs are divided by the lifetime energy production to derive the average cost of electricity.

In order to find the overall LCOE of the hybrid system, it is applied with all the cost of the generators in the numerator and all the electricity produce by all the generators in the denominator.

Discounted payback period

The discounted payback period gives the number of years to break even from undertaken the initial expenditure i.e., to make even the cost until that moment and the revenues. It is calculated by discounting future cash flows and recognizing the time value of money (Investopedia).

$$m_{PB} = \frac{-\ln\left(1 - \frac{i'|C_0|}{C_{annual}}\right)}{\ln(1 + i')}$$

Equation 8 Discounted payback period

Where i' is the real discounted rate, C_0 Capital costs, C_{annual} annual flows.

Peruvian Renewable Energy

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The legal framework of Renewable energy in Peru is based in the Law 1002 of 2008 it identifies RES as a public necessity of national interest and attributes the development of the national RE policy to the Ministry of Energy. In 2011 an amended created the main subsidy for RE in Peru base on a biannual auction that assure a long-term tariff for RES. The PPA's have a spam of 20-30 years (IEA/IRENA) [17].

On the other hand, the ministry has developed the National Plan of Country Electrification with the aim of extend the network and deploy 150,000 off-grid PV systems. Until 2015 23,993 houses and 159 communities has been provided with this PV systems [18].

There is no subsidy for the RE generation of bigger scale (0.15-1 MW_p) so the mines in the south of the country draw the electricity from the generator of the center of the country.

2. Method Experimental design

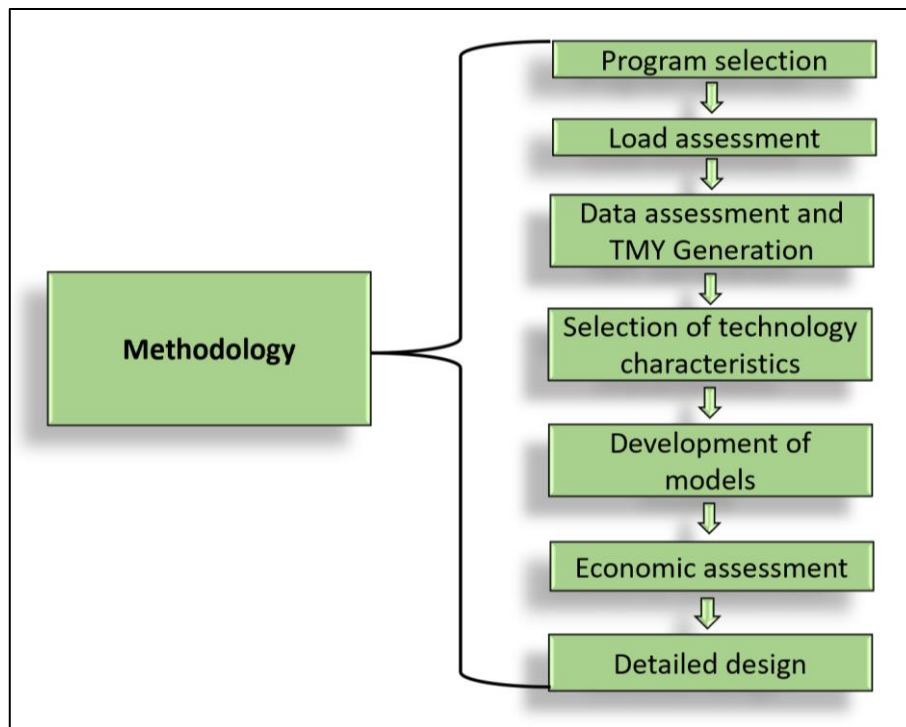


Figure 5 Methodology

2.1 Program selection

There are available more than 75 modelling programs in the world, it is required a program that supports Investment Decision (IDS) and evaluates scenarios (S) for the project. This program must be open source or a free software because there is no budget for the project. Since the project is for a specific location It is not required a program that analyses a scale of a continent thus the geographical coverage is define as National or regional. The technologies to be analyzed are diesel genset, solar panels and batteries but the program should be able to analyze more technologies. Furthermore, it should be able to analyze a wide spectrum of cost mainly Investment, Operation and Maintenance, Fuel and CO₂ emissions. The selected program must be able to calculate the emissions that the systems will produce.

The energy and electricity models usually have four main purposes

- Power System Analysis: Tool develop to deal with power systems usually used to study the power electronic of the generators (Ringkjøb et al 2018, p. 443) [19].

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- Operation Decision Support: “units develop to optimize operation dispatch/operation of the system, considering for example unit commitment” (Ringkjøb et al 2018, p. 443-444) [19].
- Investment Decision Support: “tools that optimize the investment in the energy/electricity system, usually long-term models” (Ringkjøb et al 2018, p. 444) [19] [19].
- Scenario: Tools that investigate future long-term scenarios in the energy/electricity sector. They can be used to evaluate the impact of various policies” (Ringkjøb et al 2018, p. 444) [19].

It is important to use open source or free software since it gives opportunities to other researcher to keep on doing research in the field of renewable energy modelling about the niche of renewable energy sources in different geographical sites around the world. Furthermore, an open source can be a useful tool for engineers to model without program cost projects of hybrids for different requirements.

As shown in table 1 there are three modelling programs that fulfill all the requirements: ficus, OSeMOSYS The Open Source Energy Modelling System and Oemof Open Energy Modelling Framework.

Ficus is a “mixed-integer linear programming (MILP) optimization model for capacity-expansion planning and unit commitment for multi-commodity industrial energy systems” (Atabay 2017, p. 804) [20]. Ficus objective is to find the optimal size of the processes and storages as well as the optimal power flow of all processes, storage units, commodity imports, and commodity exports to satisfy a given demand with minimal cost (Atabay 2017, p. 804) [20]. Ficus has a very wide spam and should be used to analyze the flow of inputs and output of the processes of a factory or to analyze systems like cities or district considering heating, water, electricity, etc. It is not the model require to this project because it would unnecessary complicate the electricity modelling.

Open energy modelling framework (Oemof) is a model that does not tackle the uncertainty. Thus, it is not useful for this research.

Welsch defined OSeMOSYS (Open source energy modelling system) as “a deterministic linear optimisation model, which covers all or individual energy sectors, including heat, electricity and transport. The model is driven by exogenously defined demands for energy services. These can be met through a range of technologies which draw on a set of resources, defined by their potentials and costs. On top of this, policy scenarios may impose certain technical constraints, economic

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implications or environmental targets” Welsch also add that OSeMOSYS is able to capture operating reserve and related investment requirements within a single tool and he made a comparison between OSeMOSYS and TIMES-PLEXOS for the Irish electricity market that shows a 95% match. (Welsch et al 2014, p. 602) [21]. Since OSeMOSYS is able to analyze the electricity alone and its accuracy has been proven, it is the most suitable model for the project.

It is worth to mention other programs like EnergyPLAN, it can take into account the coupling between the electricity, heat and transport sectors. Making the decision making towards 100% renewable integral.

Table 2 Purpose, Geographical spam, Technological and Economical parameters [19].

Abbreviations used in table: Purpose: IDS - Investment Decision Support, ODS - Operation Decision Support, S – Scenario; Availability: OS – Open Source, F – Free. Ren. Gen: HP – Hydropower, ROR – Run-of-river, SP – Solar Power, WP – Wind Power, ST – Solar Thermal, WaP – Wave Power, GT – Geothermal, CSP – Concentrated Solar Power, TP – Tidal Power; Storage: PHS - Pumped Hydro Storage, CAES – Compressed Air Energy Storage, B – Batteries, H – Hydrogen, TES – Thermal Energy Storage; Cost: I – Investment, O&M – Operation & Maintenance, F – Fuel, CO₂ – Carbon cost, T – Taxes, B – Balancing costs.

#	Models	Purpose	Availability	Geographical coverage	Conv. Generation	Ren. Generation	Storage	Cost	Emissions
1	BALMOREL	I & ODS	OS	Single project → Global	All	HP, ROR, SP, WP, ST, WaP	All	I, O&M, F, CO ₂ , T, B	CO ₂ , SO ₂ and NO _x
2	DER-CAM	I & ODS	F	Single project → Regional	All (Except Nuclear)	All	All	I, O&M, F, CO ₂	CO ₂
3	EnergyPlan	S, IDS	F	Local → Continental	All	All	All	I, O&M, F, CO ₂ , T	CO ₂
4	ETM (2)	S	OS	Community → International	All	All (except TP & WaP)	PHS, B, H, TES	I, O&M, F, CO ₂ , T	CO ₂
5	ficus	I & ODS	OS	Local → National	All	All	All	I, O&M, F, CO ₂	Any Pollutant
6	Oemof (SOLPH)	S, I & ODS	OS	UD	All	All	All	I, O&M, F, CO ₂ , T, B	Any Pollutant
7	OSeMOSYS	IDS	OS	Community → Continental	All	All	All	I, O&M, F, CO ₂ , B	Any Pollutant
8	RETSscreen	IDS, S	F	Single-system → Global	All	All	B	I, O&M, F, CO ₂ , T	GHG
9	urbs	I & ODS	OS	Local → National	All	All	All (Generic)	I, O&M, F, CO ₂ , B	Any pollutant

After thoroughly analysing of OSeMOSYS it had become evidence that the programme does not use meteorological data to estimate the timing of the output of the variable renewable energy generators, wind or photovoltaic farms. OSeMOSYS simply uses generator’s capacity factors to estimate which amount of each generator is necessary to reach certain amount of penetration, so it must be analysed outside the program how to match the output of different VRE generator with the load demand.

2.2 Site assessment

It has been carried an assessment of Renewable energy resources of the area, the specific location analyse is latitude: 7.63994, longitude:78.6908. The weather data was obtained from NSRDB and it was analysed from 1998 to 2017. The satellite data could not be compared with any ground measure data since Peru does not have open source data available of insolation. There was applied data quality check to the data set of missing flags, IQR outlier and duplicates. Furthermore, the closure approach was applied to filter the GHI. It shows that on average the insolation fluctuates from 4.09 to 6.72 (kWh/m²/day) during the year. On a year basis, the insolation can vary from the average, 2,007.81 (kWh/m²/year), from +7.12% to -9.13%.

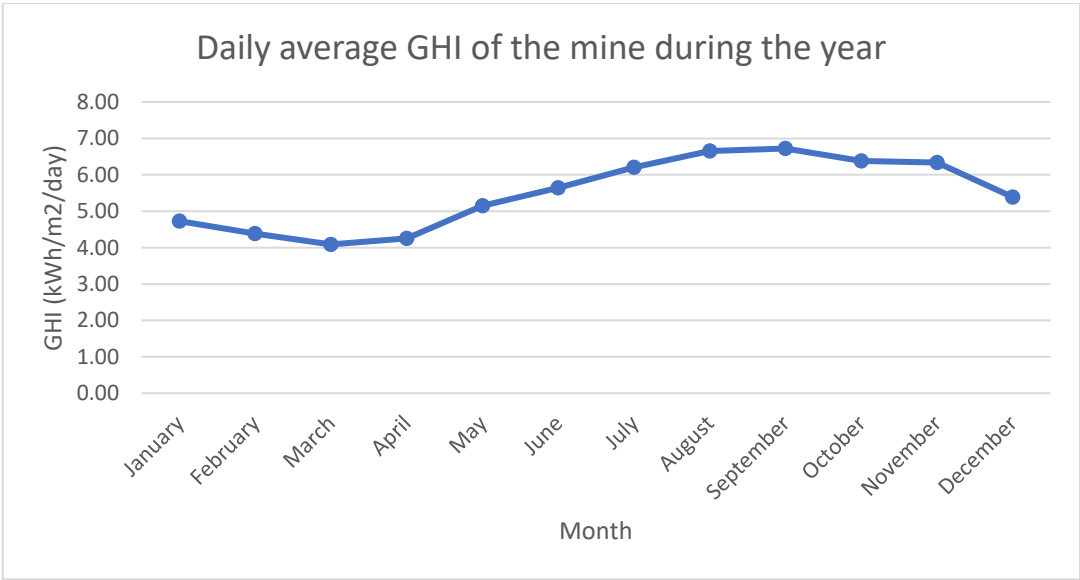


Figure 6 GHI variation at the mine site through the year

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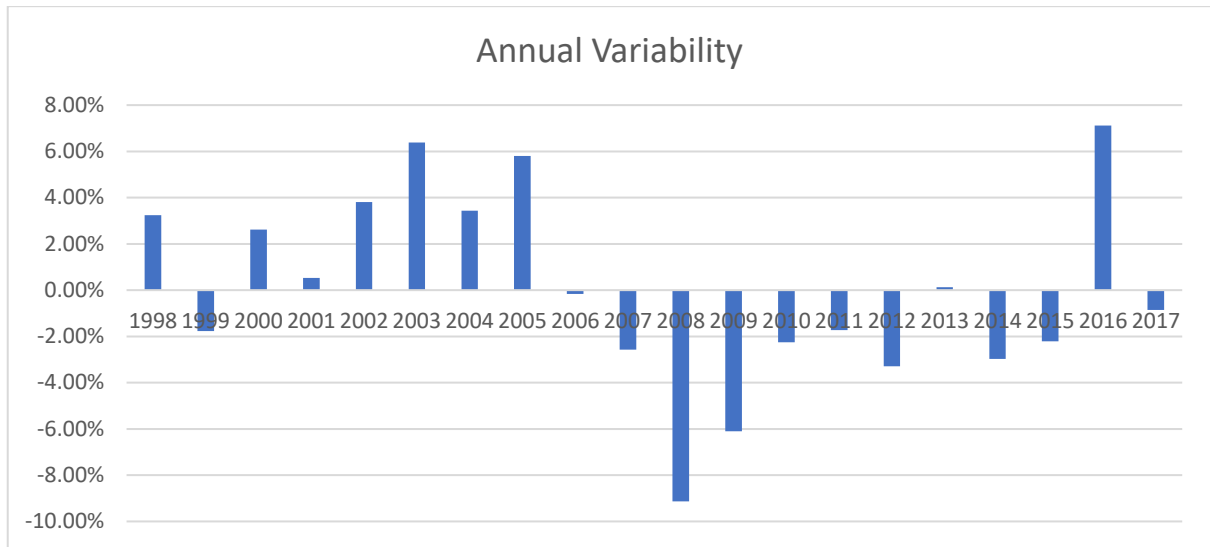


Figure 7 Annual GHI variability of the mine site

2.3 Load assessment

Table 3 Load assessment

Load category	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
Washing Machine								1800	1800									1800	1800					
Water heating						12000													12000					
Lighting	9500	9500	9500	9500	9500													9500	9500	9500	9500	9500	9500	9500
Lighting	3680	3680	3680	3680	3680														3680	3680	3680	3680		
TV							400	400				400	400					400	400					
Freezer	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
Fridge	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
Chargers	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
CONCENTRATOR PLANT																								
Conveyor belt 1	8201	8201	8201			8201	8201	8201			8201	8201	8201			8201	8201	8201			8201	8201	8201	
Conveyor belt 2	5592	5592	5592			5592	5592	5592			5592	5592	5592			5592	5592	5592			5592	5592	5592	
Conveyor belt 3	5592	5592	5592			5592	5592	5592			5592	5592	5592			5592	5592	5592			5592	5592	5592	
Crusher 1	29824	29824	29824			29824	29824	29824			29824	29824	29824			29824	29824	29824			29824	29824	29824	
Crusher 2	22368	22368	22368			22368	22368	22368			22368	22368	22368			22368	22368	22368			22368	22368	22368	
Zaranda 1	3728	3728	3728			3728	3728	3728			3728	3728	3728			3728	3728	3728			3728	3728	3728	
Lime whisk	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2	5219.2
Ball mill	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560	74560
Mud bomb	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2	8947.2
Denver bench	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640	18640
WS bank	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368
Compressor air	8201.6							8201.6	8201.6							8201.6	8201.6							8201.6
Drying press	2236.8							2236.8	2236.8							2236.8	2236.8							2236.8
Recirculation Pump 1	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824
Recirculation Pump 2	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824
Recirculation Pump 3	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824	29824
Recirculation Pump 4	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368	22368
MINA																								
Locomotive loader	7000	7000	7000																			7000	7000	7000
Kaischan compressor		74560	74560	74560	74560									74560	74560	74560	74560			74560	74560	74560	74560	
Kaeser Compressor sf 132		111840	111840	111840	111840									111840	111840	111840	111840			111840	111840	111840	111840	
Fan 6000 cfm																								
Fan 10000 cfm																								
ADMINISTRACION																								
Illumination						1444	1444	1444	1444						1444	1444	1444	1444	1444	1444				
Computer						1800	1800	1800	1800						1800	1800	1800	1800	1800	1800				
TOTAL LOAD (W)	354797.8	530759.4	530759.4	448454.4	448454.4	339423.4	327823.4	340061.8	264356.8	248874.4	324179.4	324579.4	324579.4	435274.4	438518.4	524261.8	524661.8	351123.4	267098.4	448454.4	523759.4	530759.4	527079.4	275812.8

The load is bigger at night 5,225.613 kWh than during the day 4,428.294 kWh.

2.4 Technology Characteristics

Base on the module price index publish on a monthly basic by PV magazine there are three main technologies, high efficiency; mainstream and low cost [22] . These technology prices have been matched with three brands sunpower; Canadian solar; trina solar.

Table 4 Different crystalline module prices based on the technology [22]

Module class	Value	Description
High efficiency	0.54 \$AU/W _p	Crystalline panels at 290 W _p and above, with PERC, HJT, n-type or back contact cells, or combinations thereof
Mainstream	0.44 \$AU/W _p	Modules typically with 60 cells, standard aluminium frames, white backsheets and 260 to 290 W _p — this represents most modules on the market
Low cost	0.32 \$AU/W _p	Factory seconds, insolvency goods, used or low-output modules and products with limited or no warranty

The Cost associated with the PV modules installation are the racks, electrical components, labour, rack installation, EPC engineering procurement and construction, civil works, PII permitting installation and interconnection, and contingency. All these has been measured by the national renewable energy laboratory as in the following table [7].

Table 5 Cost related to PV installation [7]

Category	Value	Description
Structural components (racking)	0.15 \$AU/W _{dc}	Fixed-tilt racking or one axis tracking system
Electrical components	0.19 \$AU/W _{dc}	Conductors, conduit and fittings, transition boxes, switchgear, panel boards, etc.
Engineering, Procurement and Construction EPC	13%	Costs and fees associated with EPC overhead, inventory, shipping, and handling

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overhead (of equipment cost)		
Direct installation labour	Electrician: \$AU 50.00 per hour; Labourer: \$45.60 per hour	Depends on state
Permitting, Inspection, and interconnection	0.15 \$AU/Wdc	For construction permits fee, interconnection study fees for testing substation, testing, and commissioning
Contingency	4%	Estimated as mark-up on EPC cost; value represents actual cost overruns above estimated cost
Rack installation	0.10 \$AU/Wp	
Civil & installation	0.21 \$AU/Wdc	

It is assumed that the installation of each module consumes one hour. The cost of each technology is the following:

For the high efficiency PV module it was selected SunPower E20-435-COM 435Wp due to its high warranty of keeping at least 92% of the power rating after 25.

Table 6 High efficiency PV module's total cost

Module class	Value	Description
High efficiency PV module (SunPower E-Series: E20-435-COM 435Wp)	0.54 \$AU/Wdc	Crystalline panels at 290 Wp and above, with PERC, HJT, n-type or back contact cells, or combinations thereof
Structural components (racking)	0.15 \$AU/Wdc	Fixed-tilt racking or one axis tracking system

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Electrical components	0.19 \$AU/Wdc	Conductors, conduit and fittings, transition boxes, switchgear, panel boards, etc.
Engineering, Procurement and Construction EPC overhead (of equipment cost)	13%	Costs and fees associated with EPC overhead, inventory, shipping, and handling
Direct installation labour	Electrician: \$AU 50.00 per hour; Labourer: \$45.60 per hour	Depends on state, it is considered half hour of each electrician and labour work for each module.
Permitting, Inspection, and interconnection	0.15 \$AU/Wdc	For construction permits fee, interconnection study fees for testing substation, testing, and commissioning
Contingency	4%	Estimated as mark-up on EPC cost; value represents actual cost overruns above estimated cost
Rack installation	0.10 \$AU/Wp	
Civil	0.21 \$AU/Wdc	
Total	1.70 \$AU/Wdc	

The mainstream PV module selected was Canadian solar CS6K-280P 280Wp, Canadian solar is place in the average warranty of no less than 80.7% of label output after 25 years for polycrystalline modules.

Table 7 Mainstream PV module's total cost

Module class	Value	Description
Mainstream (Canadian solar CS6K- 280 P 280Wp)	0.44 \$AU/Wdc	Modules typically with 60 cells, standard aluminium frames, white backsheets and 260 to 290 Wp — this represents most modules on the market

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Structural components (racking)	0.15 \$AU/Wdc	Fixed-tilt racking or one axis tracking system
Electrical components	0.19 \$AU/Wdc	Conductors, conduit and fittings, transition boxes, switchgear, panel boards, etc.
Engineering, Procurement and Construction EPC overhead (of equipment cost)	13%	Costs and fees associated with EPC overhead, inventory, shipping, and handling
Direct installation labour	Electrician: \$AU 50.00 per hour; Labourer: \$45.60 per hour	Depends on state, it is considered half hour of each electrician and labour work for each module.
Permitting, Inspection, and interconnection	0.15 \$AU/Wdc	For construction permits fee, interconnection study fees for testing substation, testing, and commissioning
Contingency	4%	Estimated as mark-up on EPC cost; value represents actual cost overruns above estimated cost
Rack installation	0.10 \$AU/Wp	
Civil	0.21 \$AU/Wdc	
Total	1.65 \$AU/Wdc	

The low-cost PV module selected is DMEGC DM215-M125-72. This panel was selected because it is no longer being offer by the manufacturer and the power output warranty is slightly smaller than the mainstreams. It warranties at least 80% of labelled output after 25 years.

Table 8 Low cost PV module's cost including installation

Module class	Value	Description
Low cost (DMEGC DM215-M125-72 215Wp)	0.32 \$AU/Wdc	Factory seconds, insolvency goods, used or low-output modules and products with limited or no warranty

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Structural components (racking)	0.15 \$AU/Wdc	Fixed-tilt racking or one axis tracking system
Electrical components	0.19 \$AU/Wdc	Conductors, conduit and fittings, transition boxes, switchgear, panel boards, etc.
Engineering, Procurement and Construction EPC overhead (of equipment cost)	13%	Costs and fees associated with EPC overhead, inventory, shipping, and handling
Direct installation labour	Electrician: \$AU 50.00 per hour; Labourer: \$45.60 per hour	Depends on state, it is considered half hour of each electrician and labour work for each module.
Permitting, Inspection, and interconnection	0.15 \$AU/Wdc	For construction permits fee, interconnection study fees for testing substation, testing, and commissioning
Contingency	4%	Estimated as mark-up on EPC cost; value represents actual cost overruns above estimated cost
Rack installation	0.10 \$AU/Wp	
Civil	0.21 \$AU/Wdc	
Total	1.48 \$AU/Wdc	

Table 9 Grid tie inverter's price including installation

Category	Value	Description
Inverter price (Sunny Tripower 15000TL)	0.431 \$/Wdc [23]	
Engineering, Procurement and Construction EPC overhead (of equipment cost)	13%	Costs and fees associated with EPC overhead, inventory, shipping, and handling

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Direct installation labour	Electrician: \$AU 50.00 per hour; Labourer: \$45.60 per hour	Depends on state
Contingency	4%	Estimated as mark-up on EPC cost; value represents actual cost overruns above estimated cost
Total	0.508 \$AU/W	

Table 10 Interactive inverter's price including installation

Category	Value	Description
Interactive inverter price	0.916 \$AU/Wdc [23]	It is supposed that the inverter has 15,000 W of capacity
Engineering, Procurement and Construction EPC overhead (of equipment cost)	13%	Costs and fees associated with EPC overhead, inventory, shipping, and handling
Direct installation labour	Electrician: \$AU 50.00 per hour; Labourer: \$45.60 per hour	Depends on state, it is considered one hour of each electrician and labour work for each inverter.
Contingency	4%	Estimated as mark-up on EPC cost; value represents actual cost overruns above estimated cost
Total	1.076 \$AU/W	

Table 11 Battery price including installation

Category	Value	Description
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Battery Li-ion (Powerpack 210 kWh it has an inverter attached to it)	588.41 \$AU/kWh [24]	
Engineering, Procurement and Construction EPC overhead (of equipment cost)	13%	Costs and fees associated with EPC overhead, inventory, shipping, and handling
Direct installation labour	Electrician: \$AU 50.00 per hour; Labourer: \$45.60 per hour	Depends on state, it is considered one hour of each electrician and labour work for each inverter.
Contingency	4%	Estimated as mark-up on EPC cost; value represents actual cost overruns above estimated cost
Total	688.97 \$AU/kWh	144,683.7 \$AU/ battery

Exchange rate

The Peruvian official exchange rate on 14th November 2019 was 3.376 soles per American dollar (Sunat 2019) [25] while the reserve bank of Australia published an exchange rate of 0.6798 \$ per Australian dollar and 0.6163 € per Australian dollar (Reserve Bank of Australia 2019) [26] .

Fuel cost

The diesel price in the city of Trujillo on 18th of November is 12.50 soles per gallon

$$12.5 \frac{S}{gal} \times \frac{1 \text{ gal}}{4.55 \text{ l}} \times \frac{\$}{3.376 S} \times \frac{\$ AU}{0.6798 \$} = 1.197 \frac{\$ AU}{l}$$

2.5 Assumptions

The following assumptions were made during the modelling of the generation system.

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Operation and maintenance cost of PV 13.24 \$AU/kW/yr that is the half of the recommended by the national Renewable energy lab (National Renewable Energy Laboratory 2018) [7] and is divided 13.08 \$AU/kW/year for the PV panels and 0.159 \$AU/kW/year for the inverters. The battery does not have maintenance.

Inflation rate in Peru 2.2%.

Discounted rate 6%.

O&M cost of the gensets are \$6.37/hour, \$4.51/hour and \$1.88/hour for the 500kVA, 350kVA and 60 kVA respectively.

Degradation of the PV modules:

- SunPower E-Series: E20-435-COM 435Wp degradation 0.32% per year.
- Canadian solar CS6K- 280 P 280Wp 0.792% of degradation per year.
- DMEGC DM215-M125-72 215Wp 0.8% of degradation.

2.6 Development of models

The modules were developed in order to target 15%, 40% and 60% penetration for each technology.

In order to select the right amount of PV and inverters installed capacity in HOMER two procedures were applied one for the selection of the inverters base on the PV module and the second to approximate the output require of each technology.

The selection of the inverters for each technology module is done by a graphic approach so for the extreme operation temperature the IV curve of the array must be inside the operation voltage of the selected inverter and beneath the operation current of it. In addition, the IV curve of the array must not heat the IV of the inverter. From the different options of SMA grid tied inverters the SMA tripower 20000 TL was the most suitable for all the PV technologies.

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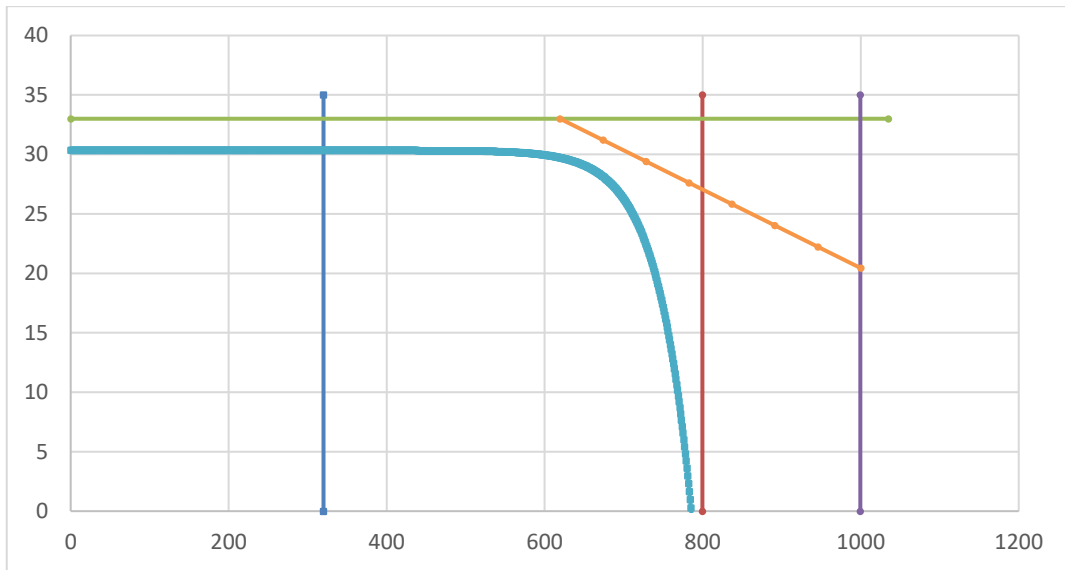


Figure 8 Graphic method for the selection of the inverters

Table 12 Selection of the inverters base on technology

Technology	Amount of PV panels	Size of inverter
High efficiency (SunPower E-Series: E20-435-COM 435Wp)	45	SMA Sunny Tripower 20000TL (20440 W)
Mainstream (Canadian solar CS6K- 280 P 280Wp)	60	SMA Sunny Tripower 20000TL (20440 W)
Low cost (DMEGC DM215-M125-72 215Wp)	85	SMA Sunny Tripower 20000TL (20440 W)

For the array sizing an excel sheet was develop to match the array size for an optimized tilt angle to match the desire penetration. The PV output was calculated on a monthly basis and for each month the amount of daily and nightly energy demand was calculated bearing in mind the different efficiency of the system for a daily night the efficiency of the battery is not considered. On the other hand, during the night the RE energy is provided by the battery so its efficiency is considered. For both cases the system and temperature efficiency were considered. So, the summation of the monthly PV output is divided by summation of the monthly energy required.

3. Experimental results

Table 13 HOMER results through different scenarios considering PV module degradation

Architecture/Sun435 (kW)	Architecture/Sun435-Inv. (kW)	Architecture/500k WGen (kW)	Architecture/Kohl360 (kW)	Architecture/CAT-100 (kW)	Architecture/Tesla PP2	Architecture/Converter (kW)	Cost/COE (\$)	Cost/NPC (\$)	Cost/Op rating cost (\$/yr)	Cost/Initial capital (\$)	System/Ren Frac (%)	System/Total Fuel (L/yr)	500kWGen/Hours	500kWGen/Production (kWh)	500kWGen/Fuel (L)	500kWGen/O&M Cost (\$/yr)	500kWGen/Fuel Cost (\$/yr)	Kohl360/Hours	Kohl360/Production (kWh)	Kohl360/Fuel (L)	Kohl360/O&M Cost (\$/yr)	Kohl360/Fuel Cost (\$/yr)	CAT-100/Hours	CAT-100/Production (kWh)	CAT-100/Fuel (L)	CAT-100/O&M Cost (\$/yr)	CAT-100/Fuel Cost (\$/yr)	Sun435/Capital Cost (\$)	Sun435/Production (kWh/yr)	TeslaPP2/Autonomy (hr)	TeslaPP2/nual Throughput (kWh/yr)	TeslaPP2/Nominal Capacity (kWh)	TeslaPP2/Usable Nominal Capacity (kWh)	Converter/Rectifier Mean Output (kW)	Converter/Inverter Mean Output (kW)
520	400	500	360	80	2	105	0.3351	19,007,790	1,088,226	1,489,547	20.62	765,598	6,293	2,320,617	610,282	40,087	730,507	3,727	450,140	146,734	16,808	175,641	1,316	26,431	8,582	2,474	10,273	1,087,200	827,019	1.0441	114,178.2	0	0	13.8923	11.6157
1092	840	500	360	80	7	311	0.3168	17,971,760	890,870	3,630,542	39.95	579,750	4,500	1,723,179	451,953	28,662	540,987	2,968	361,141	117,549	13,384	140,706	1,577	31,531	10,248	2,965	12,267	2,283,120	1,736,740	3.6543	446,006.9	0	0	54.2674	45.3735
1879	1460	500	360	80	14	583	0.3187	18,076,160	713,586	6,588,860	59.30	390,202	3,123	1,206,490	316,246	19,895	378,546	1,688	207,926	67,524	7,615	80,826	1,007	19,695	6,433	1,893	7,700	3,935,980	2,989,841	7.3085	977,823.8	0	0	118.9770	99.4767
520	400	500	360	80	2	107	0.3367	19,099,950	1,095,432	1,465,699	19.87	772,102	6,373	2,351,456	618,367	40,597	740,185	3,681	445,823	145,245	16,600	173,859	1,297	26,177	8,490	2,438	10,162	1,061,200	780,211	1.0441	107,208.1	0	0	13.0441	10.9066
1144	880	500	360	80	7	311	0.3183	18,054,990	892,840	3,682,062	39.74	581,799	4,513	1,728,648	453,382	28,749	542,699	2,983	363,048	118,165	13,451	141,443	1,577	31,545	10,252	2,966	12,272	2,334,640	1,716,465	3.6543	442,164.7	0	0	53.7998	44.9826
1950	1500	500	360	80	14	589	0.3207	18,189,440	717,519	6,638,836	58.95	393,397	3,156	1,218,537	319,413	20,101	382,337	1,688	208,509	67,677	7,615	81,009	984	19,326	6,307	1,851	7,550	3,979,500	2,925,792	7.3085	969,970.4	0	0	118.0213	98.6778
550	440	500	360	80	2	589	0.3496	19,830,490	1,110,067	1,960,651	19.92	771,562	6,367	2,350,261	618,035	40,560	739,788	3,674	445,115	145,010	16,570	173,577	1,304	26,245	8,517	2,451	10,195	1,037,520	795,344	1.0441	109,594.4	0	0	13.3345	11.1493
1200	930	500	360	80	8	357	0.3185	18,065,080	886,759	3,790,042	40.86	569,915	4,458	1,711,354	448,773	28,394	537,181	2,810	343,269	111,652	12,674	133,647	1,468	29,153	9,490	2,761	11,360	2,248,440	1,734,722	4.1763	485,162.1	0	0	59.0312	49.3569
1993	1540	500	360	80	15	593	0.3204	18,176,560	722,841	6,540,284	59.33	390,137	3,119	1,202,439	315,225	19,865	377,324	1,713	211,258	68,587	7,226	82,098	982	19,410	6,325	1,847	7,571	3,731,960	2,880,936	7.8306	1,003,833.0	0	0	122.1410	102.1227

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Table 14 Different modelled scenarios costs, COE, penetration and payback period

Architecture/ Sun435 (kW)	Architecture/ Sun435-Inv. (kW)	Architecture/ 500kWGen (kW)	Architecture/ Kohl360 (kW)	Architecture/ CAT-100 (kW)	Architecture/ TeslaPP2	Architecture/ Converter (kW)	Cost/COE (\$)	Cost/NPC (\$)	Cost/ Operating cost (\$/yr)	Cost/ Initial capital (\$)	System/ Ren Frac (%)	System/ Total Fuel (L/yr)	Sun435/ Capital Cost (\$)	m	Simple payback period
520	400	500	360	80	2	105	0.3351	19,007,790	1,088,226	1,489,547	20.62	765,598	1,087,200	21.969	15
1092	840	500	360	80	7	311	0.3168	17,971,760	890,870	3,630,542	39.95	579,750	2,283,120	46.862	22
1879	1460	500	360	80	14	583	0.3187	18,076,160	713,586	6,588,860	59.30	390,202	3,935,980		42
Architecture/ Can280 (kW)	Architecture/ Can280-Inv. (kW)	Architecture/ 500kWGen (kW)	Architecture/ Kohl360 (kW)	Architecture/ CAT-100 (kW)	Architecture/ TeslaPP2	Architecture/ Converter (kW)	Cost/COE (\$)	Cost/NPC (\$)	Cost/ Operating cost (\$/yr)	Cost/ Initial capital (\$)	System/ Ren Frac (%)	System/ Total Fuel (L/yr)	Can280/ Capital Cost (\$)	m	Simple payback period
520	400	500	360	80	2	107	0.3367	19,099,950	1,095,432	1,465,699	19.87	772,102	1,061,200	23.475	15
1144	880	500	360	80	7	311	0.3183	18,054,990	892,840	3,682,062	39.74	581,799	2,334,640	53.433	23
1950	1500	500	360	80	14	589	0.3207	18,189,440	717,519	6,638,836	58.95	393,397	3,979,500		44
Architecture/ PV (kW)	Architecture/ PV-Inv. (kW)	Architecture/ 500kWGen (kW)	Architecture/ Kohl360 (kW)	Architecture/ CAT-100 (kW)	Architecture/ TeslaPP2	Architecture/ Converter (kW)	Cost/COE (\$)	Cost/NPC (\$)	Cost/ Operating cost (\$/yr)	Cost/ Initial capital (\$)	System/ Ren Frac (%)	System/ Total Fuel (L/yr)	PV/ Capital Cost (\$)	m	Simple payback period
550	440	500	360	80	2	589	0.3496	19,830,490	1,110,067	1,960,651	19.92	771,562	1,037,520		40
1200	930	500	360	80	8	357	0.3185	18,065,080	886,759	3,790,042	40.86	569,915	2,248,440	59.595	24
1993	1540	500	360	80	15	593	0.3204	18,176,560	722,841	6,540,284	59.33	390,137	3,731,960		43

As can be appreciated in table 14 the systems with the high efficiency technology (Sun Power: 435Wp; $\eta=20.1\%$) is the best option for a low different three levels of penetration analyzed. The Initial investment of the high efficiency technology for the analyzed load is always smaller than the mainstream (Canadian Solar) an low cost technology (DMEGC).

It is shown on table 14 how the number of batteries increase as the penetration increase almost at the same pace in all the technologies.

The shortest period of payment is the scenario of 20% RE for a high technology solar panel.

4. Discussion

Most of the investment decision support programs as HOMER and REDscreen has changed from open source to commercial.

The solar data might be similar for many areas of the Peruvian highlands. The solar data of this Peruvian site shows similar patterns as the solar data of Muh research in southern Cameroon, both shows a very variable solar resource [2].

The load assessment shows a unique pattern of demand being the night demand higher than the day demand, this increase the necessity of batteries and it is completely different to the previous researches where the majority of the load occurs during the day.

As I-Yun states it is possible base on the learning curve that the cost of the battery decrease in the future to at least 150 \$/kWh. So it is spected that the LCOE will reduce in time but this will need a series of breakthrough [24].

Base on Khelif research the Peruvian fuel cost 0.738 €/liter (1.197 \$AU/liter) indicates that this project must be profitable [3].

There is a limitation on the selected site to use other technologies like wind or hydro that could bolster the renewable energy penetration due to the lack of RE resources.

Findings

- The Peruvian government does not provide subsidies for middle size commercial installations.
- The most suitable modelling program is HOMER.
- The best Solar data for Peru is the NSRDB.
- The insolation is very variable in Peru.
- The more efficient technology the higher reduction of costs its experience.
- O&M and fuel price has a small impact for this site in Peru.
- The optimal LCOE for this site and load is 0.3168 \$AU/kWh, it is around 40% of penetration and it uses the high efficiency technology.
- A high night demand increases the necessity of batteries.
- The cost of the battery has a big impact on the price.

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5. Conclusion

The goal of this thesis is to optimize a hybrid system for the mining company Lucma.

As outline in chapter one the necessity of development stimulates the installation of distributed generation in order to supply isolated loads. In this regard it has being found that due to the low cost of O&M of the generator sets, variable solar resource and high night demand it is very difficult to reduce the LCOE for an isolated mine in Peru. The best result were obtained for the high efficiency technology and the optimal price for a mine that experience a peak of 510kW is 0.31684 \$AU/kWh with correspond to 40% of penetration which represent and initial investment of 1,489,547 \$AU and a payback period of more than 44 years. On the other hand, when the mini grid is optimized for the lowest payback period the best scenario is a 20% penetration and a LCOE of 0.3351 \$AU/kWh. It must be recommended that for commercial purpose it is imperative to calculate the payback period of the mini grid.

In case there is a risk of taxes for CO₂ or GHG emissions this should be considered in the LCOE calculation.

The implementation of mini grids for this kind of industrial loads (510kWp) and resources might take an approach of increasing step by step and depending on available technology the penetration (penetration is the ratio of energy produce by RE over total energy consume during a whole year). It should be analyzed the potential of hybrid systems of sites with similar insolation apply to small communities that do not have access to electricity.

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Annexes

Table 15 SunPower E-Series: E20-435-COM

Parameter	Specification
Nominal Maximum Power (P_{max})	435 W
Optimum Operating Voltage (V_{mpp})	72.9 V
Optimum Operating Current (I_{mpp})	5.97 A
Open Circuit Voltage (V_{OC})	85.6 V
Short Circuit Current (I_{SC})	6.43 A
Module efficiency	20.1%
Operating temperature	-40° C to +85° C
Temperature characteristics:	
P_{max}	-0.35% / ° C
V_{OC}	-0.275% / ° C
I_{SC}	0.0404% / ° C
Nominal Operating Cell Temperature	
Dimensions (mm)	2067 x 1046 x 46

Table 16 Canadian solar CS6K- 280 P

Parameter	Specification
Nominal Maximum Power (P_{max})	280 W
Optimum Operating Voltage (V_{mpp})	31.3 V
Optimum Operating Current (I_{mpp})	8.95 A
Open Circuit Voltage (V_{OC})	38.2 V
Short Circuit Current (I_{SC})	9.52 A
Module efficiency	17.11%
Operating temperature	-40° C to +85° C
Temperature characteristics:	
P_{max}	-0.40% / ° C
V_{OC}	-0.31% / ° C
I_{SC}	0.05% / ° C
Nominal Operating Cell Temperature	43±3° C
Dimensions (mm)	1650 x 992 x 35

Literature review: Design of a PV-genset-battery hybrid system to supply the electricity demand of the mining company Lucma.

Table 17 DMEGC DM215-M125-72 215Wp

Parameter	Specification
Nominal Maximum Power (P_{max})	215 W
Optimum Operating Voltage (V_{mpp})	37.6 V
Optimum Operating Current (I_{mpp})	5.73 A
Open Circuit Voltage (V_{oc})	46.2 V
Short Circuit Current (I_{sc})	6.07 A
Module efficiency	16.84%
Operating temperature	-40° C to +85° C
Temperature characteristics:	
P_{max}	-0.420% / ° C
V_{oc}	-0.32% / ° C
I_{sc}	0.043% / ° C
Nominal Operating Cell Temperature	43±3° C
Dimensions (mm)	1650 x 992 x 35