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Design and implementation of rural microgrids : Laguna Grande case study

Franco Canziani Amico

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Design and Implementation of Rural Microgrids – Laguna Grande Case Study

Doctoral Thesis

Franco Canziani Amico

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Prof. Jaume Miret i Tomàs

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Nothing is too wonderful to be true
if it be consistent with the laws of nature.

Michael Faraday
(Laboratory journal entry #10,040, 19 March 1849)

“The least expensive way to achieve universal electricity access in many areas appears to be renewable energy sources: in addition to increasing grid-connected electricity generation from renewables, declining costs of small-scale solar photovoltaic (PV) for stand-alone systems and mini-grids is key in helping deliver affordable electricity access to millions. This is especially the case in remote rural areas in African countries, home to many of the people still deprived of electricity access. Decentralized solutions as a whole are the least-cost way to provide power to more than half of the population gaining access by 2030 according to our Sustainable Development Scenario.”

International Energy Agency 2019:

ABSTRACT

In 2015 the United Nations established the 17 Sustainable Development Goals: a set of interrelated objectives and a guide to reach a more sustainable and higher quality future for all humanity. The goals were set with a timeline for 2030, the seventh goal refers specifically to the universal access to “affordable and clean energy”. Taking account the considerable fraction of world population that do not have access to electricity, especially in rural areas, this goal still requires a great effort and investment. Rural hybrid microgrids, that integrate and manage solar and wind energy resources to provide electric service to remote locations, are a promising solution to reach this “last mile” scenario. However, as is reported in the literature, there is still scarce information about the performance of these systems based on measured data obtained in real working field conditions. This work aims to contribute to this aspect mainly by analyzing the data obtained in the 9 kW Laguna Grande community hybrid microgrid, which is operative since 2016 in the coast of Perú and has been equipped with sensors and data acquisition systems that measure and register solar radiation, wind speed, temperatures, and all the relevant electric parameters.

As a preliminary study, the rural electrification gap and costs are assessed, as well as the availability of solar and wind resources in the area of interest. A literature and state of the art review is undertaken followed by the definition of the microgrid concept and the different ways in which a rural microgrid can be configured. The particular way in which the Laguna Grande microgrid is configured and instrumented is described. Measured meteorological conditions as solar radiation, wind speed and temperature are analyzed and related to the power generated by the photovoltaic arrays and wind turbine. This in turn leads to a balance with respect to the power delivered to the community and consequently to the voltage levels of the battery bank. Battery dynamics concepts are used to determine the depth of discharge (DOD) of the batteries in a real time regime. The statistics of the DOD values allows for the duration of the battery to be estimated which is a key factor to the microgrid economics and reliability.

A parametric study is done to assess the effect of varying battery size on the technical and economic performance of the microgrid; similarly, with generating capacity in both photovoltaic arrays and wind turbines. Complementarily, a commercial software is used to optimize the microgrid, introducing state of the art components as lithium-ion batteries, power electronics and photovoltaic modules for a future upgrade. Finally, this study would not be complete without emphasizing the importance and adequate consideration of the human factor for the success and long-term sustainability of rural electrification projects.

RESUMEN

En el año 2015 las Naciones Unidas estableció los 17 Objetivos de Desarrollo Sostenible: un conjunto de objetivos interrelacionados y una guía para alcanzar un futuro más sostenible y de mayor calidad para toda la humanidad. Las metas se establecieron con una línea de tiempo para el 2030, la séptima meta se refiere específicamente al acceso universal a “energía limpia y asequible”. Teniendo en cuenta la fracción considerable de la población mundial que no tiene acceso a la electricidad, especialmente en las zonas rurales, este objetivo aún requiere un gran esfuerzo e inversión. Las microrredes híbridas rurales, que integran y gestionan los recursos de energía solar y eólica para proporcionar servicio eléctrico a lugares remotos, son una solución prometedora para llegar a este escenario de “última milla”. Sin embargo, como se reporta en la literatura, aún existe poca información sobre el desempeño de estos sistemas basada en datos medidos y obtenidos en condiciones operativas, reales de campo. Este trabajo busca contribuir en este aspecto principalmente mediante el análisis de los datos obtenidos en la microrred híbrida comunitaria de 9 kW en Laguna Grande, que está operativa desde 2016 en la costa de Perú. Esta microrred ha sido equipada con sensores y sistemas de adquisición de datos que miden y registran la energía solar, radiación, velocidad del viento, temperaturas y todos los parámetros eléctricos relevantes.

Como estudio preliminar se evalúa la brecha y costos de electrificación rural, así como la disponibilidad de recurso solar y eólico en la zona de interés. Se realiza una revisión bibliográfica y del estado del arte, seguida de la definición del concepto de microrred y las diferentes formas en que se puede configurar una microrred rural. Se describe la forma particular en que se configura e instrumenta la microrred de Laguna Grande. Las condiciones meteorológicas medidas como la radiación solar, la velocidad del viento y la temperatura se analizan y relacionan con la energía generada por los arreglos fotovoltaicos y la turbina eólica. Esto a su vez conduce a realizar un balance con respecto a la potencia entregada a la comunidad y consecuentemente a los niveles de voltaje del banco de baterías. Los conceptos de dinámica de batería se utilizan para determinar la profundidad de descarga (DOD) de las baterías en un régimen a tiempo real. Las estadísticas de los valores DOD permiten estimar la duración de la batería, lo cual es un factor clave para la economía y confiabilidad de la microrred.

Se realiza un estudio paramétrico para evaluar el efecto de variar el tamaño de la batería en el desempeño técnico y económico de la microrred; de igual forma, con la capacidad de generación tanto en arreglos fotovoltaicos como turbinas eólicas. Complementariamente, se utiliza un software comercial para optimizar la microrred, introduciendo componentes de última generación como baterías de iones de litio, electrónica de potencia y módulos fotovoltaicos para una futura actualización. Finalmente, este estudio no estaría completo sin enfatizar la importancia y la adecuada consideración del factor humano para el éxito y la sostenibilidad a largo plazo de los proyectos de electrificación rural.

ACKNOWLEDGEMENTS

This is a continuing work, an important part of what I live for, dedicated to:

My parents Anita and Lino, my great privilege.
My beloved wife Verónica with all her support, encouragement and bright ideas.
My beautiful sons Isabella and Leonardo and the light I see in their eyes.
The community of Laguna Grande, and all the people living in remote places to which technology can give better opportunities.

My acknowledgment to research promoting institutions like *Innovate*, *Cienciactiva* of Perú and *CYTED* of Spain for funding microgrid research and development projects, both sides of the Atlantic. A special mention and acknowledgement to my ever-enthusiastic co-workers at Waira Energía, who are willing to reach that difficult but gratifying last mile.

Enormous gratitude to my wise and kind advisors Miguel Castilla and Jaume Miret, and to the memory of inspiring teachers like Miguel Hadzich and Vassili Samsonov, who believed in sustainable solutions long before they finally became a global trend.

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Mis hermosos hijos Isabella y Leonardo y la luz que veo en sus ojos.
La comunidad de Laguna Grande, y todas las personas que viven en lugares remotos a los que la tecnología les puede dar mejores oportunidades.

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1. INTRODUCTION

In an ideal world every human being coming to life should have equal opportunities for development and prosperity through adequate access to health, education, justice and security. The availability of basic services as drinking water, sanitation, waste collection, health care, energy (both thermal and electric), mobility, education and information are transversal to this objective. These and other key issues are contemplated in the United Nations Sustainable Development Goals (SDG). It is the particular interest of this work SDG-7 [1] [2] referred to sustainable energy access.

The present situation is very far from ideal: focusing only on electricity access there are extensive areas of the world where this key service is unreliable or all together not available. This is particularly acute in Africa, South and Central America and some countries of Asia and even more critical in rural areas [3] [4], as will be detailed in section 3.1.

Conventional solutions to reduce the electrification gap in rural areas are grid extensions and the operation of diesel or gasoline electric generators. Considering remote locations in complex topography, grid extensions can be very costly and hard to finance taking account of the usual low consumption of distant communities. The projected revenue of the electric service is far too low to amortize the considerable investment in transmission lines and substations. Furthermore, in many places the grid is already close to its limit of capacity; supplying power to new connections implies costly upgrades along the line from the origin. Remote connections can also be liable to frequent service interruptions as a consequence of its peripheral situation and power line failures as will be seen in section 3.2. The operation of fuel driven electric generators is usually intermittent and very expensive due to the high cost of fuel and its transportation to remote locations, also to the relative short live and intensive maintenance of the engines. The operation of conventional fuel driven electric generators under very reduced loads is extremely uneconomical because the engines are locked to a fixed speed to maintain the AC frequency using a considerable amount of fuel and delivering very little energy. Furthermore, in the case of diesel engines this leads to severe malfunctions and premature failure by what is known as wet stacking: the accumulation of incomplete combustion residues in the exhaust system of the engine, mainly because low combustion chamber temperature [5]. There are technologies that enable diesel driven electric generators to operate in very low loads or even under variable speed, but these solutions are normally available for large powers, often exceeding the requirements of rural electrification [6].

As will be seen in section 4.2 microgrids are defined as “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. Microgrids can connect and disconnect from the grid to enable them to operate in both grid-connected or island mode” [7]. Hybrid microgrids in particular combine more than one energy resource. By capturing local energy resources like solar radiation and wind, hybrid microgrids arise as a valuable alternative to supply energy to communities in remote locations. The technological developments and cost reductions of photovoltaic modules, power electronics and batteries have allowed microgrids to outstand as a reliable and competitive alternative for rural electrification. Small wind turbines have not undergone dramatic costs reductions or technological enhancements, being a relatively mature technology, however state-of-the art small wind power systems have improved in reliability and ease of maintenance. This is addressed in section 4.3.

The potential that hybrid rural microgrids have to effectively reduce the persistent electrification gap is hampered usually by scarcity of financial resources but also because of insufficient information about their performance and reliability based on measured data in real working conditions [8]. This work aims to contribute to this aspect: analyzing the performance and costs of the Laguna Grande 9 kW hybrid microgrid using measured data of meteorological and electrical parameters taken in real working field conditions. This microgrid is working since July 2016 and has been equipped with all the necessary sensors and data loggers to measure and register relevant parameters, this is seen in section 4.4.

The behavior of both the resources and the load is stochastic, so the measured wind and solar radiation daily profiles are obtained with their respective variability in percentiles, this is also the case for the measured load profile. Daily temperature profiles are also relevant, and it is equally treated in Section 5.1.

Special attention is given to the battery as the key component with respect to reliability (Loss of Load Probability: LLP) and cost of energy (Levelized Cost of Energy: LCOE). Battery behavior is complex, and its durability strongly depends on the charge/discharge regimes and temperature it is exposed to. Additionally, in determining the Depth of Discharge (DOD) of a battery under working conditions, battery dynamics concepts and equations must be applied to account for the non-linear effects of battery current and temperature as will be seen in Section 5.2.

In the process of assessing the performance of the Laguna Grande microgrid, the battery bank is recognized as its main cost and reliability driver. This is usually the costliest component of the microgrid and the one that needs more care and attention. Different battery bank technologies and sizes have different initial costs and replacement periods, this is determinant for the microgrid´s economic profile. A larger battery capacity enhances the microgrid´s reliability but heavily affects costs, so a compromise solution must be reached between one and the other, as will be seen in Sections 5.3 and 5.4.

Varying the size of the generation components: the PV array and the number of wind turbines affects the performance parameters of costs and reliability; a parametric study is undertaken in this respect in Section 5.5. This analysis can help to take better design decisions to reach an acceptable reliability level (low LLP) at a competitive cost (unit investment and LCOE). The commercial specialized software for microgrid optimization HOMER is used to compare the results obtained and elaborate further insights for future microgrid upgrades as described in Section 5.6. Section 5.7 is dedicated to addressing the fundamental importance of the human factor and the adequate attention to social aspects to ensure rural microgrid long-term sustainability. Finally, Section 6 details the recommendations and conclusions reached in this work, as well as continuing lines of research.

2. OBJECTIVES

The objectives of this work are the following:

- To contribute to the understanding of the technical and economic performance of rural hybrid microgrids through the analysis of measured data in real working field conditions, and to apply this knowledge to enhance future designs and upgrades.
- To generate a consistent methodology that helps to assess and analyze the performance of a variety of rural microgrids used for remote electrification.
- To stablish the bases of future lines of research for the advancement of rural microgrids as a well proven and reliable solution for the electrification of remote communities.

3. RURAL ELECTRIFICATION

3.1 Rural electrification gap

Electricity is not available in many places of the World; this affects approximately 771 million persons according to the International Energy Agency (IEA) 2020 report. Most of this population is located in Africa, a minor fraction in developing Asia, Middle East and Central and South America as can be seen in Table 1 [3].

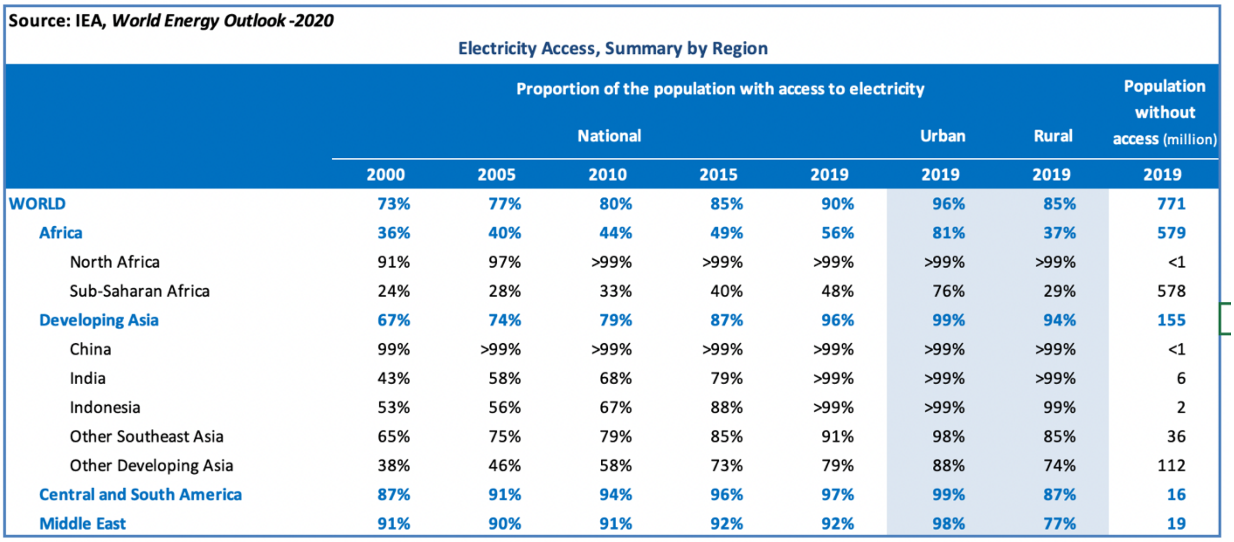
The lack of access to electricity is more pronounced in rural areas as can be seen numerically in the shaded columns of Table 1 and graphically in Figures 1 and Figure 2.

In the Peruvian case, according to IEA 2019 data 97.0 % general population has access to electricity while this is only 86.3% for the rural population. Comparing different sources as the Instituto de Estadística e Informática (INEI), the Dirección General de Electrificación Rural (DGER) of the Ministerio de Energía y Minas (MINEM) there is partial and somewhat contradictory data which can be summarized to our best knowledge in Table 2 [9] [10] (Shaded area corresponds to projected data). This is plotted in Figure 3 in which the shaded area corresponds to an extrapolation towards achieving SDG-7.

Peru has sharp socioeconomical gaps, with a considerable fraction of its population in poverty and extreme poverty levels. These levels are defined by INEI according to the buying capacity of individuals, the poverty level is established as € 86/month and the extreme poverty level as €46/month. Until 2019 the population in the poverty levels was diminishing consistently down to 20.2%, because of the COVID-19 pandemic it has gone up dramatically to 30.1% in 2020. Poverty is much harder on rural than on urban areas: 45.7% and 26% respectively. Similarly, for extreme poverty is 13.7% rural and 2.6% urban [11]. Giving access to electric service to rural areas is one of the effective ways to fight poverty and work towards sustainable social and economic development. Many electrification requirements, if viewed by the traditional ways of grid extensions or diesel electric generators, are far from being cost effective. However, these same projects have an excellent social profitability, bringing development and opportunities to remote and sometimes forsaken communities, helping to close the acute gap between rural and urban areas.

There are several levels of access to electric service, it is not enough to have a connection, it is very important to qualify the service according to several parameters of capacity, availability, reliability, affordability and others as it is done with the Energy Sector Management Assistance Program (ESMAP) of the World Bank [12]. This methodology establishes a Multi-Tier Framework (MTF) according to 7 service attributes qualified in 5 tiers as shown in Table 3. The attributes are assessed separately and the overall tier results from the lowest qualification obtained. Minimum requirements for a household are specified in Table 4.

Table 1: Electricity access by regions



Source: IEA, *World Energy Outlook -2020*

Electricity Access, Summary by Region

	Proportion of the population with access to electricity							Population without access (million)
	National					Urban	Rural	
	2000	2005	2010	2015	2019	2019	2019	2019
WORLD	**73%**	**77%**	**80%**	**85%**	**90%**	**96%**	**85%**	**771**
Africa	**36%**	**40%**	**44%**	**49%**	**56%**	**81%**	**37%**	**579**
North Africa	91%	97%	>99%	>99%	>99%	>99%	>99%	<1
Sub-Saharan Africa	24%	28%	33%	40%	48%	76%	29%	578
Developing Asia	**67%**	**74%**	**79%**	**87%**	**96%**	**99%**	**94%**	**155**
China	99%	>99%	>99%	>99%	>99%	>99%	>99%	<1
India	43%	58%	68%	79%	>99%	>99%	>99%	6
Indonesia	53%	56%	67%	88%	>99%	>99%	99%	2
Other Southeast Asia	65%	75%	79%	85%	91%	98%	85%	36
Other Developing Asia	38%	46%	58%	73%	79%	88%	74%	112
Central and South America	**87%**	**91%**	**94%**	**96%**	**97%**	**99%**	**87%**	**16**
Middle East	**91%**	**90%**	**91%**	**92%**	**92%**	**98%**	**77%**	**19**

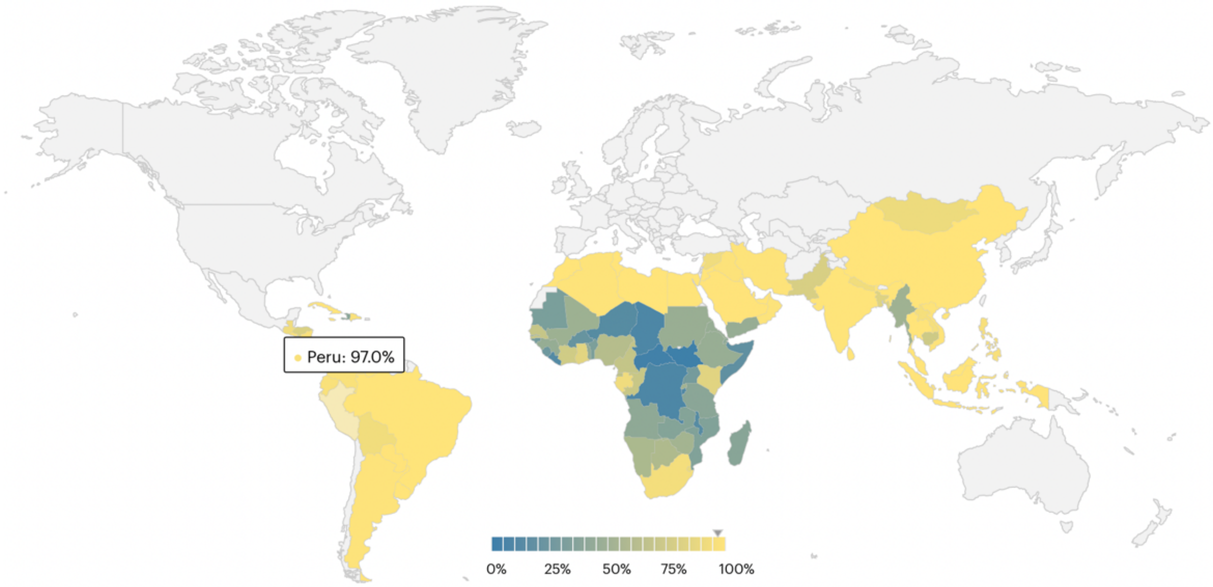


Figure 1:Global access to electricity (2019)

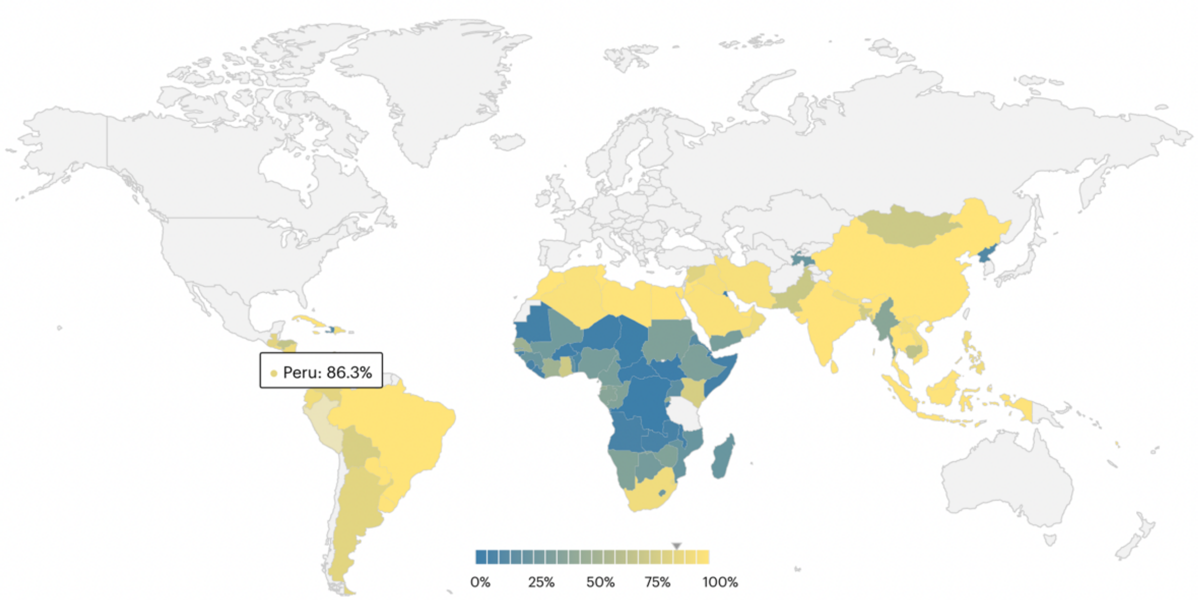
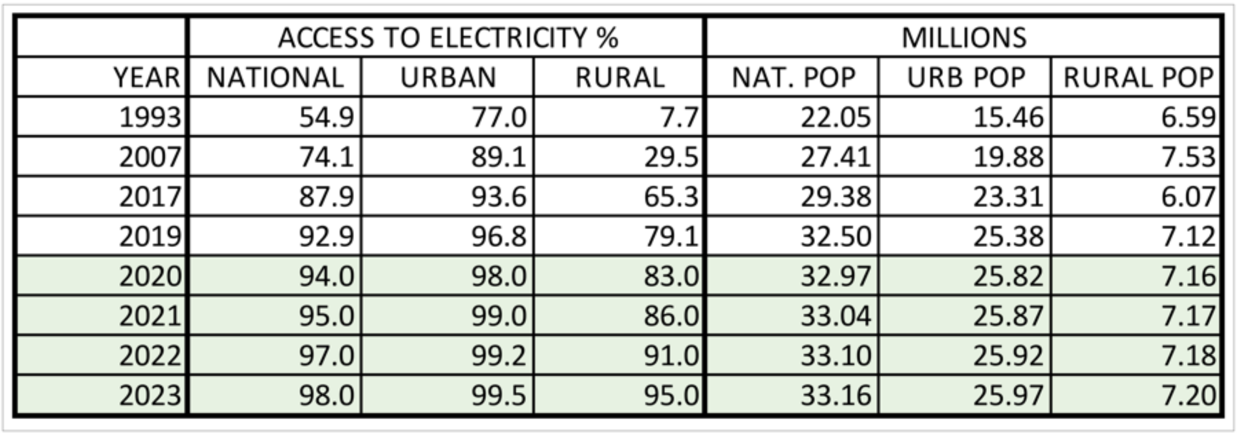


Figure 2: Rural access to electricity (2019)

Table 2: Electricity access for Peruvian urban and rural population.



	ACCESS TO ELECTRICITY %			MILLIONS		
YEAR	NATIONAL	URBAN	RURAL	NAT. POP	URB POP	RURAL POP
1993	54.9	77.0	7.7	22.05	15.46	6.59
2007	74.1	89.1	29.5	27.41	19.88	7.53
2017	87.9	93.6	65.3	29.38	23.31	6.07
2019	92.9	96.8	79.1	32.50	25.38	7.12
2020	94.0	98.0	83.0	32.97	25.82	7.16
2021	95.0	99.0	86.0	33.04	25.87	7.17
2022	97.0	99.2	91.0	33.10	25.92	7.18
2023	98.0	99.5	95.0	33.16	25.97	7.20

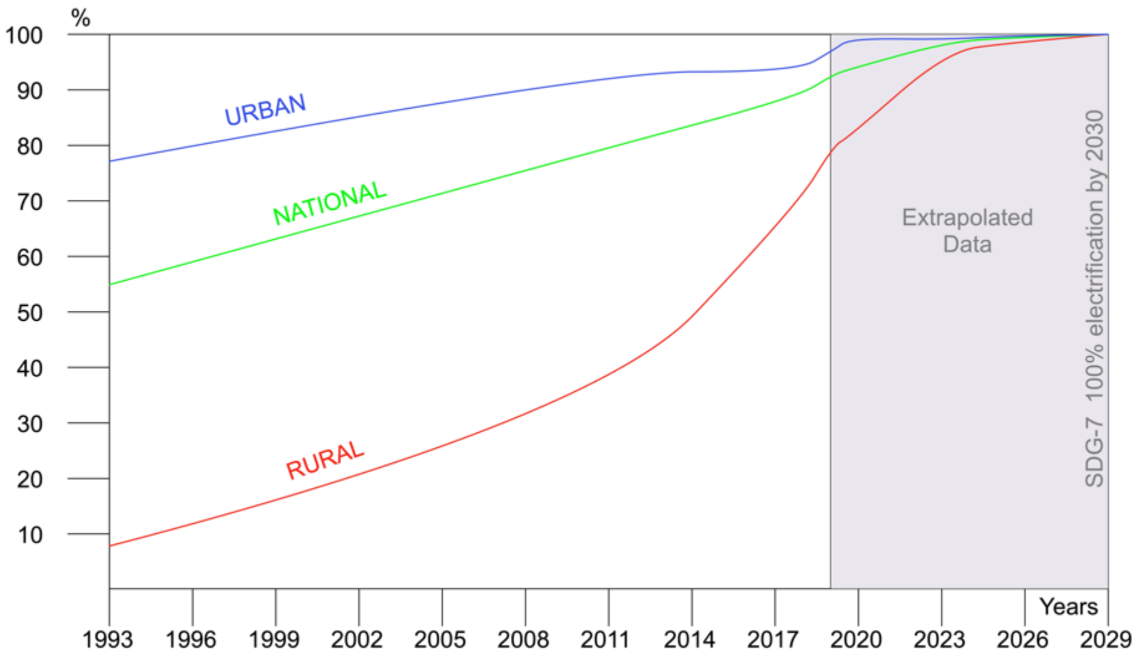
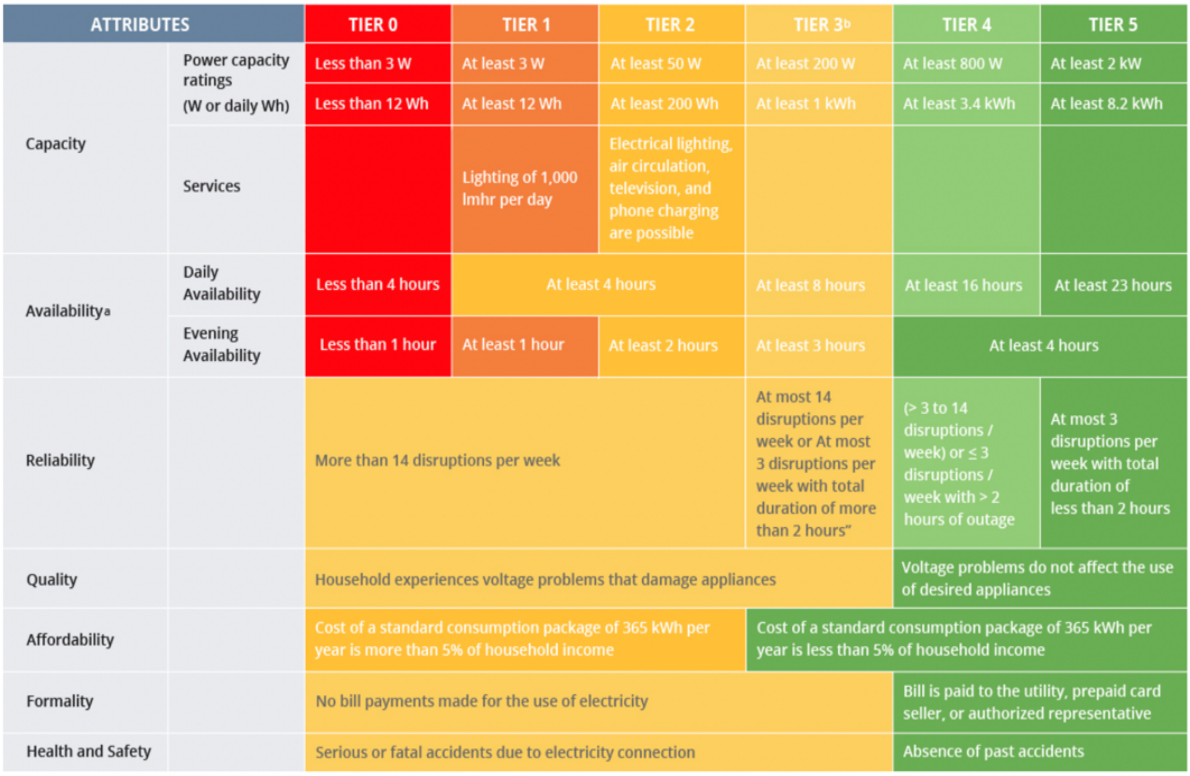


Figure 3: Evolution of access to electricity for Peruvian urban and rural population

Table 3: Multi-Tier Framework scheme for assessing the quality of an electric service



ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3[b]	TIER 4	TIER 5
Capacity	Power capacity ratings (W or daily Wh)	Less than 3 W	At least 3 W	At least 50 W	At least 200 W	At least 800 W	At least 2 kW
		Less than 12 Wh	At least 12 Wh	At least 200 Wh	At least 1 kWh	At least 3.4 kWh	At least 8.2 kWh
	Services		Lighting of 1,000 lmhr per day	Electrical lighting, air circulation, television, and phone charging are possible			
Availability[a]	Daily Availability	Less than 4 hours	At least 4 hours		At least 8 hours	At least 16 hours	At least 23 hours
	Evening Availability	Less than 1 hour	At least 1 hour	At least 2 hours	At least 3 hours	At least 4 hours	
Reliability		More than 14 disruptions per week			At most 14 disruptions per week or At most 3 disruptions per week with total duration of more than 2 hours"	(> 3 to 14 disruptions / week) or ≤ 3 disruptions / week with > 2 hours of outage	At most 3 disruptions per week with total duration of less than 2 hours
Quality		Household experiences voltage problems that damage appliances				Voltage problems do not affect the use of desired appliances	
Affordability		Cost of a standard consumption package of 365 kWh per year is more than 5% of household income			Cost of a standard consumption package of 365 kWh per year is less than 5% of household income		
Formality		No bill payments made for the use of electricity				Bill is paid to the utility, prepaid card seller, or authorized representative	
Health and Safety		Serious or fatal accidents due to electricity connection				Absence of past accidents	

Table 4: Multi-Tier Framework minimum requirements of a household electric service

Tier 0	Tier 1	Tier 2
Electricity is not available or is available for less than 4 hours per day (or less than 1 hour per evening). Households cope with the situation by using candles, kerosene lamps, or dry-cell-battery-powered devices (flashlight or radio).	At least 4 hours of electricity per day is available (including at least 1 hour per evening), and capacity is sufficient to power task lighting and phone charging or a radio. Sources that can be used to meet these requirements include a SLS, a solar home system (SHS), a minigrid (a small-scale and isolated distribution network that provides electricity to local communities or a group of households), and the national grid.	At least 4 hours of electricity per day is available (including at least 2 hours per evening), and capacity is sufficient to power low-load appliances—such as multiple lights, a television, or a fan (see table 1)—as needed during that time. Sources that can be used to meet these requirements include rechargeable batteries, an SHS, a mini-grid, and the national grid.
Tier 3	**Tier 4**	**Tier 5**
At least 8 hours of electricity per day is available (including at least 3 hours per evening), and capacity is sufficient to power medium-load appliances—such as a refrigerator, freezer, food processor, water pump, rice cooker, or air cooler (see table 1)—as needed during that time. In addition, the household can afford a basic consumption package of 365 kWh per year. Sources that can be used to meet these requirements include an SHS, a generator, a mini-grid, and the national grid.	At least 16 hours of electricity per day is available (including 4 hours per evening), and capacity is sufficient to power high-load appliances—such as a washing machine, iron, hair dryer, toaster, and microwave (see table 1)—as needed during that time. There are no frequent or long unscheduled interruptions, and the supply is safe. The grid connection is legal, and there are no voltage issues. Sources that can be used to meet these requirements include diesel-based mini-grids and the national grid.	At least 23 hours of electricity per day is available (including 4 hours per evening), and capacity is sufficient to power very high- load appliances—such as an air conditioner, space heater, vacuum cleaner, or electric cooker (see table 1)—as needed during that time. The most likely source

Providing basic access to electricity is a great step towards enhancing people´s quality of life, however this does not necessarily result in sustainable development. For this to be possible the income and economy of the individuals and the community as a whole has to be improved. If the electric service provides the required power and consistency for its productive use, then it will have a positive impact on the local economy, and this can lead to sustainable development. MTF is also applied more stringently to qualify an electric service for productive uses as is shown in Table 5.

Table 5: Multi-Tier Framework minimum requirements of a productive use electric service

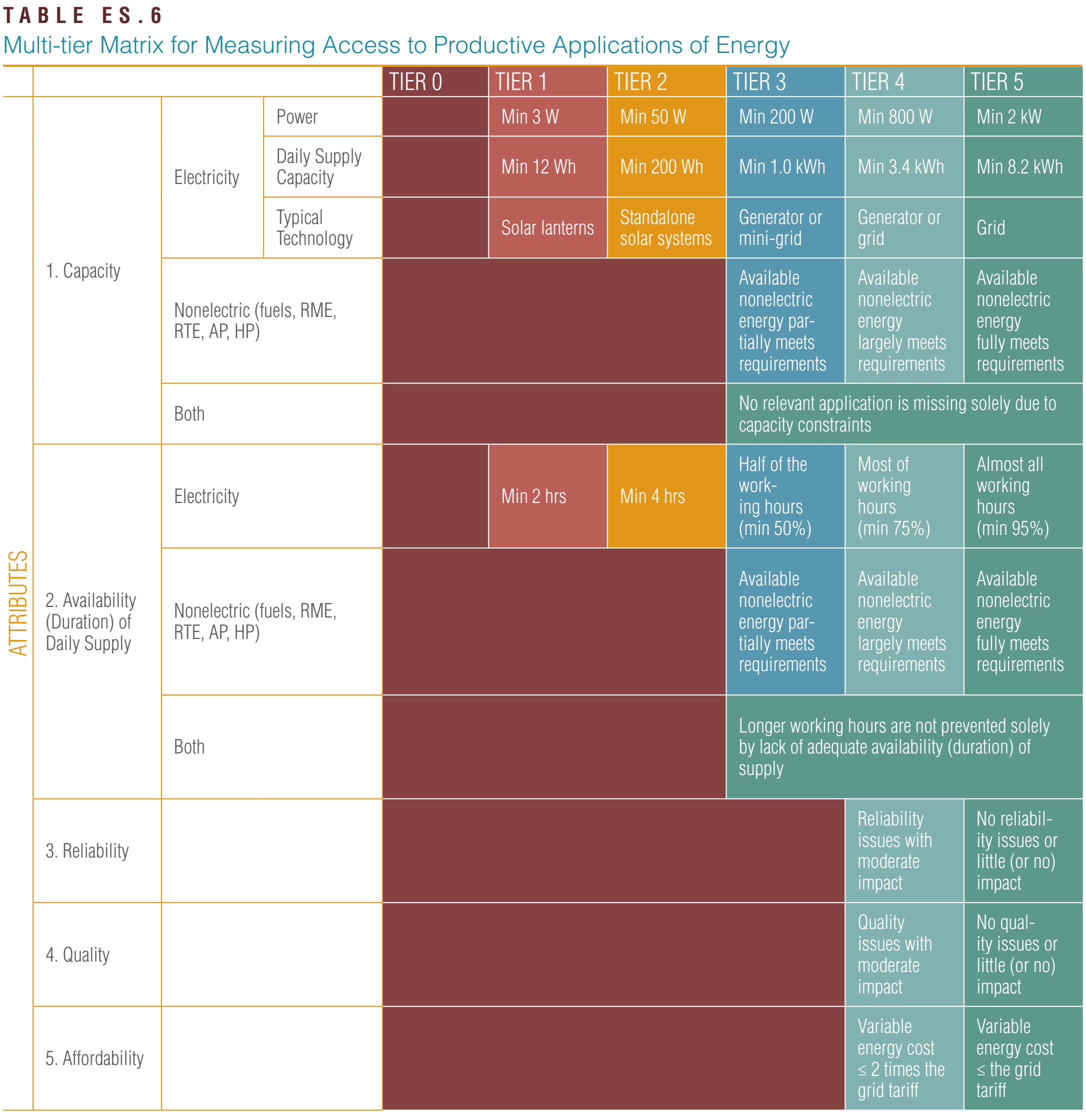


TABLE ES.6

Multi-tier Matrix for Measuring Access to Productive Applications of Energy

ATTRIBUTES			TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
1. Capacity	Electricity	Power		Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
		Daily Supply Capacity		Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
		Typical Technology		Solar lanterns	Standalone solar systems	Generator or mini-grid	Generator or grid	Grid
	Nonelectric (fuels, RME, RTE, AP, HP)					Available nonelectric energy partially meets requirements	Available nonelectric energy largely meets requirements	Available nonelectric energy fully meets requirements
	Both					No relevant application is missing solely due to capacity constraints		
2. Availability (Duration) of Daily Supply	Electricity			Min 2 hrs	Min 4 hrs	Half of the working hours (min 50%)	Most of working hours (min 75%)	Almost all working hours (min 95%)
	Nonelectric (fuels, RME, RTE, AP, HP)					Available nonelectric energy partially meets requirements	Available nonelectric energy largely meets requirements	Available nonelectric energy fully meets requirements
	Both					Longer working hours are not prevented solely by lack of adequate availability (duration) of supply		
3. Reliability							Reliability issues with moderate impact	No reliability issues or little (or no) impact
4. Quality							Quality issues with moderate impact	No quality issues or little (or no) impact
5. Affordability							Variable energy cost ≤ 2 times the grid tariff	Variable energy cost ≤ the grid tariff

3.2 Cost of Energy in Rural Areas

When faced with the need to electrify a remote rural community all the different possibilities and scenarios must be considered with the aim to offer the most reliable, sustainable and cost-effective solution. If possible, conventional solutions as grid extension and diesel electric generators are to be considered as well as the adequate use of local renewable energy resources. The correct and equitable procedure to evaluate the various alternatives that have different initial investments, operation and maintenance costs distributed in time is to apply the concept of Levelized Cost of Energy (LCOE expressed in US$/kWh) defined by [13] :

$$LCOE = \left(I_0 + \sum_{t=1}^{n} \frac{M_t + F_t}{(1+r)^t} \right) \Big/ \left(\sum_{t=1}^{n} \frac{E_t}{(1+r)^t} \right) \qquad (1)$$

where I_0 is the initial investment, M_t is the annual maintenance cost, F_t is the annual fuel cost (particularly for the diesel generator case), E_t is the annual energy generated and delivered, n is the years of life cycle of the electrification project (20 years), and r is the financial discount rate. This last term deserves special attention as applying financial discount rate to energy may seem strange. In this regard it is important to consider that both monetary expenditures and energy generation are distributed in a long period of time and for correct assessment and comparison they are both brought to present value dividing each value of the distribution by $(1+r)^t$.

In fact, the LCOE formula (1) takes in account the way in which expenditures and energy generation are distributed in time. Energy generation normally has an even distribution, but expenditures can be concentrated at the beginning of the project, as is the case for grid extension and microgrids, or more evenly distributed for the case of diesel electric generators. Discount rates may vary considerably according to the nature of the project, state financed projects may consider values as low as 2 to 3%, more commercial or private projects may be closer to 10 or 12%, In this analysis a moderate discount rate is considered at 6%. Other factors as energy consumption growth, inflation, variations in the price of fuel and electricity may be considered in the analysis, but for the sake of simplicity they are not incorporated in this basic electrification project comparison.

To illustrate these possibilities and their approximate costs, a hypothetical and simplified set up is considered with a small village of 35 houses needing a total of 30 kWh/day of electricity. The village is located at 10 km from the nearest grid substation, has access to a hydraulic resource at 1 km and is in a zone with an annual average irradiation of 5,5 kWh/m2.day and 5 m/s of annual average wind speed. The initial investment as well as the annual operation and maintenance costs are detailed to determine key economic indicators as unit investment (expressed in US$/kW) and LCOE (expressed in US$/kWh).

3.2.1 Grid extension

In this case the possibility of using a point of connection at a substation 10 km from the village is considered taking account the commercial medium voltage tariff of 0.0658 US$/kWh. The cost of the transmission line is calculated with local standards at US$ 8195 per km which is within the ranges considered by the Alliance for Rural Electrification [14]. In the same way the costs of the distribution lines with the corresponding 35 service points with pre-payment meters is calculated to US$ 6030. The yearly lines maintenance expenses are estimated to 5% of their value. These results are shown in Table 6 and Figure 4.

Table 6: Grid extension costs

GRID EXTENSION	Period	
Initial investment		US$
Transmission line: 30 kW, 10 km (8,195 US$/km)		81950
Distribution lines with 35 pre-payment meters		6030
Total Initial Investment	Initial	87980
Yearly expenditures		
Lines maintenance (3.5%)	yearly	3079
Energy purchase (30 kWh/day , 0.0658 US$/kWh)	yearly	721
Delivered Energy		kWh
30 kWh/day for 365 days	yearly	10950
LCOE (r= 6%)	US$/kWh	1.05
LCOE (r= 0)	US$/kWh	0.75
Effect of distribution	40%	

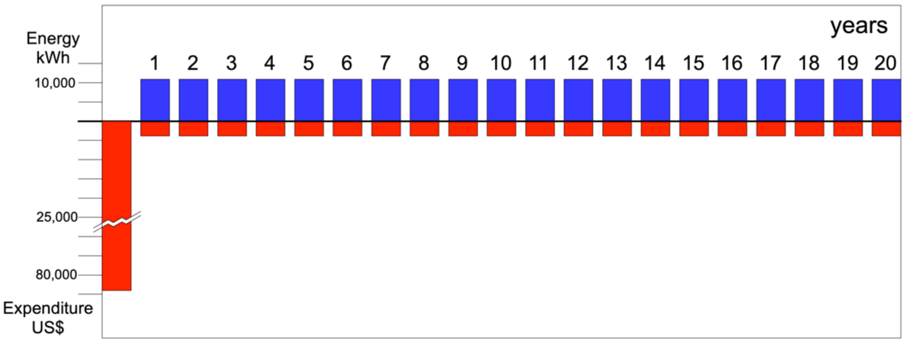


Figure 4: Case study: grid extension, energy and expenditure distribution in time

3.2.2 Diesel electric generators

Diesel electric generators normally have a relatively low initial cost, 10 kVA capacity is considered because smaller units commonly work with gasoline and are very short lived, furthermore the higher volatility of gasoline makes the operation much more dangerous. Diesel engines under low load operation are very uneconomical as they must run at a fixed speed to keep the AC frequency stable. They also present problems due to “wet stacking”, the accumulation of unburned fuel in the exhaust ducts, that will lead to premature failure or excessive maintenance cost. For this reason, diesel electric generators in rural electrification systems normally operate only at certain hours of the day. In this case we have assumed a working regime from 6 am to 10 pm. The cost of routine maintenance interventions is considered at 250 hours and heavier interventions each 6.250 hours. The engine duration is approximately 25000 hours, so renewals are considered every 4 years [14]. These results are shown in Table 7 and Figure 5.

Table 7: Diesel electric generator costs

DIESEL ELECTRIC GENERATOR (16/24 regime)	Period	
Initial investment		**US$**
Diesel 10 kW generator purchase and installation		5263
Distribution lines with 35 pre-payment meters		6030
Total Initial Investment	Initial	11293
Yearly expenditures		
Engine maintenance	yearly	1080
Fuel consumption	yearly	6290
Equipment replacement	4 years	5263
Delivered Energy		**kWh**
30 kWh/day for 365 days	yearly	10950
LCOE (r= 6%)	**US$/kWh**	**0.86**
LCOE (r= 0)	US$/kWh	0.82
Effect of distribution	5%	

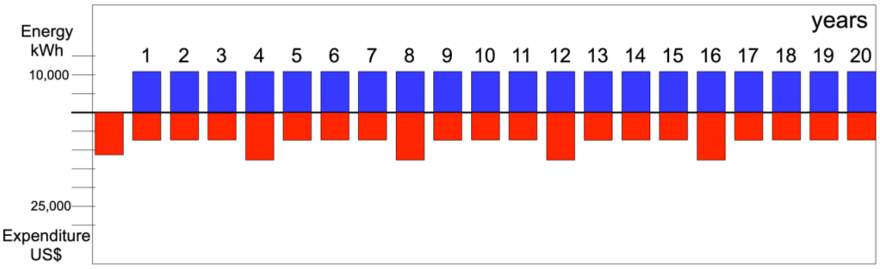


Figure 5: Case study: diesel electric generator, energy and expenditure distribution in time

3.2.3 Small hydraulic turbine generator

If the village is located near a hydraulic resource, of suitable height, flow and consistency, it is most likely that this will constitute its best energy source both in reliability and economy. Unfortunately, not all places have access to hydraulic resources. In this case a 5kVA hydraulic turbine and generator is installed being connected to the village with a 1 km transmission line, the whole set up requiring very low expenditures in maintenance. These results are shown in Table 8 and Figure 6.

3.2.4 Hybrid microgrid with VRLA-Gel Batteries

A typical hybrid microgrid is configured for this hypothetical electrification project. Consisting of a 7.2 kWp PV array, one 3 kW wind turbine, a 38.4 kWh Valve Regulated Lead Acid: VRLA-Gel battery bank with suitable controllers and inverters. Here the annual expenses are more complicated as the batteries will need replacement every 3.5 years, the electronics every 10 years and the wind turbines will require regular maintenance every 5 years. These results are shown in Table 9 and Figure 7.

Table 8: Small hydro generator costs

SMALL HYDRO GENERATOR	Period	
Initial investment		**US$**
Small Hydro turbine and generator 5kW		8950
Transmission line: 1 km (8,195 US$/km)		8195
Distribution lines with 35 pre-payment meters		6030
Total Initial Investment	Initial	23175
Yearly expenditures		
Equipment and lines maintenance (5%)	yearly	1156
Delivered Energy		**kWh**
30 kWh/day for 365 days	yearly	10950
LCOE (r= 6%)	**US$/kWh**	**0.29**
LCOE (r= 0)	US$/kWh	0.21
Effect of distribution	38%	

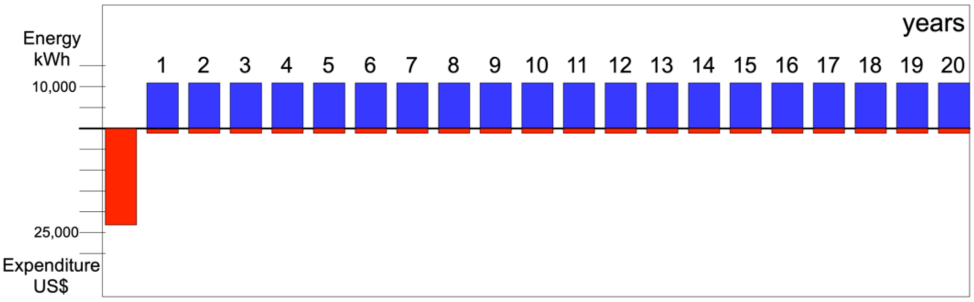


Figure 6: Case study: small hydro generator, energy, and expenditure distribution in time

3.2.5 Hybrid microgrid with Lithium-Ion Batteries

Replacing VRLA-Gel batteries for Lithium-Ion (LiFePO4) units in the microgrid brings multiple benefits thanks to their substantial longer duration which can reach more than 3500 cycles, depending on the working conditions: mainly DOD and temperature. Li-ion batteries also can work to higher levels of DOD without considerably affecting their lifetime, as a result less total storage capacity can be installed, this reduces the impact of the higher unit cost of this technology.

Other benefits are related to reduced freights and console sizes due to their higher specific energy and density (kWh/kg and kWh/m^3 respectively). In this case the Li-ion battery bank is replaced only once in year 10 as opposed to VRLG that will require 5 renewals along the 20 years lifetime of the microgrid. These results are shown in Table 10 and Figure 8.

Table 9: Hybrid microgrid costs with VRLA-Gel batteries

HYBRID MICROGRID 10.2 kW VRLA-GEL Bateries	Period	
Initial investment		**US$**
Hybrid Microgrid 7.2 kWp + 3 kW Wind Turbine		23510
Distribution lines with 35 pre-payment meters		6030
Total Initial Investment	Initial	29540
Yearly expenditures		
PV cleaning	yearly	112
Battery renewal	3.5 years	7632
Wind turbine maintenance	5years	388
Electronics renewal	10 years	5586
Delivered Energy		**kWh**
30 kWh/day for 365 days	yearly	10950
LCOE (r= 6%)	**US$/kWh**	**0.45**
LCOE (r= 0)	US$/kWh	0.35
Effect of distribution	29%	

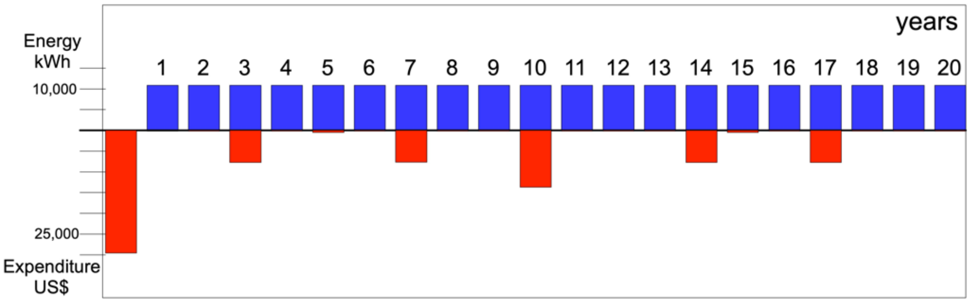


Figure 7: Case study: hybrid microgrid with VRLA batteries, energy and expenditure distribution in time

Table 11 shows the comparative results of the 5 different rural electrification solutions analyzed for the hypothetical village. Grid extension results as the most expensive alternative mainly because of the important investment in the transmission line that is hard to recover with the low energy consumption regime of the village (30 kWh/day). Diesel electric generator is also very expensive even if it has the lowest initial investment. Maintenance and mainly fuel costs make the day-to-day operation very expensive and this results in a high LCOE. It is important to highlight the fact that the diesel generator alternative only gives service 16 hours per day while the other alternatives can offer continuous service. Considering continuous service for the diesel generator case is not representative of real operations as this results in excessive fuel and maintenance costs. A small hydro operation is very attractive having a relatively low initial investment and very low operation cost, leading to a very competitive LCOE. If there is a suitable hydraulic resource at a reasonable distance from a village, then it is probably the best choice, however this is seldom found to be the case. A usable wind resource has a greater probability to be available for a rural community. Solar resource is available in all places of the globe in greater or lesser extent. Hybrid microgrids that combine these two resources offer moderate initial investment and maintenance leading to LCOE values that are only bettered by the small hydro alternative. Reliability, expressed through LLP, can be very variable, some values are included as reference.

Table 10: Hybrid microgrid costs with Lithium-Ion batteries

HYBRID MICROGRID 10.2 kW Lithium-Ion Bateries	Period	
Initial investment		**US$**
Hybrid Microgrid 7.2 kWp + 3 kW Wind Turbine		26810
Distribution lines with 35 pre-payment meters		6030
Total Initial Investment	Initial	32840
Yearly expenditures		
PV cleaning	yearly	112
Battery renewal	10 years	11130
Wind turbine maintenance	5years	388
Electronics renewal	10 years	5586
Delivered Energy		**kWh**
30 kWh/day for 365 days	yearly	10950
LCOE (r= 6%)	**US$/kWh**	**0.35**
LCOE (r= 0)	US$/kWh	0.24
Effect of distribution	46%	

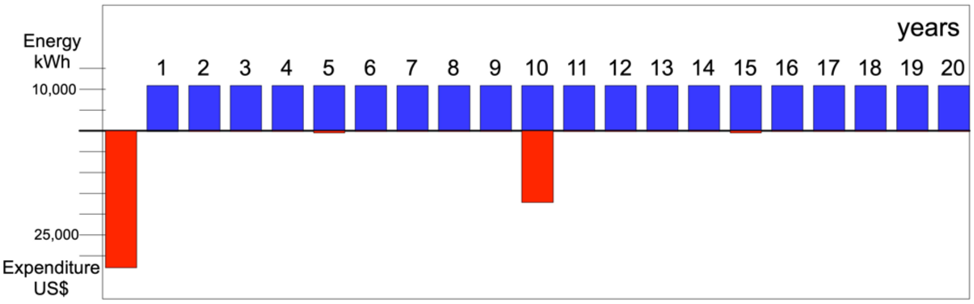


Figure 8: Case study: hybrid microgrid with Lithium-Ion batteries, energy and expenditure distribution in time

Peripheral grid connections with long transmission lines can be subjected to frequent service interruptions, diesel electric generator’s reliability depends on the quality of their maintenance and fuel supply
and even small hydro operations can be subjected to maintenance problems and water flow shortages. Hybrid microgrids, that combine different resources and energy storage, can constitute the best choice for a rural electrification project, offering a good balance between cost and reliability. Furthermore, microgrids that operate with a high component of renewable energy contribute to the reduction of greenhouse gases emissions and lead the way towards sustainable development.

The cost distribution factor is an indicator of how sparse or concentrated the expenses are along the project´s lifetime. Considering a discount rate of 6% this factor can go from 0% for an evenly distributed expense, with no initial investment, to 74.4% for the case of full initial investment with null subsequent distributed expenditure. This factor can help to assess the financial support the project will need to be implemented: diesel electric generator needs low financial support while microgrids with lithium-ion storage technology requires the highest support.

Table 11: Summary of rural electrification alternatives

SUMMARY OF ALTERNATIVES	Investment	Unit Investment	LCOE	Cost Distrib.	Estimated LLP
Rural electrification solution	US$	US$/kW	US$/kWh	Factor	
Grid extension 30 kVA 10 km	87980	2933	1.05	40%	2 - 10%
Diesel electric generator 10kVA	11293	1129	0.86	5%	2 - 10%
Small Hydro generator 5 kVA	23175	4635	0.29	38%	2 - 5%
Hybrid Microgrid 10.2 kW (VRLA-Gel)	29540	2896	0.45	29%	3 - 10%
Hybrid Microgrid 10.2 kW (Li-Ion)	32840	3220	0.35	46%	2 - 5%

Table 12: Summary of rural PV electric tariffs 2016 and 2022 run by state or private companies with or without FOSE subsidy.

		Rural PV Electric Tariff US$ /kWh (aprox 25 kWh/month)			
		2016		2022	
		w/o FOSE	w/FOSE	w/o FOSE	w/FOSE
State Managed	Coast	0.69	0.14	0.73	0.15
	Andean	0.68	0.14	0.71	0.14
	Jungle	1.01	0.20	1.05	0.21
Privatly Managed	Coast	1.14	0.23	1.22	0.24
	Andean	1.12	0.22	1.18	0.24
	Jungle	1.57	0.31	1.65	0.33

3.2.6 Commercial electricity tariffs for PV rural projects in Perú

The Peruvian state establishes the allowed electric tariffs for rural PV electrification systems through private or state initiatives. Since 2001 exists a compensatory charge to urban electric services to subsidize the rural sector. This 2001 law created the FOSE: “Fondo de Compensación Social Eléctrico” or *Social Compensatory Electric Fund* to subsidize the more expensive electrification sites [15]. These allowed tariffs are shown in Table 12 and it is evident comparing with Table 11 that microgrids with no applied subsidy compete favorably in this market.

3.3 Availability of Energy Resources

3.3.1 Solar energy resource

There are several sources that can be used as references to assess Global Horizontal Irradiation (GHI) values for a given location: In the case of Perú there is the “Atlas Solar del Perú” [16], which shows the average daily irradiation values (kWh/m^2.day) for each month for the whole Peruvian territory. The source of this information is based on the register of approximately 120 meteorological stations used as reference for modelled extrapolations. These models are based on available sunshine hours, latitude and temperature with their corresponding influence. Figure 9 shows a color coded mean annual irradiation for Perú, Figure 10 is specific during typical months for the Ica region where Laguna Grande is located.

Figure 9: Solar irradiation map of Perú showing annual mean values of GHI in kWh/m2.day

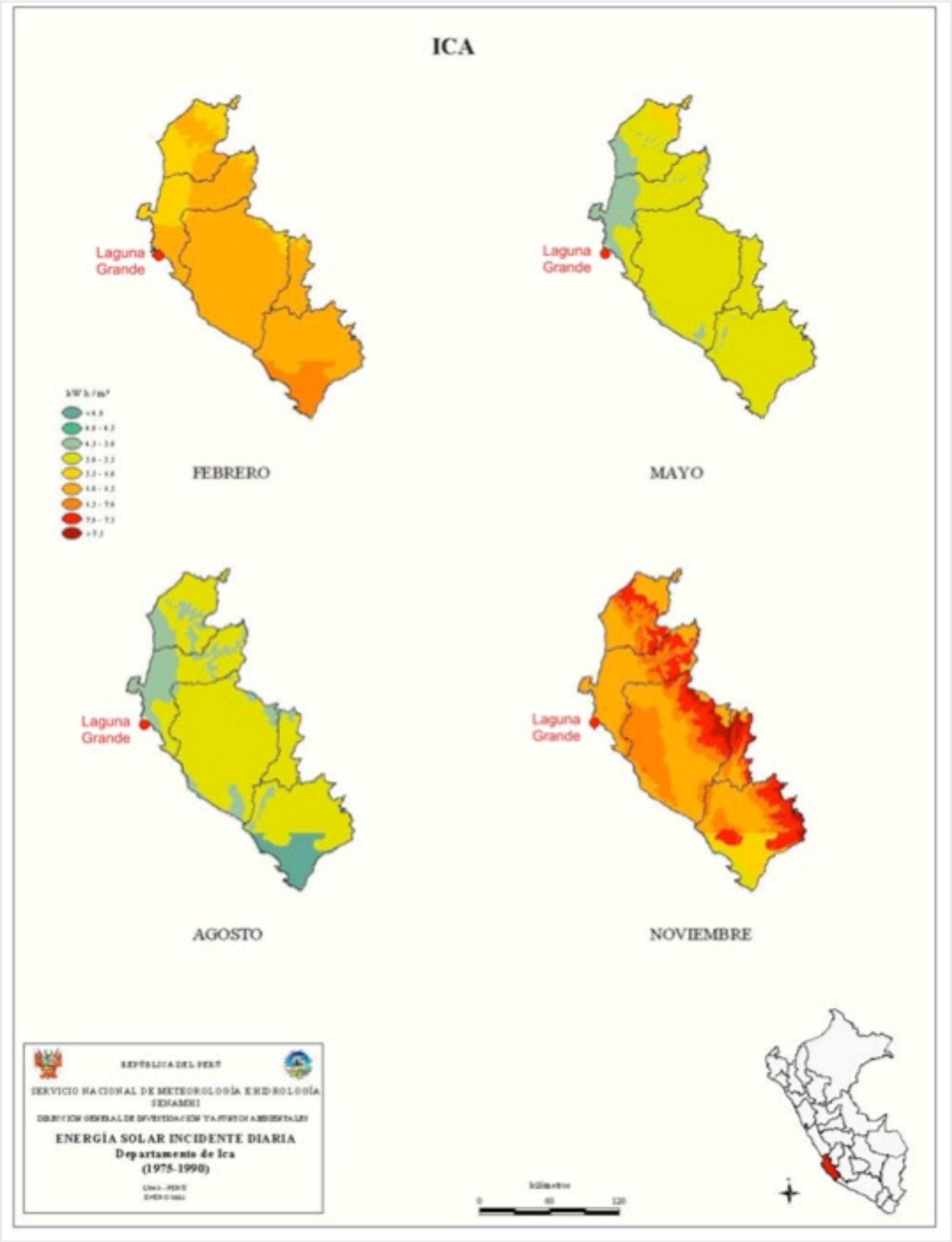


Figure 10: Solar irradiation map of the Ica Region showing typical monthly mean values of GHI in kWh/m2.day

Table 13:Comparative values of monthly average of daily solar irradiation (GHI) from different sources and direct measurement

	NASA	PVGIS	Atlas Solar Perú	Measured on site
	Laguna Grande: GHI (kWh/m2.day)			
JANUARY	7.00	7.32	6.25	6.55
FEBRUARY	6.92	6.90	6.25	6.23
MARCH	6.72	6.75	5.75	n/a
APRIL	6.07	5.87	5.75	n/a
MAY	4.98	5.24	4.75	n/a
JUNE	3.84	4.47	4.25	n/a
JULY	3.62	4.29	4.25	n/a
AUGUST	4.21	4.97	4.75	n/a
SEPTEMBER	5.26	6.23	5.75	n/a
OCTOBER	6.38	7.29	5.25	7.36
NOVEMBER	6.84	7.07	6.25	7.68
DECEMBER	6.87	7.24	6.75	7.10
	5.73	**6.14**	**5.50**	

Overall, the solar resource is very good, this is confirmed by other data bases and by the direct measurements themselves. Other valuable sources of information are NASA´s "Prediction of Worldwide Energy Resources" (POWER) that is based on complex models relying on satellite data, meteorological parameters and data assimilation procedures [17]. This last term refers to the continuous comparison and adjustments needed to be made to keep an adequate correlation with real measured data. A similar resource is the European Union´s Science Hub project on Photovoltaic Geographical Information System (PVGIS) which used to be only for Europe and Africa but know covers important parts of North and South America [18]. All these data base resources are subject to uncertainty and errors due to their models and extrapolations, it is common to find that irradiation is sometimes overestimated, especially in cloudy seasons. Nothing can be better than direct measurements with a well calibrated pyranometer and data logger. Table 13 shows the comparative results from various sources and direct measurement of GHI in Laguna Grande during certain months. As can be seen, there are substantial variations in the data, this shows the need to be prudent and conservative with the assessment of the solar energy resource: consult several data bases, consider the lower values and if possible, measure directly.

3.3.2 Wind energy resource

If the information from data bases and models regarding the solar energy resource must be addressed with reserve and prudence, this is even more so in the case of wind energy resource. Wind is a much more complex phenomenon that interacts strongly with local topography and landforms. As opposed to solar irradiation, wind velocity can change notably in a scale of less than 1 km. Furthermore, as wind power is proportional to the cube of the velocity, the effect of these variations is much amplified.

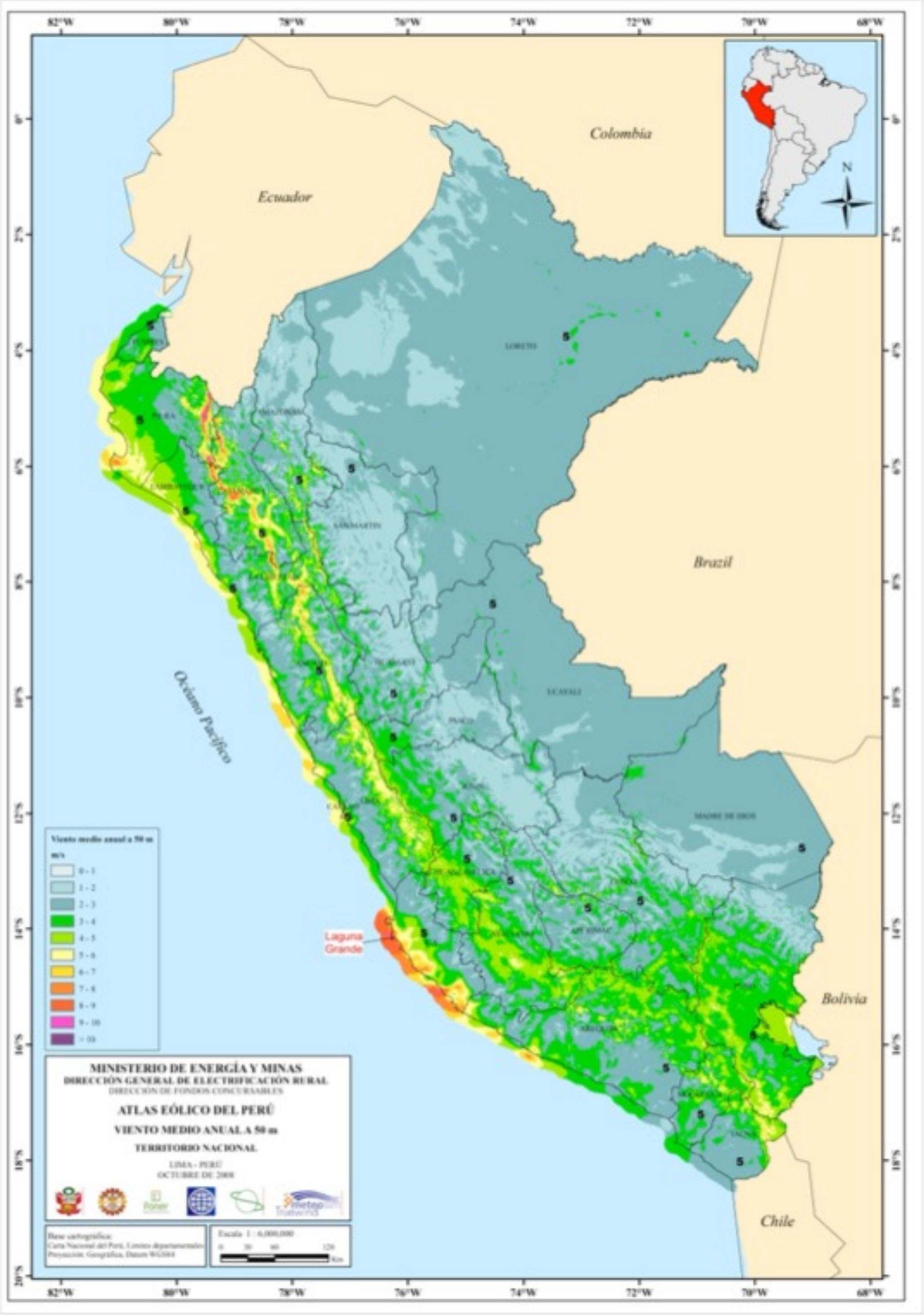


Figure 11:Annual average wind speed at a height of 50m

NASA´s POWER database [17] offers wind estimates at 10m height which largely underestimates the resource at Laguna Grande. The “Atlas Eólico del Perú” [19] is based on a Mesoscale Atmospheric Simulation System (MASS) and offers color coded maps for monthly average wind speeds at 50 and 80m. These heights are appropriate for wind farm projects but not very adequate for small rural electrification projects. The maps are available for annual average wind speed for all the territory as shown in Figure 11 and for different seasons and regions as is shown in Figure 12 corresponding to the Ica region where Laguna Grande is located.

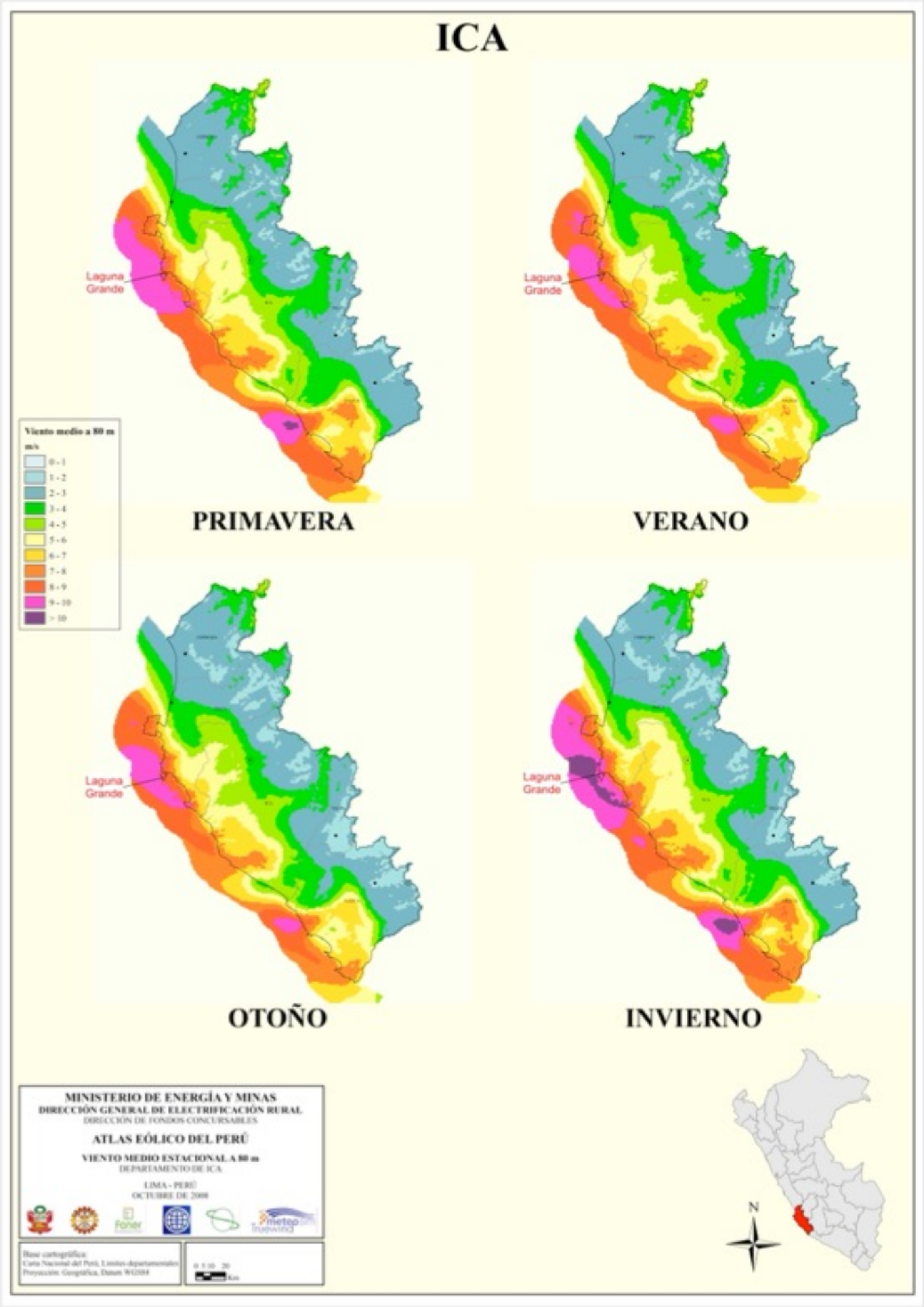


Figure 12: Seasonal average wind speed at a height of 80m for the Ica region

Table 14: Comparative values of monthly average of wind speed from different sources and measured data

	NASA	Atlas Eólico	Measured
	H = 10m	Perú H = 80m	H = 6m
	m/s	m/s	m/s
JANUARY	4.52	8.5	8.29
FEBRUARY	4.27	9.5	7.95
MARCH	4.38	9.5	8.20
APRIL	4.65	9.5	7.74
MAY	4.87	8.5	5.69
JUNE	5.21	9.5	5.47
JULY	5.55	9.5	6.38
AUGUST	5.55	9.5	7.06
SEPTEMBER	5.50	9.5	6.83
OCTOBER	5.31	9.5	6.61
NOVEMBER	5.05	9.5	7.29
DECEMBER	4.80	8.5	9.04
Annual Avr.	**4.97**	**9.25**	

Note: shaded entries are correlations from Pisco meteorological station, 45.5 km to the north

Table 14 shows the great variations that can be found in different data bases regarding wind speeds for a certain site as Laguna Grande. Thus, measuring wind speed on site is highly recommended to be sure of the real magnitude of the resource and its detailed characteristics. For instance, besides speed averages, it is of great importance the hourly distribution of wind speed to assess the complementarity with other resources like PV. Nighttime wind is very convenient to supply power during peak consumption hours and keep batteries charged while PV arrays are inactive. Measuring and registering wind speed and direction requires the installation of an anemometer, wind vane and data logger set.

4. METHODOLOGY

4.1 Literature review – State of the art

There is a great volume of literature about hybrid microgrids and their potential uses for rural electrification, most of it related to modelling and optimizing their design for particular locations and availability of resources. A substantial fraction studies a variety of modelling and computational tools applied to microgrids; a particular popular optimization tool is the commercial software HOMER. As noted by [8], [20] and [21] there is a remarkable scarcity of works that are based on real measured data of working systems under field conditions, and is in this aspect that the present work aims to contribute. In the following sections an overview of the relevant literature is shown.

4.1.1 General Reviews

[22] reviews a considerable amount of literature about different methods to assess the feasibility of off-grid electrification projects considering mainly five options: worksheet calculations, optimization tools, multi-decision-making (MCDM), system based participatory tools and hybrid methods. The author recommends this last option to incorporate the complex interaction of all the variables that must be considered.

[23] reviews the benefits of hybrid renewable energy systems and their potential applications in diverse scenarios. Several renewable energy resources are assessed with their corresponding contribution to energy supply both in grid connected and remote off-grid locations. Simulation and optimization software packages as HOMER, iHOGA, HYBRID 2, TRNSYS, SOLSYM, RAPSIM are reviewed.

[24] offers a comprehensive review recognizing the potential of hybrid (wind-solar) microgrids for sustainable energy generation and establishes research topics. The unpredictable nature of the resources is highlighted as a problem to be overcome with good design, analysis and modelling, in this aspect the hybrid combination of at least two sources is shown to increase reliability. The importance of meteorological data assessment and statistical treatment is highlighted as well as the convenience of several optimization software tools as HOMER, iHOGA, and algorithms as particle swarm optimization (PSO), RETScreen, genetic algorithms (GA), ant colony optimization (ACO) and others.

[25] is an extensive review of the state of the art in microgrid research and pays special attention to the alternatives to optimize the use or scheduling of the distributed energy resources (DER) with other software tools and algorithms as multiple integer linear programming (MILP) and Monte Carlo simulations.

[26] presents a review about mathematical modelling procedures and optimization techniques for off-grid electrification systems suggesting the possibility of using artificial intelligence to enhance their prediction capacity.

[27] provides an overview of the different modelling techniques and available simulation software, particularly focusing on the comparison of HOMER and iHOGA results with ESA Microgrid Simulator developed by the University of West Attica. Concluding that more research is needed to study the different outputs of these software under specific conditions.

[28] describes several hybrid renewable energy systems (HRES) and various modelling techniques and software to attain optimal sizing. Up to 25 types of computational tools are evaluated particularly HOMER, Genetic Algorithms and Particle Swarm Optimization.

[29] covers the whole perspective of energy use in rural environments and practical issues leading to good practices and success for remote areas electrification, bases in extensive experiences in Africa. Another publication [30] is more focused on technical aspects of rural microgrids and presents several case studies located in South Asia.

4.1.2 Works based on measured data

The most relevant work in the line of research of this thesis is found in the publications of Henry Louie; [20] analyses the operation of a 5 kW wind-solar hybrid microgrid installed in Muhuru Bay, Kenya. This microgrid was instrumented with measuring devices and data loggers to register minute by minute key parameters as battery voltage, currents from the wind turbine and solar PV array and current delivered to the loads. This information allows the author to analyze the microgrid´s energy supply, its reliability and efficiency. Furthermore, the author uses this data to enhance the performance of the microgrid and alert operators of events that can lead to premature failure.

In [31] the same author describes the applications and issues related to data acquisition systems in off-grid remote microgrids. As new registering devices are developed and the cellular telecommunications network broadens its coverage, the possibility to have real time information about the working parameters of a remote microgrid is increasingly available. This has great value to analyze its performance and supervise its adequate operation in order to enhance its performance and duration. Continuing the same line of work, in [32] the author and contributors report the use of registered data from an energy kiosk in Filibaba, Zambia to determine the reasons for a sudden reduction of PV generation. This exemplifies the value of remote monitoring and data acquisition for remote diagnosis and prompt maintenance.

In another publication in which H. Louie participates [33], comparisons are made between real measured energy consumption habits in rural communities in Kenya with assumed or modelled quantities. The conclusions of this work are very relevant for rural electrification projects that can run into financial or technical problems by overestimating the electric loads of rural communities.

A most interesting paper [34] shows how the analysis of measured data from microgrids working in real field conditions can lead to very important findings regarding mismatch between available resources and consumption. PV generation is curtailed considerably in this case and corrective measures like demand response are encouraged to enhance the performance of the system. This is another case in which the microgrid design assumptions result in substantial deviation with the real working system behavior, highlighting the importance of contrasting models with field evidence through measured data.

The work in [35] reports how by using measured data from the operation of a 17.5 kW microgrid island electrification project in Thailand an upgrade was successfully undertaken incorporating lithium-ion batteries instead of lead acid units. Lead acid batteries still are extensively used in many projects because of their lower initial cost even if the evidence shows that resulting energy costs in the long term are higher.

The publication [36] reports an interesting work that compares measured performance of a 3 kW PV islanded installation in Cluj-Napoca, Romania with the predictions of the commercial photovoltaics software PV*SOL and an analytical model developed by the local university. A good correlation was found between the three data sets.

The work in [37] combines the use of measured and estimated meteorological data to assess the performance of a grid connected wind-solar microgrid. A sensitivity analysis is performed showing the much greater uncertainty relative to the wind resource and its effect on the microgrid economics. An unstable grid is considered and the alternative with a high-performance flow battery is chosen to provide a higher quality service.

[38] is an interesting work that offers open access data measured and registered every second, during more than 3 years, from a working PV-battery microgrid installed in a research building in Japan. All the relevant working parameters of the microgrid are made accessible to researchers so that their models and simulations can be tested and compared with reality.

The work in [39] revisits 7 different off-grid rural electrification projects in India, measuring their real performance and power losses. A re-design procedure is undertaken with the aim of reducing LCOE and enhancing the quality and performance of new initiatives.

[40] is a study that measures the consumption patterns of 196 households connected to a 120 kW PV plant in Sundarban area of West Bengal, India since 2005. This work presents valuable real data for future rural electrification projects to be adjusted to the expected loads and their collective behavior.

The Alliance for Rural Electrification issued a very valuable publication [41] summarizing the lessons learned by the numerous members of the Alliance for Rural Electrification regarding their experiences in the field. It includes important references about the electrification gap, ranges of unitary costs of alternatives for rural systems, components, business models, economic and social considerations.

The publication [42] reports the valuable experience gained in an isolated microgrid supplying power to the nearly 100 inhabitants of Eigg Island in Scotland´s

Hebrides. Data collected is analyzed and used to perform an ex-post optimization that could lead to an upgrade.

[43] is a ground-breaking publication by the National Renewable Energy Laboratory in which several Village Power rural electrification projects in Alaska, Ghana, Mexico and Chile are discussed. No detail data are shown but is a relevant report regarding the importance of multidisciplinary approach and “people first” view of rural projects. The role of incorporating renewable energy sources to change the traditional paradigm of grid extensions to remote locations is also highlighted.

The National Renewable Energy Laboratory has issued this most valuable document [8] based on the real operating experience of 36 microgrids installed in sub-Saharan Africa and provided with a total of 4660 smart meters. Systematized metering and analysis of operational microgrids is recognized as a way to increase actual performance understanding, lower risks and validate business models to increase their growth as a global electrification gap solution. There is no study on operative microgrid performance with a wider base of data and variety of conditions. There are interesting findings regarding quality of service, customer satisfaction and more technical aspects as voltage and frequency stability. Furthermore, the important role that the power factor can have in the distribution network and the economics of the microgrid.

4.1.3 Publications about diverse computational algorithms

There is a remarkable abundance of optimization algorithms that can be applied to microgrids of different configurations and under different conditions in order to obtain alternatives that can reach a convenient balance between reliability investment and energy costs. Each of these algorithms has its own particularities, advantages and limitations, using them requires certain level of specialization, describing them is beyond the scope of this work. In that sense the reviews available in the literature are helpful. Other optimization methodologies are integrated in professional software products that have originated in research laboratories like DER-CAM, MDT and HOMER. Publications related to each of these algorithms or software are shown in Table 15, being an incomplete list, as there are several more.

4.1.4 Publications using HOMER software for microgrid modelling

HOMER is a very popular and widely used software for microgrid optimization, originally conceived by the US Department of Energy (DOE) in 1993 and promoted by the National Renewable Energy Laboratory (NREL) as a tool for optimize different energy sources, afterwards it was managed privately by Homer Energy who was recently acquired by the Underwriters Laboratories (UL). This software allows to easily combine different energy resources, storage systems and loads to optimize the microgrid design, it includes a flexible sensitivity analysis tool and graphical displays that facilitate balanced decisions. The number of publications using HOMER is very large, Table 16 displays a selection that has been categorized according to the interest and relevance related to the present study, including reviews that refer to many more.

Table 15: Optimization algorithms and the publications using them

Description	References
Reviews about optimization algorithms	[44][45][46]
Particle swarm optimization (PSO)	[47][48][49][50][51][52][53]
Multi-objective optimization	[54][55][56][57][52]
Genetic algorithm (GA)	[58][59][60][61][52]
Teaching-learning based optimization (TLBO)	[52][48]
Invasive weed optimization (IWO)	[50]
Backtracking Search Optimization Algorithm (BSA)	[50]
Montecarlo method	[62][63][64][65]
Time Optimization Resources, Scheduling (TORSCHE)	[66]
Artificial Neural Network (ANN)	[67][56]
Fuzzy Logic Control Algorithm	[68]
Machine learning	[69]
Differential evolution (DE)	[70]
Artificial Bee Colony Optimization	[68]
Ad-hoc mathematical method	[71][72][73][74][75][76][77] [78][79][80][81]
Professional Software	
Distributed energy resources customer adoption model (DER-CAM, Berkeley Labs)	[82][83][84]
Microgrid design toolkit (MDT, Sandia Labs)	[85]
Hybrid optimization of multiple energy resources (HOMER, originally from NREL)	(see next section 4.1.4)

4.2 Microgrid definition

4.2.1 Historic perspective

Electricity is a phenomenon long known to humanity in its static form: electric charges segregated by rubbing different materials producing high voltage sparks in a largely uncontrollable manner. It was not until the invention of the Leyden jar in 1746 that these charges could be stored in a “condensed” way, a denomination that remains current in our days in the alternate denomination for the capacitor. The discoveries of Luigi Galvani and the works of Alessandro Volta led to the production of electricity by controlled electro-chemical processes in 1800. In 1831 Michael Faraday discovered the principles of the electric generator, motor, and transformer through his laws of electromagnetic induction.

Table 16: Publications using HOMER for microgrid optimization

Description	References
Reviews about HOMER microgrid optimization publications	[86][87]
HOMER microgrid optimization publications of interest	[88][89][90][91][92][93][94][95] [96][97][98][99]
HOMER microgrid optimization publications of moderate interest	[100][101][102][103][104][105][106][107][108][109][110][111] [112][113][114][115] [116][117]
HOMER microgrid optimization publications of lower interest and relevance	[118][119][120][121][122][123][124][125][126] [127][128][129][130][131][132][133][134][135][136][137]

All these fundamental breakthroughs could be qualified as Annus *Mirabilis* in his own right, comparable to Newton´s (1666) or Einstein´s (1905) extraordinary contributions to the development of Natural Science achieved in a single year. In 1862 another great physicist: James Clerk Maxwell integrated all electric and magnetic phenomena in his essential field equations [138].

With these developments in electrical knowledge, it may be surprising that its commercial use did not start to flourish faster. Initially used for some punctual industrial applications like electric arc furnaces or electroplating, electricity was not generated and distributed to multiple users until 1882 when Edison´s Pearl Street Generating Station lighted Wall Street in downtown New York. This 50-year lapse from first principles to broad application is an emblematic case of “engineering gap” caused mainly by the insufficient understanding of the geometry of induction [139] but also because a sort of “chicken-egg” situation that was broken by Edison´s entrepreneurial drive. Pearl Street having 600 kW of installed power, with its six steam driven dynamos can be recognized as history´s first working microgrid even if it was not called so.

Reportedly the first time the term microgrid was used is in the late 1990s when US Department of Energy (DOE) proposed distributed energy concepts to the US congress as an alternative to alleviate the overburdened national grid [140]. More recently microgrids got a burst of noticeable attention in 2011 when the University of California San Diego was able to keep its important hospitals active thanks to its independence from the grid and its failing transmission lines saving numerous lives.

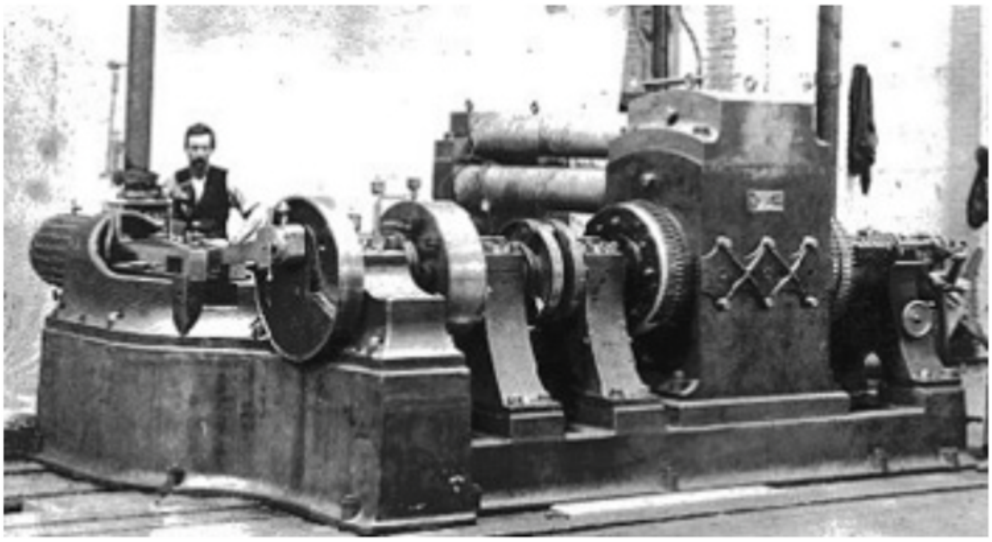


Figure 13: Vapor driven electric generator at Pearl Street Generating Station 1882

A similar case occurred in 2012 when Superstorm Sandy hit the Northeastern US and a generalized black out affected vast areas, while Princeton University in New Jersey kept all activities uninterrupted thanks to its in-campus microgrid. Nowadays microgrids have developed tremendously for multiple applications as energy security, cost reduction, sustainability and rural electrification. According to market reports the global market for microgrid technology is near 25 billion dollars and it will reach 42 billion by 2026. Regarding access to electricity, NREL reports that by 2016 approximately 8.6 million people in the world are provided of electric service through rural microgrids and that annual investments of the order of 51 billion dollars are required to reach SDG-7 by 2030 [8].

4.2.2 Present definition

The definition of microgrid has been changing slightly through the years as its concept and essence are clarified.

PIKE RESEARCH defines a microgrid as an integrated energy system consisting of distributed energy resources and multiple electrical loads operating as a single, autonomous grid either in parallel to or “islanded” from the existing utility power grid [141].

CIGRE 2015 by the International Council on Large Electric Systems working group WG6.22 defines microgrids as electricity distribution systems containing loads and distributed energy resources (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power grid or when they work as islands [142].

Present and most accepted definition: The Department of Energy offers a more formal definition for a microgrid, describing it as: “A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. Microgrids can connect and disconnect from the grid to enable them to operate in both grid-connected or island mode" [7] .

Some frequent misconceptions are that microgrids:

- Must include more than one source of power.
- Must include renewable energy resources.
- Must always be capable of connecting to the main grid.
- Must include some sort of energy storage capacity.
- Must be smaller than 100 kW otherwise it is to be called "mini-grids".

As can be seen in the DOE definition there are no such restrictions, the essence of the microgrid is that:

1) It has a defined control boundary incorporating one or several distributed energy resources (DER) and connected loads.
2) It can operate connected to the main grid or in islanded mode

4.3 Rural microgrid configurations

One of the remarkable attributes of microgrids is the possibility to configure them in many ways and to admit a variety of energy sources both in AC and DC [143]. In rural environments the most common sources are PV, wind turbines and diesel electric generators. Sources like micro-hydro and biomass are very site specific, and more challenging sources like tidal, wave and geothermal energy require a minimum size to be viable that usually greatly exceeds the demand of rural electrification projects.

The main microgrid typologies are AC and DC according to the type of electricity of the bus bars where the power generating sources are connected. In this work we will consider only solar, wind and diesel engine as available sources. Figure 14 shows a typical pure solar-wind DC microgrid in which the PV array is connected to the DC busbar by means of a MPPT controller while the wind turbine is connected through a rectifier and PWM controller combined with a dump load. The small wind turbine has a permanent magnet synchronous generator (PMSG) and requires the dump load to dispose of possible excess generation capacity. Being driven by the wind, it always needs to be under load to avoid a runaway situation, if it is power is no longer required by the load or the battery, it must be dissipated as heat. Figure 15 shows a solar-wind and diesel microgrid. In this configuration the diesel electric generator can supply DC current to the bus bar in case of insufficient power from the PV and wind turbine. The AC power delivered by the diesel electric generator can be rectified and supplied to the bus bar or directly to the AC load by an automatic commutation device.

In Figure 16 a typical AC microgrid is exemplified. The diesel electric synchronous generator (SG) is the main driver of the AC bus, receiving the contributions of the PV array through an on-grid inverter and the wind turbine through a "back-to-back" AC/DC/AC electronic interphase. The battery supplies or receives power through a bidirectional inverter-charger according to the power balance of the system, allowing the diesel engine to be inactive as much as possible.

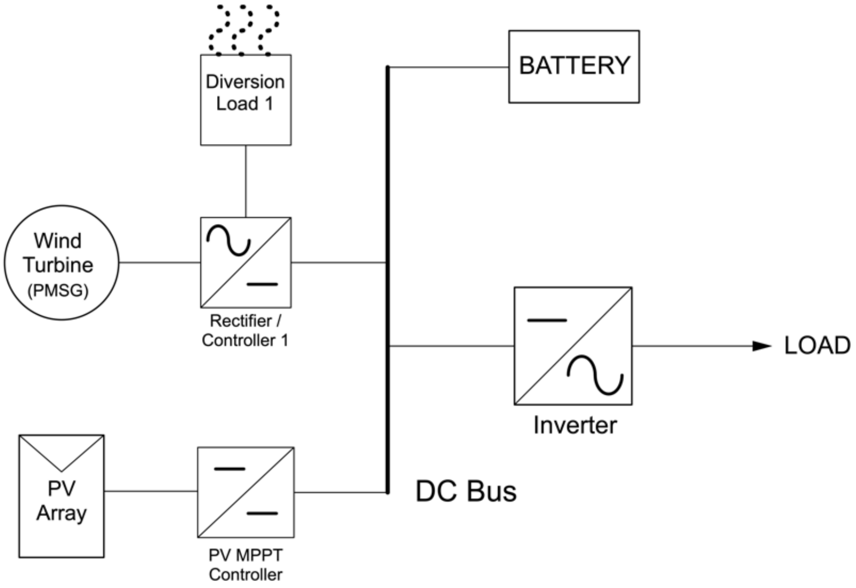


Figure 14: Pure Solar and wind DC microgrid

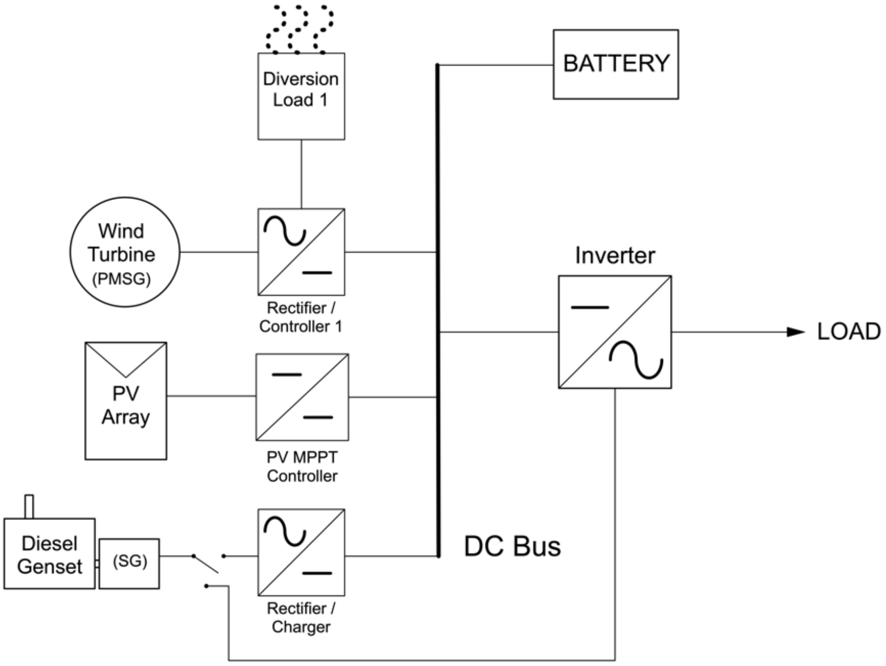


Figure 15: Solar, wind and diesel DC microgrid

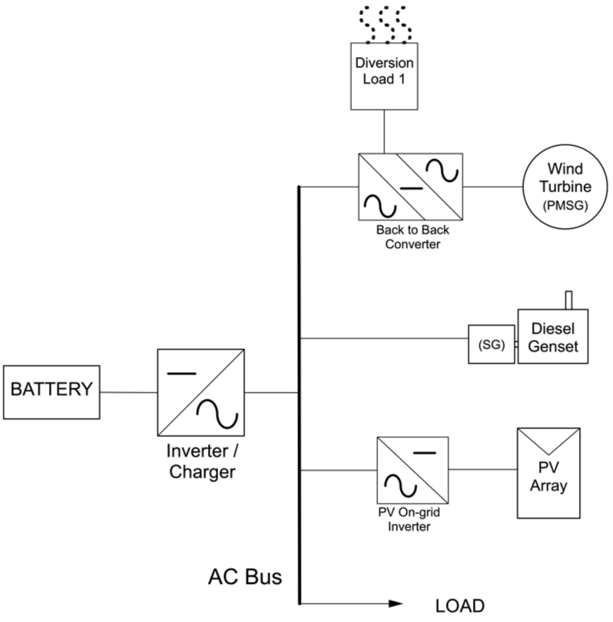


Figure 16: Solar, wind and diesel AC microgrid

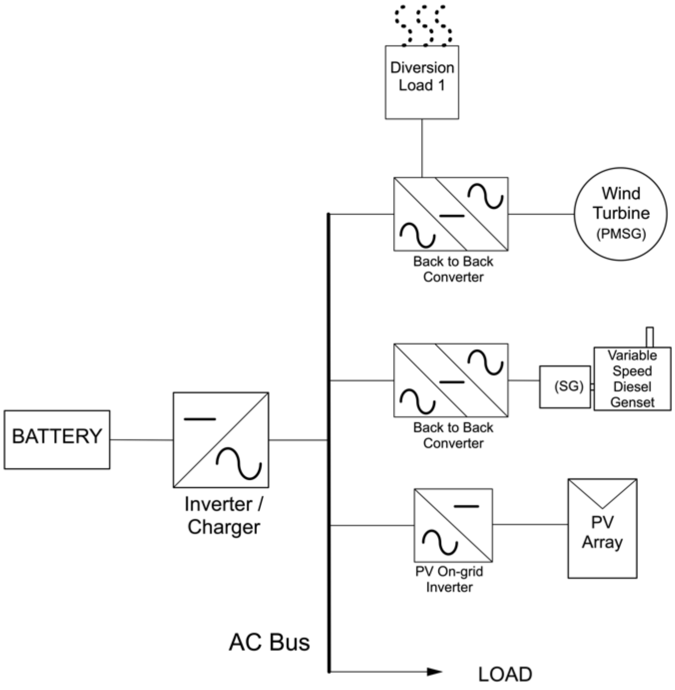


Figure 17: Solar, wind and variable speed diesel AC microgrid

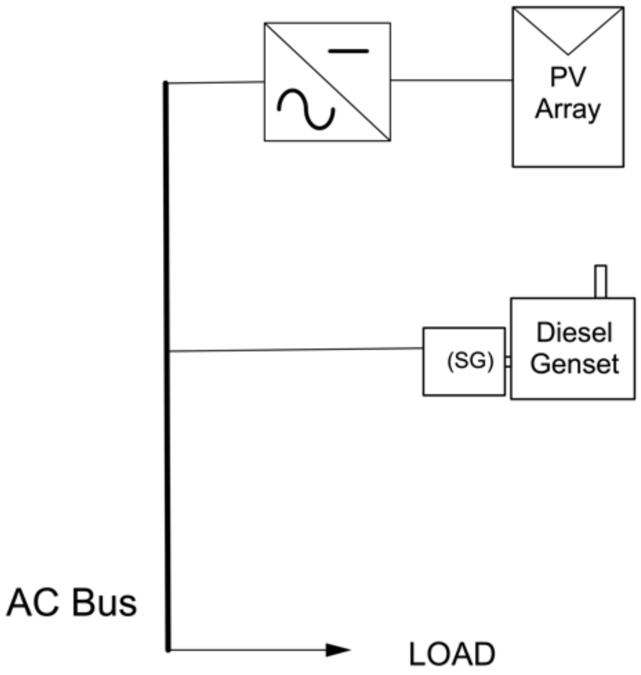


Figure 18: Solar-diesel AC microgrid

When a conventional diesel engine driven generator is activated, it has to run at a minimum of 50% of its nominal capacity otherwise it is exposed to “wet stacking” problems. As mentioned above, a low load regime leads to incomplete combustion due to low combustion chamber temperature, and this to the accumulation of unburned fuel residues in the exhaust system and consequently to premature engine failure.

Besides, the operation of the diesel electric generator under these conditions is very uneconomic because its fixed regime of 1800 RPM, even if very little power is produced. Variable speed diesel generators (VDG) are able to work at different RPM regimes thanks to a sophisticated AC/DC/AC interphase that converts a variable electric source into a stable AC supply both in voltage and frequency. This configuration is shown in Figure 17. The limitation here is the high cost of VDG units and that they are mainly available for large units that can exceed the requirements of many rural electrification projects [6] .

A solar-diesel AC microgrid without battery is shown in Figure 18, in this case the genset SG is the driver of the AC bus and the PV array contributes to it through a on-grid inverter. There are several commercially available solutions of this type in which the solar input is used to reduce fuel consumption of a continuously running diesel unit, however the PV penetration is limited to the sunshine hours and by the minimum 50% regime of the engine. These commercial systems have a typical minimum size of 500 kW that can be far too large for many rural projects.

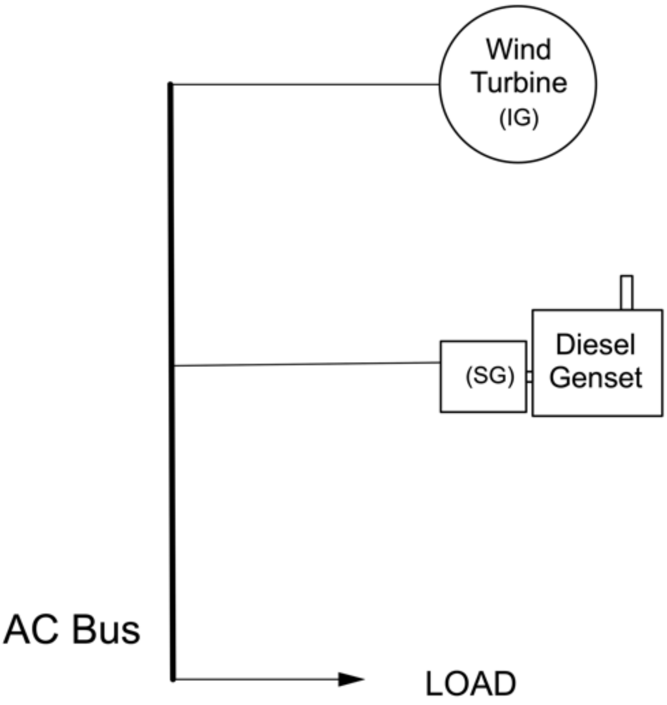


Figure 19: Wind-diesel AC microgrid

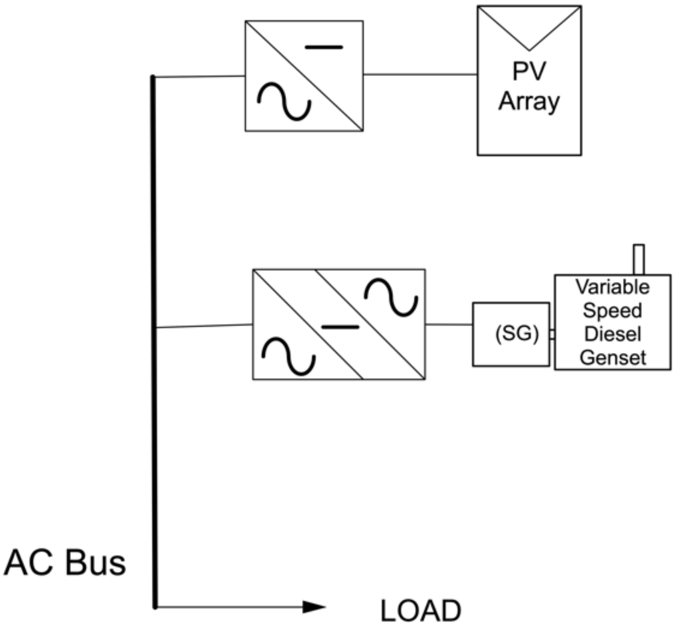


Figure 20: PV-Variable diesel AC microgrid

Figure 19 shows a similar arrangement but with and induction generator (IG) wind turbine instead of a on-grid PV, a wind-diesel microgrid with no battery. There are several commercial solutions of this type specially used in Alaska´s remote locations [144].

Here the diesel electric generator drives the AC bus and the wind turbine is coupled directly to it using the asynchronous IG slip for that purpose. This type of coupling limits the power of the wind turbines to approximately 15% of the DG power [145][146], higher penetrations can be attained with a more advanced and expensive AC/DC/AC interphase.

There are some interesting examples of VDG working with PV installation under a high penetration regime, Figure 20 [6] in Tasmania, avoiding the use of large battery banks and reaching very competitive levels of LCOE and reliability. Doing the same with wind turbines is substantially more difficult due to the nature of the resource. Wind power is subjected to abrupt changes with gusts and extreme winds which is not the case with solar power which is limited by a maximum radiation intensity of little more of 1000 W/m2 and is easier to control.

4.4 Laguna Grande microgrid setup

4.4.1 General overview

Laguna Grande is located in the southern part of the Paracas National Natural Reserve in the Ica region, approximately 300 km south of Lima, the capital of Perú, Figure 21.

Geographically it is a remarkable place where a large natural seawater open lagoon has been formed by the perfect balance between the powerful wave-driven longshore drift, that creates a natural boulder-strewn barrier, and the tidal currents that breaks it, as shown in Figure 22. The lagoon has the sufficient size as to generate the required tidal currents to keep it open to the sea.

A smaller volume would not have avoided being closed by a bar as is the case found further south, which has turned into a salty marsh. This is an example of the outstanding features of the Paracas Reserve, with its extraordinary marine and desert landscapes, exuberant biodiversity, pre-Hispanic archeological sites and touristic potential to which the Laguna Grande microgrid aims to contribute.

In Laguna Grande there are two working microgrids for the fishermen´s coves “Muelle”, which is hybrid (3 kW wind and 6 kWp PV) installed in 2016 and the focus of this work, and “Rancherio” which for the moment is PV only with an installed capacity of 3.75 kWp, installed in 2019. The location is 35 km from the nearest grid connection point.

(**a**) (**b**)

Figure 21: (a) Coastline of Perú showing the location of the Ica region and Paracas; (b) detail of Laguna Grande and the location of the 9 kW microgrid. (14◦08′50” S, 76◦16′06” W. Reference: Google Earth)

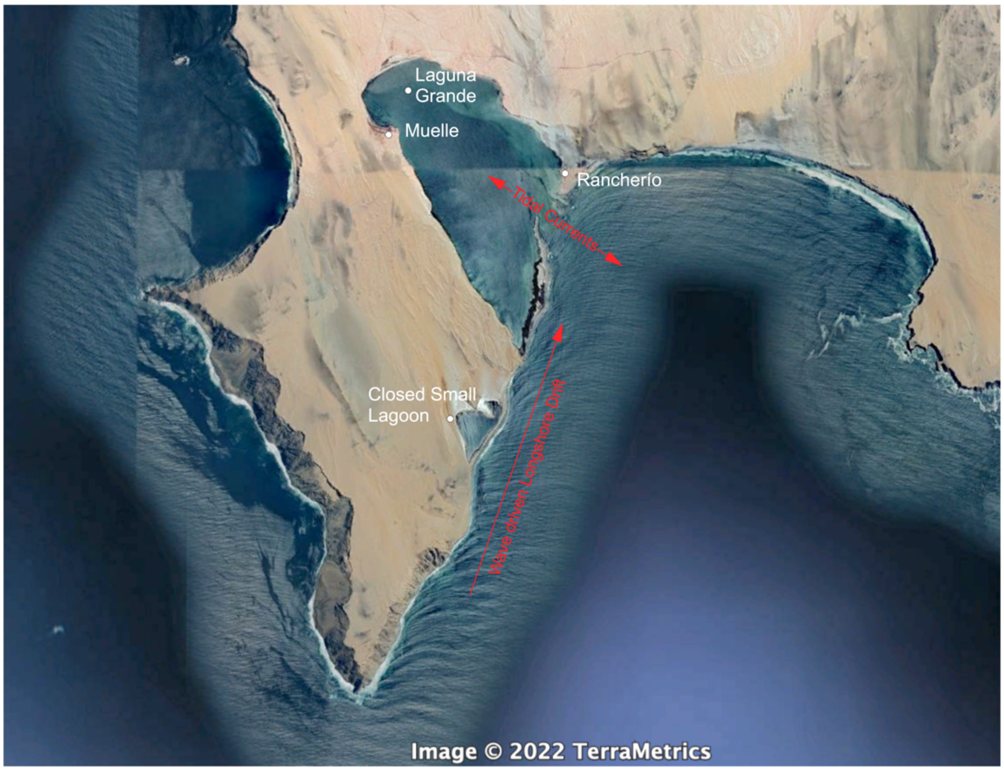


Figure 22: Close up of the Laguna Grande zone showing the position of “Muelle” and “Ranchería” settlements, the bar forming longshore drift and tidal current keeping the lagoon open.

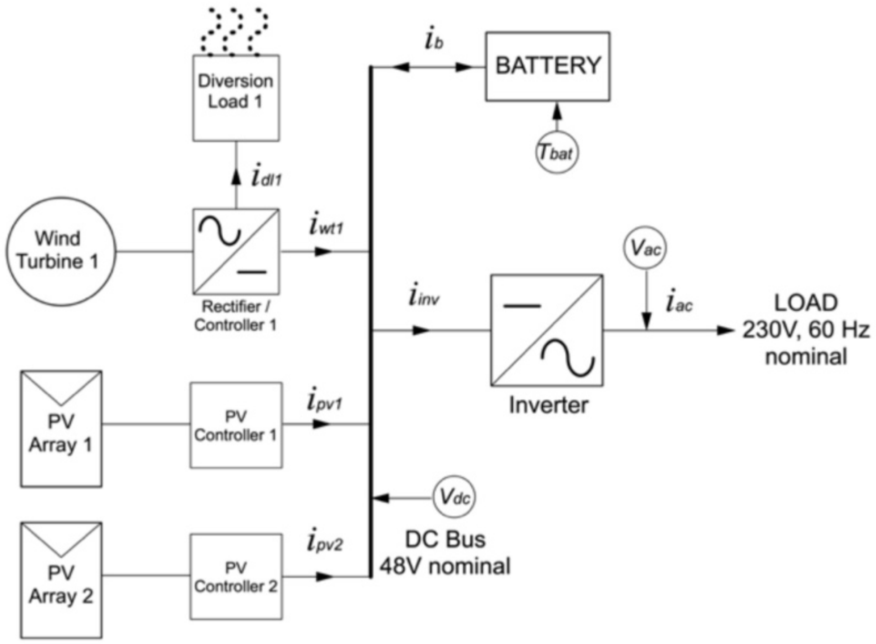


Figure 23: Scheme of Laguna Grande hybrid microgrid

The author got to know Laguna Grande when being involved in a first electrification attempt in 1992 with the aid of the Swiss cooperation agency. At that time a 1kW wind turbine was installed with the aim of lighting the pier of the “Muelle” cove. The system worked for nearly 3 years until the challenging marine conditions and very strong winds ruined the turbine. Much later, in 2015, the opportunity of the Interamerican Development Bank (IDB) contest “IDB-IDEAS” raised. Our project was one of the six winners of the fund between 280 proposals in Latin America and the Caribbean, with the idea of a hybrid microgrid for productive uses. In the second half of 2016 the 9 kW microgrid was installed in the “Muelle” community and it is working since then. The population of this community is variable from 50 to 200 persons, depending on the seasons and the fishing activity. Most of the houses, shops and restaurants are connected to the system, each with its corresponding energy meter. From the very beginning special attention was paid to the social aspects of the project as a key strategy towards assuring its sustainability, promoting the active participation of the community members in some operations, and stablishing the communitarian administration of the electrification system.

Simple written agreements were elaborated and signed by all who were interested in having a connection to the system. These simple contracts stablished the managing committee, the conditions of the service and tariffs. At the beginning there was a dose of distrust from many members of the community, but as people started to witness the progress achieved and the houses and stores being lighted, many more joined the project [147]. The microgrid was designed following a methodology that can be qualified as “intuitive” according to some literature [148], having to estimate an expected demand from the community´s future consumers and configured with the technology that was available at that time in the Peruvian market. The final design consisted of two 3 kWp PV arrays, one 3 kW wind turbine, power electronics, and an 800 Ah-48V lead-acid-gel battery bank. Figure 23 shows the microgrid´s diagram and Table 17 details its components.

Table 17: Microgrid component specifications

Component	Type	Specification
Photovoltaic array	Poly-crystalline	6 kWp (24 × 250 Wp)
PV controller	MPPT	2 × 80 A
Wind turbine	Permanent magnet	1 × 3 kW @ 12 m/s
Wind turbine controller	PWM + dump load	1 × 3 kW @ 48 V
Batteries	VRLA-GEL	800 Ah @ 48 V, C10 = 95 Ah (38.4 kWh @ 100% DOD)
Inverters	Pure sine wave	48 Vdc/230 Vac

4.4.2 Measuring and registering setup

As the main objective of this work is to assess the technical and economic performance of the Laguna Grande hybrid microgrid, all its relevant variables must be measured and registered to be properly analyzed. A key meteorological variable as solar radiation intensity is measured in W/m^2 by means of a pyranometer, similarly wind speed in m/s with an anemometer at a proper height in the vicinity of the wind turbines. Wind power has a cubic dependence with speed, so it is mandatory to perform precise wind speed measurements [149].

A wind vane is also installed to register wind direction, this is of secondary relevance but can supply some information about the consistency of the resource. Ambient temperature is important for the performance of the PV arrays [150], furthermore the temperature of the battery bank is of outmost importance to its performance and long-term durability, taking this into account a temperature sensor attached to the exterior wall of one of the batteries is included.

In parallel to meteorological readings all relevant electrical parameters are measured and registered. The current going in and out of the battery bank (i_b) and the corresponding voltage of the DC bus bar (V_{DC}) are very important as they are the variables through which the battery DOD is calculated.

The output voltage of the inverter (V_{AC}) indicates if the microgrid is on or if there is a power failure, AC current delivered to the load (i_{AC}) and the corresponding power factor are fundamental to calculate the active power delivered. The DC current supplied to the bus bar from the corresponding MPPT controllers of the two PV arrays (i_{PV1}) and (i_{PV2}) and the current coming from the wind turbine rectifier-regulator (i_{WT1}), together with (V_{DC}) allow the total generated power to be determined. Eventual DC current going to the dump load of the wind turbine regulator is registered to determine the excess power that is dissipated. All these measured and registered electric parameters are shown in Figure 23, the characteristics of the electric sensor and data logger are given in Table 18 and their layout in Figure 24.

Table 18: Measuring equipment specifications

Component	Type	Specification
Anemometer	Cups, magnetic pickup	NRG-40C
Wind vane	Potentiometer	NRG 200P
Pyranometer	Silicon photodiode	LI-COR LI200R
Thermometer	Integrated circuit sensor	NRG 110S
Meteorological data logger	Multichannel	NRG Symphonie PRO
AC current sensors	Open coil CT	Egauge 50 A
DC current sensors	Closed coil Hall effect	Egauge 100 A with power supply
Electrical data logger	Multichannel	Egauge Pro

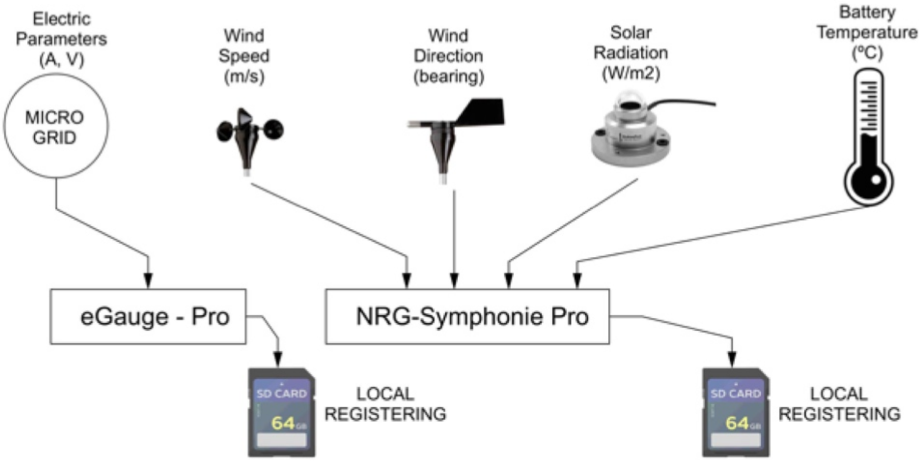
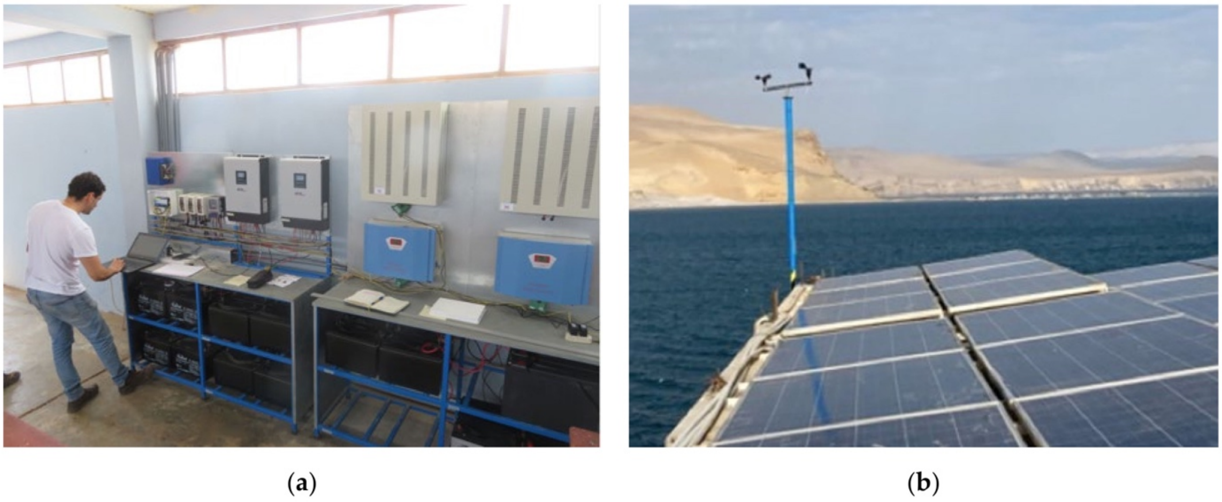


Figure 24: General setup for data collection and registering

There are two data loggers working with the same data collection granularity of readings every second and registering averages every 10 minutes. These data loggers could be reached by telecom with the appropriate accessories, unfortunately Laguna Grande is far from the cellular network and so far all data has to be stored in SD cards and retrieved periodically.

Figure 25(a) shows the interior of the community building where the microgrid battery bank electronic controls and data loggers are kept. The well-ventilated and spacious room allows a stable temperature to be maintained. The PV arrays and wind turbine are located on the roof of the same building so that no other on-site intervention was undertaken to install the microgrid, to avoid possible objections from the natural reserve´s authorities. Figure 25(b) shows the typical coastal desert marine landscape of Paracas where frequent dust storms occur with over 18 m/s wind speeds. These events are appropriately named “Paraca” and represent an important challenge for the operation and maintenance of wind turbines as well as for the electronics and PV arrays. Figure 26 displays the two wind turbines installed on the roof of the same building.



(a) (b)

Figure 25: (a) Overview of the inverters, controls, and battery consoles of the Laguna Grande microgrid, (b) view of the rooftop-mounted PV array with the anemometer and wind vane in the background.

Figure 26:Two 3 kW wind turbines with 3m diameter rotor with 5 blades on the roof of the Laguna Grande community building

Figure 27: (a): The 500m distribution line being installed, (b): typical connection at a service point with energy meter, power limiting and main switches.

The single-phase distribution line has more than 500m and connects 35 users with loads that are mainly LED lighting, TVs, kitchen appliances, refrigerators and a few freezers. Figure 27 shows part of the distribution line and a typical user connection. All service points have an energy meter, a power limiting thermo-magnetic switch and a main switch. Every month one member of the committee verifies the meter reading difference and notes the amount to be paid by the user according to the agreed tariff. There is a flat connection fare that is equivalent to 10 kWh, that must be paid monthly even if there is no consumption at all. The funds collected in this manner are saved in a bank account to be used for maintenance, spares and battery replacements. In the almost 6 years of operation the use of electric energy has brought benefits to the community as a better quality of life through lighting, refrigeration and entertainment, above all it is important to promote the productive uses of electricity. With this in mind, it is rewarding to witness that the initial level of average consumption per connection of 0.7 kWh/day has consistently increased to reach a present value of 0.85, mainly due to the incorporation of more direly needed refrigeration units in restaurants and food stores. Consistent growth in electric consumption is key to generate more annual revenue that helps to sustain the economy of the communal microgrid.

4.4.3 Data treatment

Measurements were performed and registered from October 2019 to June 2020 with a sampling frequency of 1Hz and a granularity of 10 minutes averages. All the microgrid´s relevant electric parameters are measured, registered and analyzed according to the 25% quartile, median and 75% quartile to reflect their variability. The same applies to battery exterior wall temperature. The pyranometer allows irradiation profiles and total daily irradiation to be obtained with their corresponding percentiles. Wind speed and wind direction are measured and processed to obtain the hourly wind speed distribution in percentiles. Wind speed daily profile is very important to be able to support the load during evening and nocturnal peak hours.

5. RESULTS AND DISCUSSION

5.1 Measured resources, temperature and load

In this section the measured data corresponding to environmental conditions at Laguna Grande site are presented: solar irradiance, wind speed and battery wall temperature. Additionally, the measured hourly load profile of the whole community is also studied as an existing requirement as reported in [151]. This is all shown in Figure 28.

5.1.1 Solar irradiance

Figure 28(a) displays the global tilted irradiance (GTI) hourly profile. This is obtained by placing the pyranometer tilted with the same angle as the plane of the PV array. As can be seen by the closeness of the median to the 75% percentile, the solar resource is consistent, with registered values reaching over 1000 W/m2 at noon. Nevertheless the 25% percentile curve shows that there are some cloudy days with low irradiance that can be critical for the microgrid.

5.1.2 Wind speed

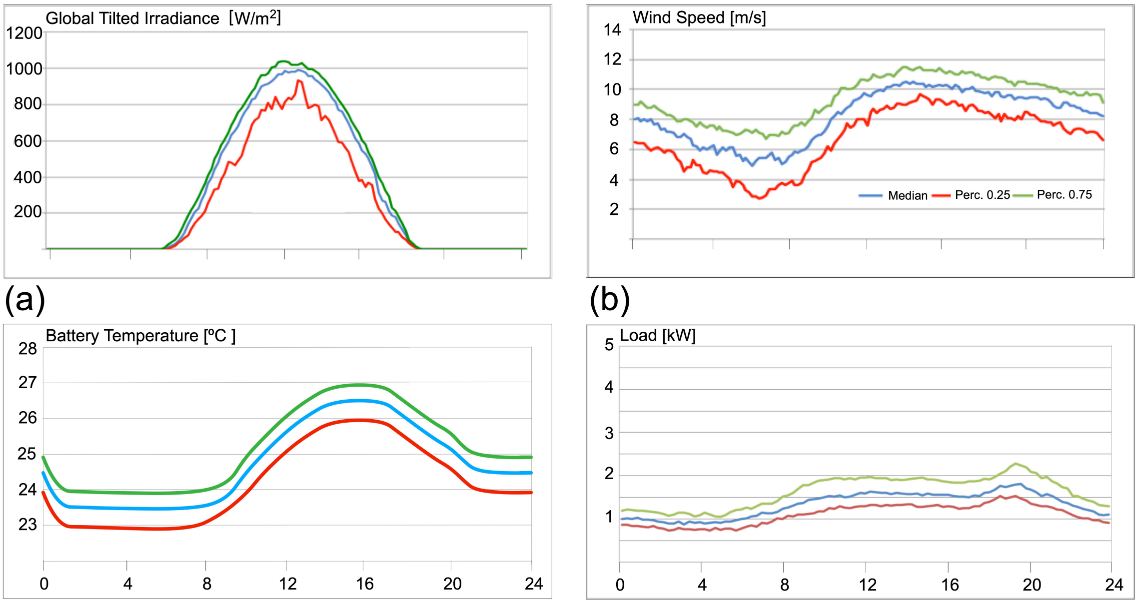
The hourly wind speed behavior in m/s is exhibited in Figure 28(b) evidencing that this resource is very favorable in Laguna Grande, especially because it is present at night, particularly during the loads peak hours.

5.1.3 Battery exterior wall temperature

Battery exterior temperature behavior along the day is considerably stable along the day, oscillating from 23 to 27ºC, as can be seen in Figure 28(c). The well ventilated and ample space that the community building offers helps in this respect, together with the fact that the battery currents are moderate. Therefore, the effect of temperature variations is not considered for their durability and performance.

5.1.4 Load characteristics

As mentioned above, the 500m electric distribution line in Laguna Grande is AC 230V, 60 Hz single phase and is connected to 35 power supply points. The aggregated power demand profile is fairly consistent, occasionally going over 2.5 kW, but normally being between 1 a 2 kW, as shown in Figure 28(d). Peak hour consumption typically occurs between 6 and 8 pm. In this aspect, the small fisherman´s cove behaves in an analogous way to a big city. The load register is also very useful to detect service interruptions (V_{AC} = 0) mainly because a low battery voltage condition.



(a) (b)

(c) (d)

Figure 28: (a): Hourly profiles of GTI; (b): Hourly profiles of wind speed; (c): Hourly profiles of battery temperature; (d): Hourly profiles of load

5.2 Power Generation, battery voltage and derived DOD

5.2.1 Potential and measured power

Available wind and solar resources can be applied to the respective installed capacities by means of the exposed areas of wind turbine rotor and PV arrays. Then the efficiencies of the conversion systems, electronic devices and diverse losses are applied to obtain the potential power that can be incorporated to the system.

The real power going into the microgrid system happens to be a fraction of this potential, mainly because limited battery size and the interference of simultaneous wind and solar generation. Measuring the real power inputs and outputs to the microgrid allows its power balance to be determined and correlated with the battery voltage levels. Battery voltage levels, in turn, can be correlated with DOD taking into account its dynamics for which temperature and battery current are of outmost importance. What follows is a description of these calculations, results, and their discussion.

The first step is to find wind power per unit area P_W (in W/m^2) which is proportional to the cube of wind speed (v_w), considering an air density of 1.23 kg/m^3 which corresponds to sea level and 25ºC ambient temperature.

$$P_W = \frac{1}{2} \rho v_w^3 \qquad (2)$$

Table 19: PV and wind turbine performance factors

Factor	Symbol	Value
PV conversion efficiency	η_{PV}	15.4%
MPPT controller efficiency	η_{PVC}	95%
PV cell temperature effect	$PV_{\Delta T}$	10%
PV aging effect	PV_{ag}	4%
PV soiling effect	PV_{so}	10%
PV conductor losses	c_{PV}	2%
PV total area	A_{PV}	38.9 m^2
Wind generator efficiency	η_G	90%
Mechanical transmission efficiency	η_{MT}	99%
Turbine controller efficiency	η_{TC}	95%
Rotor power coefficient	c_P	0.42
Conductor losses	c_T	3%
Total rotor area	A_T	7.1 m^2

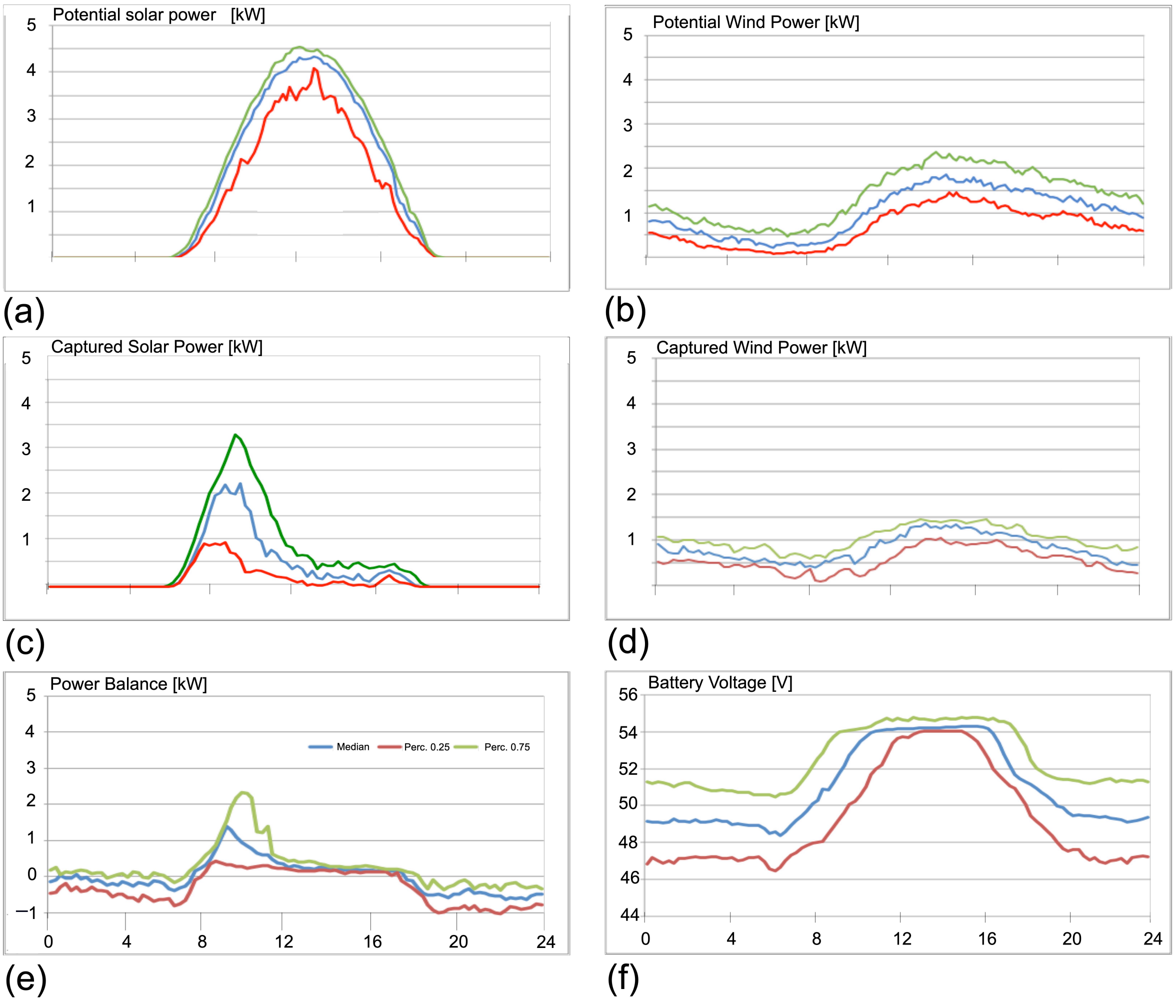
The solar resource *GTI* is already in W/m^2 so it can be applied to the area of the PV arrays as P_W is applied to the area of the 3m diameter rotor of the wind turbine. Considering the power losses and efficiencies listed in Table 19, the potential captured power can be calculated [149][150], then the resulting input from the PV arrays and the turbine can be written as:

$$P_{PV} = \eta_{PV}\eta_{PVC}(1 - PV_{\Delta T})(1 - PV_{ag})(1 - PV_{so})(1 - c_{PV})A_{PV}GTI \tag{3}$$

$$P_T = \eta_G\eta_{MT}\eta_{TC}c_P(1 - c_T)A_TP_W \tag{4}$$

Thus, using (3) and (4) these potential solar and wind power inputs are calculated and shown in Figures 29(a) and 29(b) respectively. When comparing these calculated potential powers with real measured powers shown in Figures 29(c) and 29(d) substantial differences can be noted. In the case of PV arrays this occurs mainly because the batteries absorption stage is reached around midday and therefore the MPPT controllers start to work at constant voltage and decreasing currents, as documented by H. Louie in [20]. Another factor in this respect is the wind turbine that on windy days has a more dominant role in battery charging. It has been observed that the corresponding rectifier-controller has a higher working voltage than the solar MPPT controllers. It is frequent to witness the MPPT controllers inhibiting from contributing with any current when the wind turbine is active.

Measured power from the wind turbine results sometimes as low as 65% of the potential or calculated power. This substantial difference may be explained by different factors as overestimation of the rotor power coefficient (c_P) given by the manufacturer, the efficiency of the generator or dirty blades. Here again the competition or interference between the two sources, sun and wind, to charge a limited capacity storage can be seen as the main limiter of power capture. This is evidenced comparing Figures 29(b) and 29(d): it is during sunshine hours that the difference between potential and measured wind power is more acute.



(a) (b) (c) (d) (e) (f)

Figure 29: (a): Hourly profiles of potential solar power; (b): Hourly profiles of potential wind power; (c): Hourly profiles of captured solar power; (d): Hourly profiles of captured wind power (e): Hourly profiles of power balance; (f): Hourly profiles of battery voltage

A better use of the installed capacity could be attained by shifting loads to afternoon hours when there is excess generating capacity but, considering their characteristics and nature, it very difficult to encourage demand response activities. Another way to enhance power capture is through a bigger battery bank. As will be seen in section 5.4, a larger storage capacity implies a higher initial investment and energy costs in the long run.

5.2.2 Power balance

From the measured powers coming into the battery bank, both from the PV arrays and the wind turbine, and the active power delivered to the load, a balance can be made along the day. For this purpose, the inverter efficiency must be accounted for, because the measurement is taken in the AC output and not from the DC bus bar. The inverter efficiency is estimated at 97% according to the specifications of the manufacturer and their verification in field conditions.

At this stage it is important to mention that power factor of the load is considerably stable with an average of 0.89 and a minimum registered value of 0.85 and maximum of 0.93. It is advisable to pay close attention the load´s power factor as it will alert operators of possible excesses in demanded reactive power that can compromise the stability and economy of the microgrid as reported in [152]. This excessive reactive energy consumption may be originated from inadequate habits like leaving many cellular phone chargers and other inductive devices plugged in a stand-by condition.

The hourly DC power balance at the bus bar is shown in Figure 29(e). Integrating these percentile curves, a daily energy balance can be obtained. An approximate equilibrium is kept for the median while the 25% percentile has a deficit of 7.2 kWh/day, and the 75% percentile results in an energy surplus of 6.3 kWh/day surplus. This exposes the risk condition that if two or more days of low resources were to occur consecutively, a possible service interruption will follow as a consequence of the battery bank reaching its cut off voltage.

5.2.3 Battery voltage and derived DOD

The battery bank is the key and pivotal component of the off-grid rural microgrid; its behavior and performance determine the overall success or failure of the electrification system, its economy and sustainability. The daily and hourly fluctuations of generated vs. demanded energy must be supported by the battery bank storing momentary surplus to account for deficits a few hours later. This pattern can be clearly seen in Figure 29(e), and this naturally results in noticeable battery voltage levels as seen in Figure 29(f).

The battery bank tends to be fully charged from 12:00 to 17:00 hours when solar and wind production are highest, and in its lowest levels of charge early in the morning after many hours of lower nocturnal wind production and regular consumption. The characteristics of these daily energy transfers to and from the battery bank relate directly to the DOD and are manifested through the voltage level $V_{DC.}$ The frequency distribution of the daily DOD values is key to the duration and performance of the battery bank, and this in turn is determinant to the economy, performance and overall sustainability of the microgrid.

Batteries have a deceivingly simple exterior appearance, their complex internal behavior being determined by a diversity of overlapping electrochemical phenomena such as ion solvation and transport, polarization, diffusion and double layer effects [153][154]. There is a great volume of literature about batteries and the usual approach is to analyze them as system in which battery current and ambient temperature are the input signals while the output signals are battery open-circuit voltage, battery temperature, battery internal resistance and most important: battery state of charge (SOC) and state of health (SOH) [155].

In this context, it is very important to take into account that if battery voltage is used to determine the real SOC, or its complementary value which is DOD, in an operative situation there are currents being supplied or extracted from it. Lead-acid battery technology is very well known and the relation between measured voltage, working current, battery capacity and temperature has been extensively studied

[156][157] leading to equations as the following for the discharge and charge stages of single 2V cells:

$$V_d = \left(2.085 - 0.12(1 - SOC) - \frac{I}{C_{10}}\left(\frac{4}{1+I^{1.3}} + \frac{0.27}{SOC^{1.5}} + 0.02\right)(1 - 0.007\Delta T)\right) \tag{5}$$

$$V_c = \left(2 + 0.16SOC + \frac{I}{C_{10}}\left(\frac{6}{1+I^{0.86}} + \frac{0.48}{(1-SOC)^{1.2}} + 0.036\right)(1 - 0.025\Delta T)\right) \tag{6}$$

$$DOD = 1 - SOC \tag{7}$$

where V_d and V_c are the battery voltage in discharge and charge stage respectively; I is the battery current; C_{10} is the 10 h rated capacity taken from the specifications of the battery and $\Delta T = T_{bat} - 25$ °C. In equations (5) and (6), the first terms have to do with the electrolyte concentration while the second terms account for the variation in internal resistance. The Laguna Grande microgrid works with a 48V 800Ah battery bank composed of eight strings of four 100Ah 12V VRLA-Gel batteries connected in series, thus 24 units of 2V cells must be considered.

Furthermore, the battery current must be divided by 8 equal branches. Having obtained battery voltage, current and temperature by direct measurement, equations (5), (6) and (7) allow DOD to be obtained in a real time operative situation. These calculations are performed particularly in early morning hours when the battery bank is in discharge mode and the highest values of DOD are reached.

In order to validate the above-mentioned equations, the voltage vs. DOD behavior of a sample VRLA-GEL battery unit was studied in discharge tests under laboratory conditions. These measurements were performed in a stepwise manner and in equilibrium, waiting a minimum of 15 minutes for the battery to stabilize, the results projected to 4 12V batteries in series are shown in Figure 30.

Battery manufacturers specify battery end of life in terms of number of charge-discharge cycles until a SOH of 60% is reached. This naturally depends strongly on the intensity of the cycles given by the DOD. This information is shown in Figure 31 for the currently installed VRLA-Gel batteries and for VRLA-AGM (absorbent glass mat) and Lithium-Ion LiFePO4 (Lithium Iron Phosphate) technologies as alternatives.

As mentioned before, the registered data evidence that the highest DOD occurs early in the morning, and its frequency distribution is key in projecting the expected lifetime of the bank in terms of daily charge–discharge cycles. The battery current and voltage time series are taken as inputs to calculate DOD using equations (5), (6) and (7) so that a derived DOD time series is obtained. The maximum daily DOD are taken, subsequently its distribution by 10% percentile increments is obtained and correlated with the lifetime in terms of number of charge-discharge cycles specified in Figure 31.

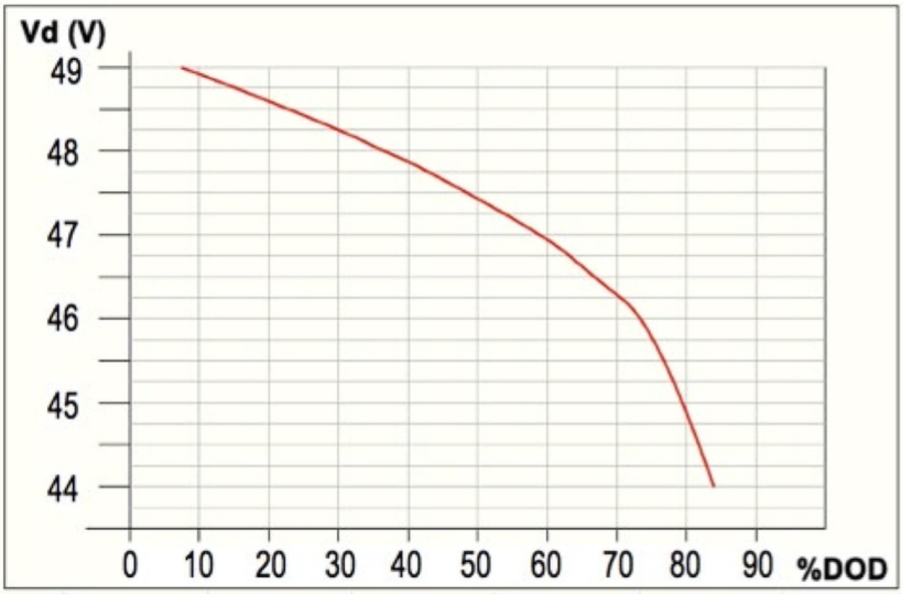


Figure 30: Battery bank voltage measured in discharge and corresponding DOD

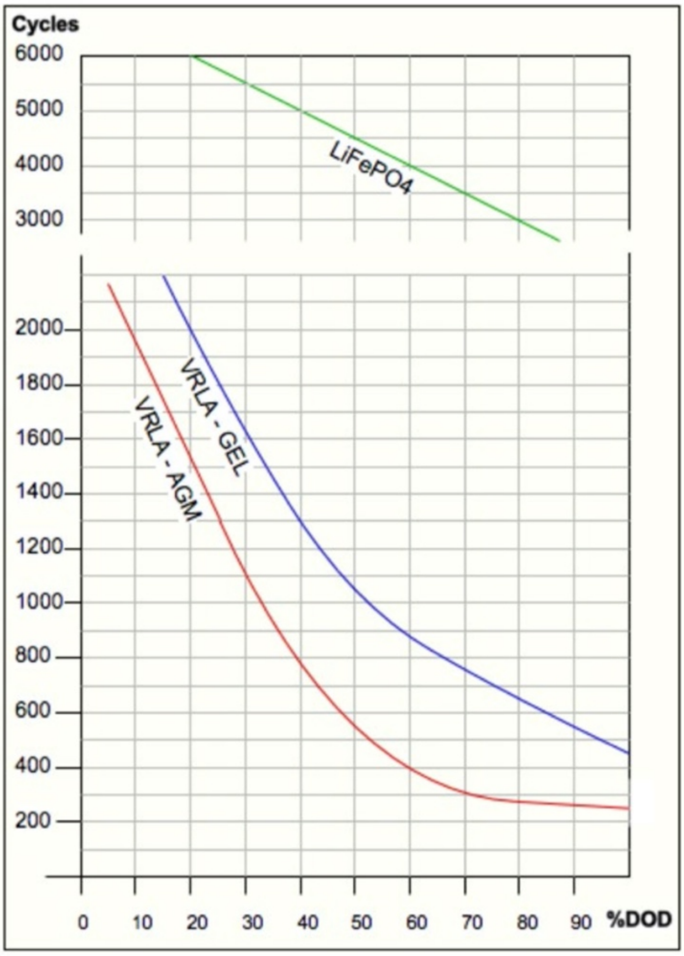


Figure 31: Battery duration to 60% SOH in charge –discharge cycles for different DOD and technologies

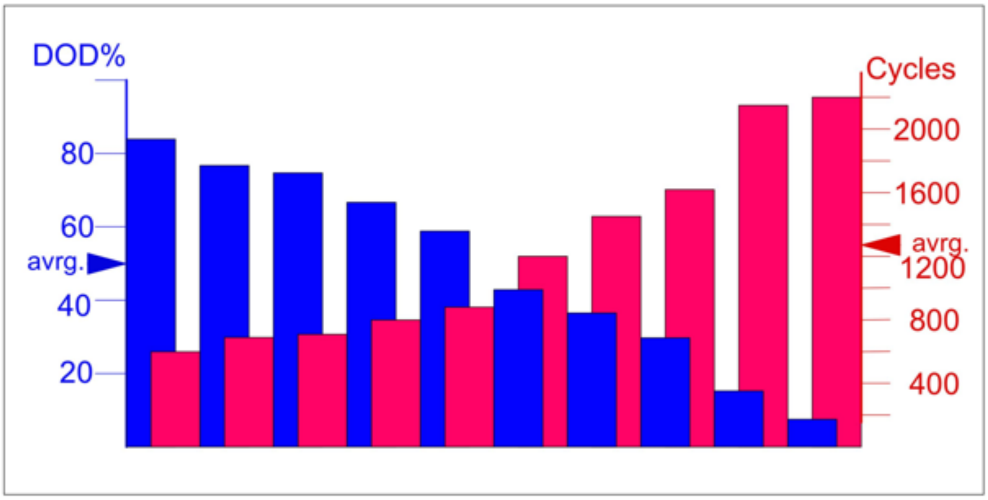


Figure 32: Frequency distribution of DOD and corresponding expected battery duration in cycles

5.2.4 Battery DOD distribution and expected duration

These results are shown in Figure 32 that establish an average DOD of 55%, close to the design parameter, and a corresponding expected lifetime of 1230 cycles. Considering daily occurrence of charge-discharge cycles, this number of cycles results in a battery bank duration of 3.37 years, leading to 5 renewals in the 20-year lifetime of the microgrid. These calculated projections fit reasonably well with the experience accumulated in running the Laguna Grande microgrid for more than 5 years. However, it must be emphasized that this is a simplified analysis and that the stochastic characteristics of the charge-discharge regimes, together with the complex behavior that batteries exhibit can result in premature failure of some of the batteries of the bank or, in more fortunate outcomes, a longer duration.

5.3 Microgrid technical and economic performance

In this section the technical and economic performance of the Laguna Grande microgrid is analyzed in terms of reliability, investment and LCOE using measured data.

5.3.1 Reliability

Reliability is the most important technical performance indicator which is quantified by means of the loss of load probability (LLP). This is defined as:

$$LLP = \sum t_L / t_M \tag{8}$$

where t_L is the time duration of the events when the microgrid is unable to supply power to the load and t_M is the total time being analyzed [158]. A high LLP directly affects the quality of the electric service that the microgrid gives to the rural community and must be kept to an acceptable minimum. LLP also affects the economy and sustainability of the electrification system because when it is not active it does not generate revenue through the delivery of energy to the service points.

In the case of Laguna Grande, the frequent availability of nocturnal wind helps to support the peak hours loads on to the next day. If wind is low during the night and there are important loads present, the battery voltage may drop below the minimum working level of 43V before dawn, causing a power loss until the sun is up again and PV generation is activated.

Close scrutiny of the time series shows that not all loss of load events are caused by a low battery condition, in some instances an overload, user mishandling or operator absence can cause an interruption of the service. In the present state approximately a LLP of 7% can be attributed to a low battery condition.

5.3.2 Investment and LCOE

The economic aspects of the microgrid are of fundamental importance for its viability and success as a competitive alternative to conventional solutions like grid extensions and diesel electric generators. What follows are the details of the original costs of implementation of the Laguna Grande microgrid at the time of its completion in 2016, its unit investment indicator (US$/kW) and projected LCOE along its expected 20-year life cycle.

Table 20 specifies all the components of the Laguna Grande 9 kW microgrid and its corresponding 500m single phase distribution line that includes 35 service points equipped with a standard energy meter. Unitary and aggregated costs are shown together with the unit investment cost that results in 2,435 US$/kW, which can be considered very competitive.

Table 21 shows the total initial investment and the projected operation and maintenance cost along the expected 20-year life cycle of the microgrid. A yearly expenditure of PV cleaning of US$ 112 is considered. This includes the monthly maintenance to the PV array and other minor supervision activities by the operator. Battery renewals are expected every 3.5 years, overhauling, and painting the wind turbine is programmed every 5 years and the electronics are expected to last 10 years. On the other hand, the energy delivered to the community and registered in the set of meters is accounted as a daily average of 30 kWh to which a LLP of 7% is applied, resulting in 10,184 kWh/year of net delivered energy.

Table 22 shows the yearly expenditures distribution and Figure 33 shows the same in graphical form. The procedure to calculate LCOE is applied according to equation (1) of Section 3.2 to obtain a value of 0.44 US$/kWh considering a financial discount rate of 6%. This is very near and confirms the result obtained in Section 3.2.4. The frequent VRLA-Gel battery renewals result in a higher energy cost than Lithium-ion technology, even if this implies an additional investment of 10 to 20%.

Table 20: Original cost of installed components

DESCRIPTION	BRAND	QTY	PRICE	SUBTOTAL
9 kW Microgrid				
250Wp PV modules	Chinaland Solar	12	165	1980
Aluminium support structure for PV	Local manuf.	12	30	360
Integrated 4 kW Inverters-MPPT controls	MPP Solar	2	1250	2500
3 kW Wind turbine	HY-Energy	1	3650	3650
3 kW wind turbine controller and dump load	HY-Energy	1	925	925
4 m tilting pole for wind turbine	Local manuf.	1	1200	1200
VRLA-Gel Batteries 100Ah-12V	Rittar	32	245	7840
Metal console for batteries and electronics	Local manuf.	2	550	1100
Accesories, cables and connections	Local manuf.	1	650	650
Transport		1	900	900
Installation labour (2 installers-day)		6	135	810
			TOTAL US$	**21915**
			Unit investment US$/kW	2435
500m Distribution Installation				
Wires AWG8 (meters)	Indeco	1000	1.14	1143
SAP PVC tubing (meters)	Tigre	500	0.86	429
Standard meters	KBC	35	15.71	550
Plastic meter boxes	KBC	35	14.29	500
Accesories and connections	Miscelaneous	1		144
Transport		1		80
Labour (2 installers-day)		8	135.00	1080
			TOTAL US$	**3925**

Table 21: Total initial investment and the projected operation and maintenance costs

INITIAL AND YEARLY EXPENDITURE	**Period**	
Initial investment		**US$**
Hybrid Microgrid 6 kWp + 3 kW Wind Turbine		21915.00
Distribution lines with 35 standard meters		3925.00
Total Initial investment	**Initial**	**25840.00**
Yearly expenditures		
PV cleaning	yearly	112.00
Battery renewal	3.5 years	7840.00
Wind turbine maintenance	5 years	*500.00*
Electronics renewal	10 years	2500.00
Delivered Energy		**kWh**
30 kWh for 365 days	yearly	10950.00
LLP = 7% discount	yearly	766.50
Net Delivered Energy		**10183.50**

Table 22: Expenditures and energy distribution in 20-year life cycle

(r=6%)	Expenditure	Present	Delivered	Present
Year	US$	Value US$	Energy kWh	Value kWh
0	25840.00	25840.00		
1	112.00	105.66	10184.00	9607.55
2	112.00	99.68	10184.00	9063.72
3	7952.00	6676.65	10184.00	8550.68
4	112.00	88.71	10184.00	8066.68
5	612.00	457.32	10184.00	7610.08
6	112.00	78.96	10184.00	7179.32
7	7952.00	5288.53	10184.00	6772.94
8	112.00	70.27	10184.00	6389.57
9	112.00	66.29	10184.00	6027.89
10	10952.00	6115.54	10184.00	5686.69
11	112.00	59.00	10184.00	5364.80
12	112.00	55.66	10184.00	5061.14
13	112.00	52.51	10184.00	4774.66
14	7952.00	3517.18	10184.00	4504.39
15	612.00	255.37	10184.00	4249.43
16	112.00	44.09	10184.00	4008.89
17	7952.00	2953.09	10184.00	3781.98
18	112.00	39.24	10184.00	3567.90
19	112.00	37.02	10184.00	3365.94
20	112.00	34.92	10184.00	3175.42
TOTAL:	71280.00	51935.69	203680.00	116809.68
	LCOE (r=6%)		US$/kWh	0.44
	LCOE (r=0%)		US$/kWh	0.35
	Effect of distribution			27%

In summary, the technical performance of the Laguna Grande microgrid is given by its measured LLP of 7% and its economic performance by its competitive unit investment of 2,435 US$/kW, resulting in a not so competitive and improvable LCOE of 0.44 US$/kWh. In fact, this LCOE is substantially higher than the present communitarian electric tariff of 0.21 US$/kWh (0.7 soles/kWh at 2016 exchange rate to the dollar) that was established that year. This tariff was calculated with a longer battery lifetime of 5 years instead of the field proven 3.5 years; a higher energy consumption of 48 kWh/day instead of the measured 30 kWh/day and a currency exchange 17% more favorable between the Peruvian Sol and the US dollar. Furthermore, the simple way to calculate LCOE was used, without considering the financial discount rate. At this stage it is important to adjust the tariff to assure the economic sustainability of the microgrid. This will not be an easy task.

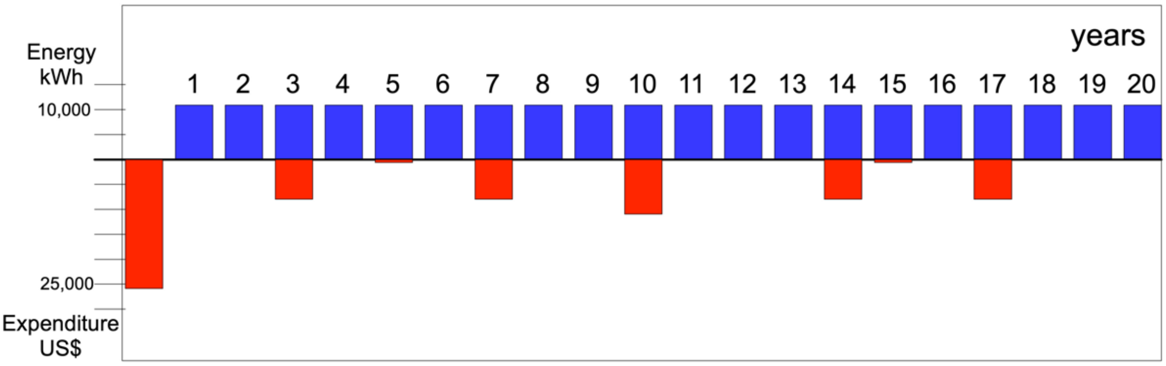


Figure 33: Distribution of yearly expenditures and projected annual energy generation in the Laguna Grande microgrid

5.4 Parametric study with battery size and type

As mentioned above, the battery is the most important component in a microgrid, defining its economy, performance and overall sustainability; therefore, defining its adequate size is of paramount importance. A rational balance must be reached between reliability (low LLP), unit investment and LCOE. Naturally, a bigger battery will lower LLP but as a consequence unit investment will rise and also LCOE, as will be shown next by assessing the effect of varying the size of the battery bank *ceteris paribus*.

The effect of battery size on LLP can be calculated from the time series, being similar to what is found in the literature [159][160]. The value of LLP tends to zero in an asymptotic manner with larger battery size as shown in Figure 34(a). In a pure solar-wind hybrid microgrid there is no diesel electric generator as back-up so there is always a probability of service interruption, however small it may be. Figures 34(b) and 34(c) show the expected behavior of increasing investment and unit investment when a larger battery cost is accounted without increasing installed capacity.

The behavior of LCOE requires deeper analysis as there are various counter-acting factors. Larger battery size leads to proportionally lower levels of DOD and consequently longer battery duration and less renewals along the 20-year life cycle of the microgrid. Furthermore, as mentioned above, a larger battery has the benefit of lowering LLP which leads to more energy being delivered which in turn lowers LCOE. However, according to the calculations, these favorable effects do not compensate the larger initial cost of the larger battery bank and its periodic renewal even if they are less frequent. Thus, LCOE increases with battery bank size as can be seen in Figure 34(d).

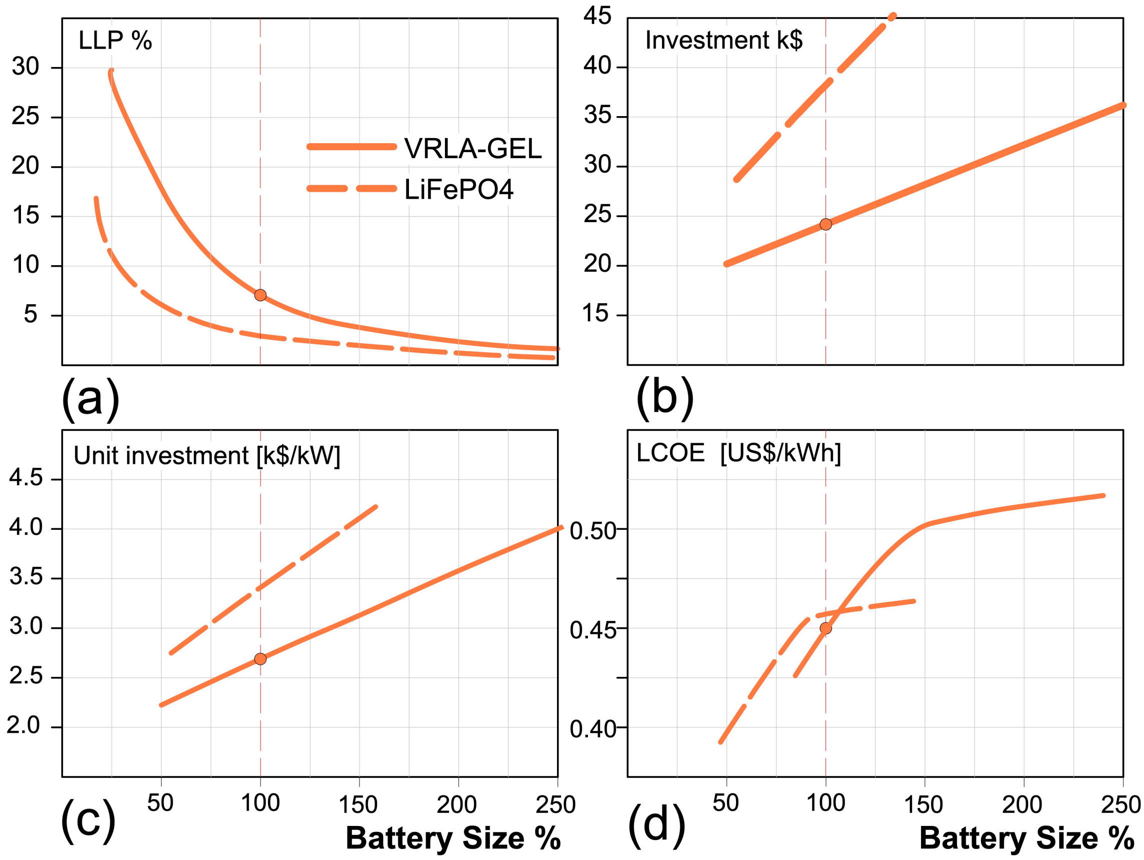


Figure 34: (a): LLP for varying battery bank sizes; (b): Investment for varying battery bank sizes; (c): Unit investment for varying battery bank sizes; (d): LCOE for varying battery bank sizes (present situation is shown with a dot). Solid line is for VRLA-GEL; dashed line is the projected behavior for LiFePO4 technology

Figure 34(d) also shows the projected performance indicators of the Laguna Grande microgrid with a lithium-ion battery bank (LiFePO4). In this case LLP is substantially enhanced due to the fact that lithium-ion batteries are more efficient in charge-discharge cycles and can work with up to 90% of DOD keeping a duration of close to 3000 cycles, as can be seen in Figure 31.

Regarding unit initial cost of storage (US$/kWh), if nominal capacity is considered, lithium-ion technology is approximately 3 times more expensive; but if the higher working levels of DOD (90 vs. 50%) are considered this is reduced to only 1.6 times. This initial investment increase is shown in Figure 34(b) and 34(d). Projected LCOE with lithium-ion technology exhibits a clear benefit, mainly due to its longer duration. Other minor positive effects, especially in distant locations, can be attributed to greater specific energy which lead to freight reductions, also greater energy density that allows more compact and economic cabinets to be considered.

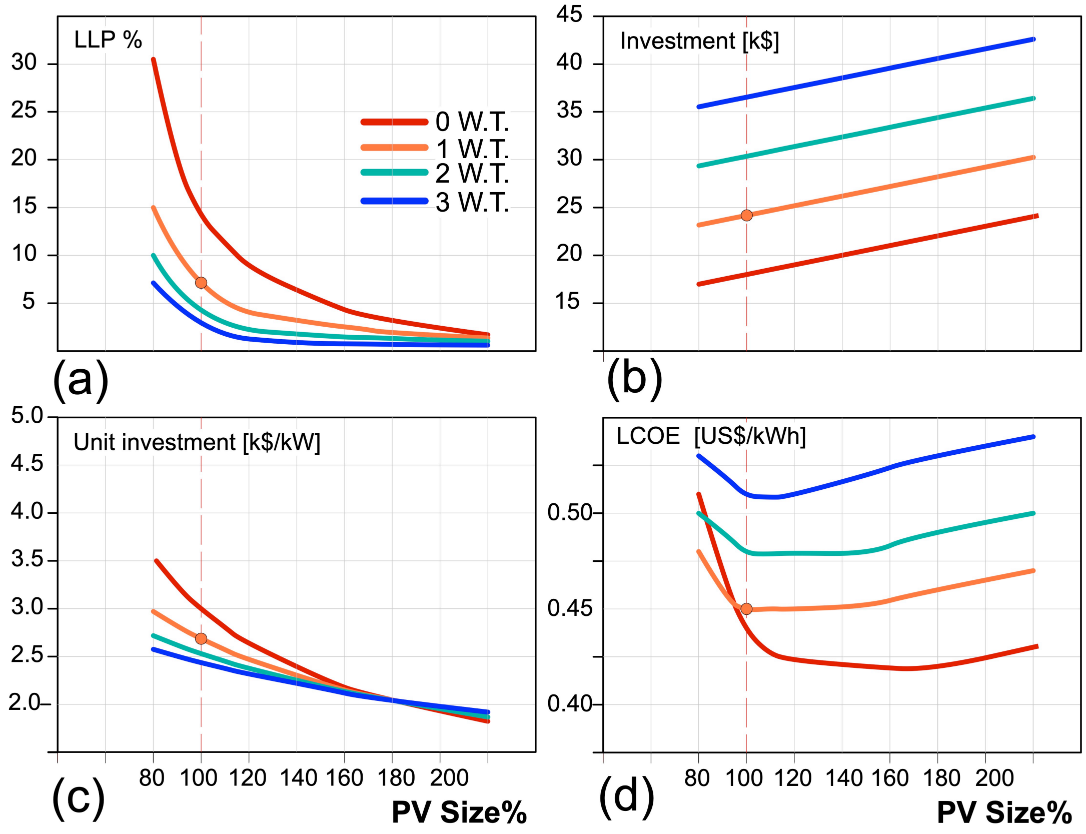


Figure 35: (a): LLP for varying sizes of PV arrays and number of wind turbines with a fixed demand and VRLA-GEL battery bank size of 38.4 kWh; (b): investment for varying sizes of PV arrays and number of wind turbines with a fixed demand and VRLA-GEL battery bank size of 38.4 kWh; (**c**): unit investment for varying sizes of PV arrays and number of wind turbines with a fixed demand and VRLA-GEL battery bank size of 38.4 kWh; (**d**): LCOE for varying sizes of PV arrays and number of wind turbines with a fixed demand and VRLA-GEL battery bank size of 38.4 kWh (present situation is shown with a dot).

5.5 Parametric study with generation size

As seen above battery size has a strong influence on the technical and economic performance of the microgrid, and a rational compromise must be reached between the opposed objectives of low LLP and competitive costs. Another valuable study is to assess the effect of varying installed generating capacity of both PV and wind turbines. In this section calculations are made to obtain LLP, investment and LCOE with a PV array that goes from 80% to 220% of present size (6kWp) and 3 kW wind turbines that go from none to 3 units, while VRLA-Gel Battery size is kept fixed at 38.4 kWh and load is also fixed at 30 kWh/day. These results are shown in Figure 35. As can be expected, LLP is reduced when installed generating capacity is increased, the inclusion of a single wind turbine has a great positive impact as it supplies power during peak hours and possibly in the critical early morning hours. There is a diminishing effect as 2 or 3 turbines are added, as can be seen in Figure 35(a). Investment increased proportionately with installed power, but unit investment (US$/kW) decreases because battery size is kept constant as shown in Figures 35(b) and 35(c). Here again LCOE behaves according to the opposing effects of greater investment and lower LLP that allows more energy to be delivered. When no wind turbine is considered and PV is reduced to 80%, LCOE increases dramatically because of a large LLP that seriously affects delivered energy as can be seen in Figure 35(d). Including wind turbines in Laguna Grande clearly enhances the reliability of the microgrid, installing more turbines instead of PV increases LCOE as the unit costs of small wind turbines is substantially greater than PV (3200 vs. 1950 US$/kW). In the last decades the spectacular development of the PV technology and market has led to a more than 10-fold cost reductions while it has not been the case for small wind turbines. Thus, installing small wind turbines is only economically justifiable in very windy locations with annual wind speed average above 7 m/s, especially if the probability of nocturnal wind is high.

5.6 Optimization and upgrade

As stated in section 2, the main objective of this work is to apply the knowledge and experience gained in more than five years of running the Laguna Grande microgrid, and the analysis of the measured data to optimize future designs, including the possibility of upgrading this same microgrid in the near future.

Since the original design stage was completed in early 2016, several product improvements have become available in the dynamic renewable energy market. Commercial medium sized poly-crystalline PV modules have now been overcome by large format mono-crystalline half-cell PERC modules. PERC stand for passivated emitter rear cell, a technology developed by the University of New South Wales in 1989 [161][161], by including a dielectric surface passivation step in the manufacturing process and reducing the metal-semiconductor contact area in the rear of the cell, better light capture and reduced electron-hole recombination was achieved, as a consequence PV cell efficiency surpassed 21%. This PV cell technology, at first developed at prototype scale, has finally reached the market. Additional improvements are half-cell technology, that reduces electric conduction losses, and a bigger module size; resulting in more efficient and economic PV arrays that now can be incorporated to rural microgrids.

Lithium-ion batteries that were once confined in applications like portable computers, cameras and handheld tools or to the high-tech world of electric vehicles, now are available from diverse manufacturers in convenient formats and voltages to be used in microgrids at an increasingly accessible price. These lithium-ion batteries come equipped with sophisticated battery management system (BMS) that effectively regulate the voltages applied and the currents coming in and out of the multiple sets of cells that configure the battery, also allowing for communication with other devices and the operator. The correct operation of the BMS is vital for the stability and long-term duration of the lithium-ion battery, this in turn is its greatest contribution to achieve higher microgrid performance.

Table 23: HOMER optimized microgrid configurations compared with present case

Case	PV	Wind Turbines	Storage	LLP	LCOE	Net Present Cost (r=6%)	Unit Initial Invest.
	(kWp)	(3 kW Units)	(kWh)	(%)	(USD/kWh)	(USD)	(USD/kW)
1	6.60	1	LiFePO4: 17.5	3.00	0.33	39717	2708
2	3.96	2	LiFePO4: 14.00	5.00	0.34	40233	2754
3	5.28	1	LiFePO4: 14.00	7.50	0.31	35801	2801
Base	6.00	1	VRLA-GEL: 38.40	7.20	0.44	51935	2435

Power electronics have also evolved positively and now key products like MPPT controllers and inverters are more reliable, compact, and flexible. An outstanding feature is the development of advanced communication between the components, including the lithium-ion battery, and to a central supervisory system that can be remotely accessed by telecommunications.

As seen in sections 4.1.3 and 4.1.4 there are several algorithms and optimization software available. The most widely used software is HOMER (Hybrid Optimization for Multiple Energy Resources). Originally a free software created in 1993 by the National Renewable Energy Laboratory (NREL), it has now evolved to be a highly commercial and increasingly complex software owned by the consultancy and certification giant UL. The measured data of load, wind speed and solar radiation are fed to this software, together with the specifications and costs of the state-of-the-art components that we can now use. The results of these optimization process are shown in Table 23 in which the present or “base” case is also included for comparison.

Table 23 shows very valuable information to assist the rural microgrid designer in making the correct decisions between battery technologies and reaching a compromise solution between LLP, investment and LCOE. Firstly, the initial investment shows that with an additional expenditure of no more than 15% lithium-ion technology can be implemented, resulting in up to 30% reduction in LCOE. Secondly, the compromise that must be reached between LLP and LCOE is evidenced: case 3 has the lowest cost of energy but has an LLP of 7.5% while case 1 is slightly higher in energy cost but offers an acceptable LLP of 3%. Case 2 replaces PV capacity for a second 3kW wind turbine, as mentioned above, unit costs of small wind turbines are substantially superior to PV technology, this is reflected in a higher LCOE and not too good LLP mainly because insufficient generation in low wind morning hours.

It is important to mention at this point that simulation software can be a sort of “black box”, normally there is no access to understand the algorithms and assumptions that are applied in internal calculations. It is always convenient to perform independent calculations or use alternate software to confirm and validate results.

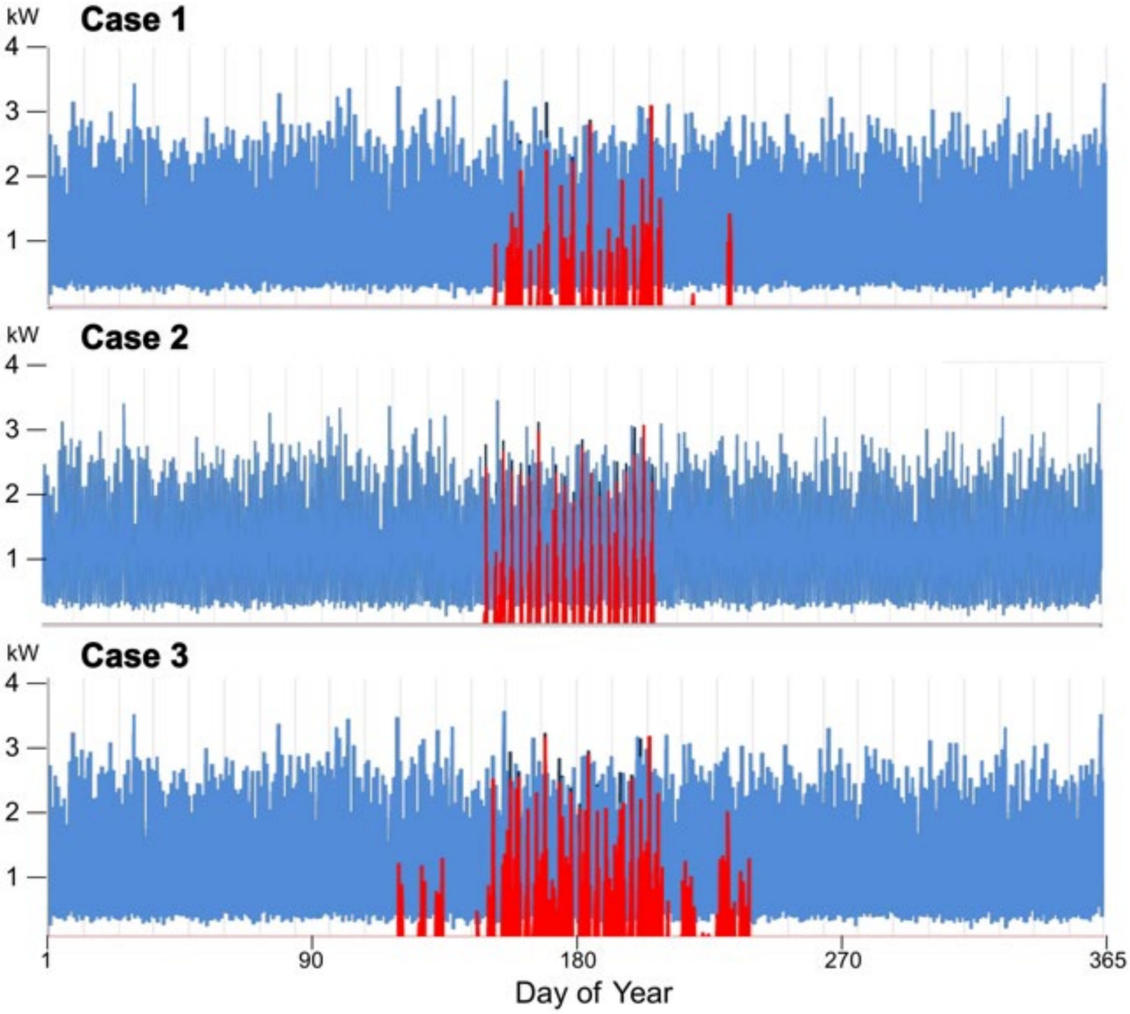


Figure 36: Annual profiles for load (in blue) and capacity shortage (in red) for HOMER-optimized cases 1, 2, and 3

An interesting output of HOMER is shown in Figure 36 displaying the load profile along a whole year and the capacity shortage or its equivalent: LLP for the 3 optimized cases. The same can be said about Figure 37 which very visually allows the SOC be perceived along the whole timeframe of the year. It is evident from both sets of graphs that the critical months for the Laguna Grande microgrid are from June to August, being consistent with the months when lower radiation and gentler winds occur and higher levels of LLP are observed.

From Table 21 a well-balanced and favorable choice for an upgrade will be Case 1, with an intermediate unit cost and LCOE but with the lowest LLP of 3%. This is a compromise solution, assuring the best service of all cases and having slightly higher costs. This upgraded version of the Laguna Grande microgrid will be configured with the components detailed in Table 24.

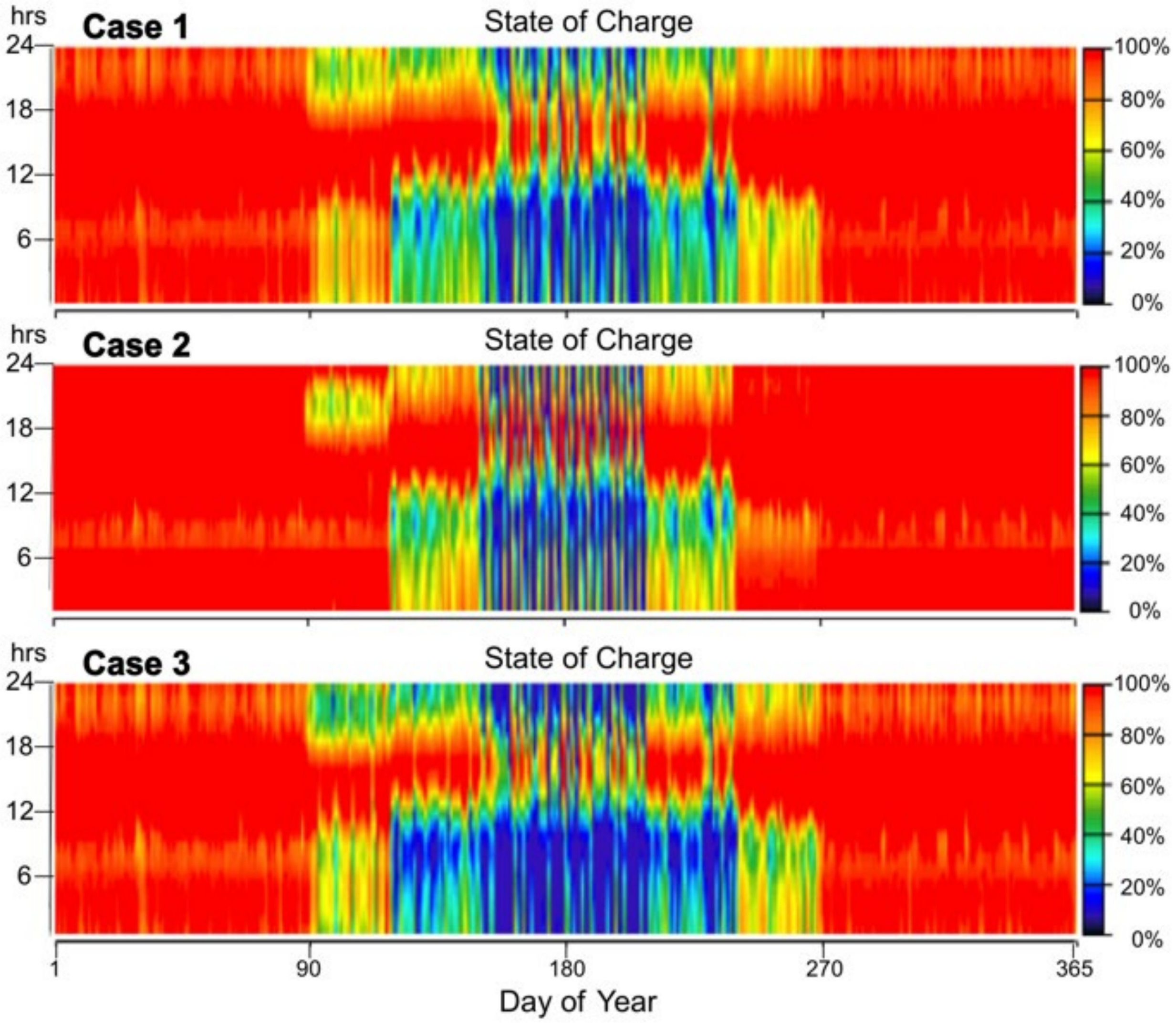


Figure 37: Annual profiles for SOC for HOMER-optimized cases 1, 2, and 3

Table 24: Upgraded microgrid component specifications

Component	Type	Specification
Photovoltaic array	Half-cell-PERC	6.6 kWp (15 × 440 Wp)
PV controller	MPPT	2 × 80 A
Wind turbine	Permanent magnet	1 × 3 kW @ 12 m/s
Wind turbine controller	PWM + dump load	1 × 3 kW @ 48 V
Batteries	LiFePO4	(17.5 kWh @ 100% DOD)

Figure 38: Signing of the agreement for the electrification of Laguna Grande, Ica, Perú by means of a hybrid microgrid (July 2016)

5.7 Microgrid sustainability

The initiatives of harnessing sustainable energy with hybrid microgrids to supply electricity to remote communities and bring them closer to social equity and development opportunities, must be *themselves* sustainable. It is not sufficient to perform a good design and use the best materials, technology and equipment to assure the long-term success of a rural electrification project. The human factor is key to attain social and economic sustainability and must be considered and incorporated in the project from the very early stages and all along its life cycle [162][163][164][165][166].

When approaching a target community to be electrified, a multidisciplinary team must be considered, not only with engineers but also social sciences professionals, all with good disposition to observe and listen. It is not uncommon that a prescribed project must be substantially modified to be better suited for the community needs. There are many unfortunate examples of expensive projects that “solve” non-existing problems.

It is of great importance that the target community has a minimum social structure and stability; permanence is naturally an essential requirement. There must be a clear and well stablished leadership in the community and if possible, a formal legal status of both the community and its representatives. If this leadership or status does not exist, it must be promoted and guided from the beginning, as part of the project itself. Following is the constitution of an elected electrification managing committee, integrated by a president, secretary and treasurer. This is best done through a public act with the participation of as many members of the community as possible (Figure 38). The main functions of this committee will be the operation and maintenance of the system as well as collecting the energy consumption monthly fees. Experience teaches that the leadership of the women of the community is essential and must be invited to contribute, often they have better administrative skills and a clearer perpective of the community´s needs and future development. Agreements must be elaborated and signed by all community members that freely wish to have a service point served by the electrification system. This relatively simple and straightforward document states the conditions and responsibilities of having a service point including the energy tariff and flat membership monthly fee.

An organizational model to assist the sustainability of rural communitarian services has been introduced by ITDG-Practical Action [167]. It considers the different stakeholders of the electrification system as: the owner, the managing committee, the users and a supervising controller. The owner has the duty to provide maintenance and spares to the system and gets correspondingly paid, the committee collects the energy consumption fees and flat tariffs and manages the system´s funds by means of a bank account, whose balances must be accessible to all associates. Finally the controller verifies the correct compliance of the respective functions of the parties and helps to solve possible disputes, as seen in Figure 39.

To help to increase the community´s sense of belonging and empowerment towards the electrification project, it is very important to include some of its members in early low risk activities like excavation, foundations, laying distribution lines and other installations activities, naturally, with proper training and personal protection. If possible, the community can collaborate with the development of the project with labour, some materials or funds as collateral investment. In this manner the community members will perceive and internalize its value as their own, and not as an external gift. In that sense it is vital to explain to all members of the community the fact that even if the electrification system originates from a donation, state grant or social program, and that the energy resources are essentially free, it is still compulsory to pay for the energy consumed to assure sustainability. It is also a good practice to include a flat basic connection fee, so that even if there is no consumption revenue is generated by all members of the electrification system.

Relatively recent developments in the technology of energy meters, their communications and managing software have originated very clever solutions that contribute to the sustainability of rural microgrids [8]. Smart meters that work in a pre-payment scheme and that also store and report detailed hourly energy consumption provide very valuable information for the microgrid operator and also a very precious feedback to the designer. Pre-payment is a much more viable and trouble-free management model for rural microgrids. Experience evidence that there are sporadic conflicts related to the payments and particularly with a few associates that repeatedly incur in delays. In extreme cases, and in accordance with the signed agreements, the service may be intervened and suspended; an action that can dangerously lead to violence. In the pre-payment and remotely monitored scenario offered by the new technology, the service is automatically interrupted when the credit is exhausted.

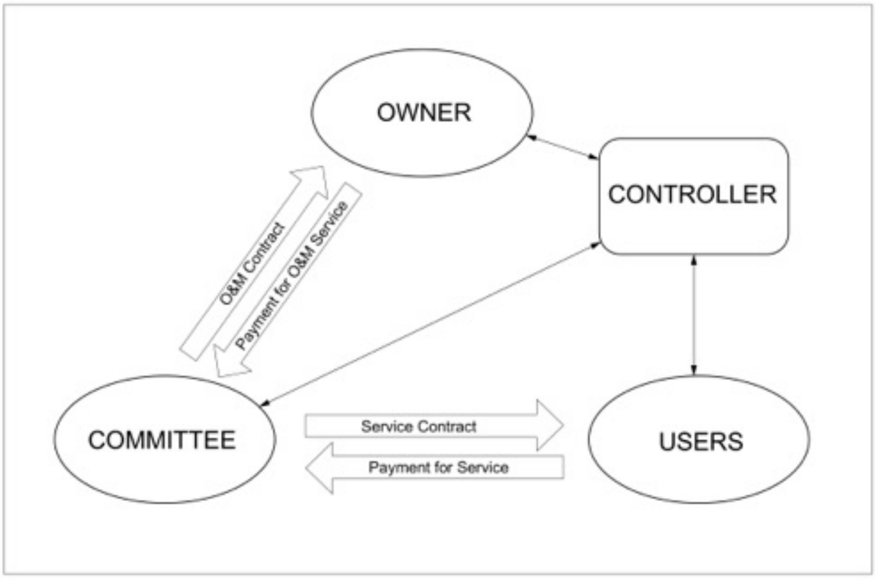


Figure 39: Rural electrification system management model including Committee, Users, Owner and Controller

Furthermore, the maximum power assigned to each service can be adjusted and, in case of abuse, the service will be temporarily interrupted up to ten times, after that reestablishment requires the intervention of the operator. Monitoring hourly consumption habits of each service point also allows for different tariffs to be created, promoting demand response towards hours when generation is active. Another benefit of this metering technology is to keep track of reactive energy increments that can stress the inverters and affect microgrid overall performance.

In summary, technology developments as ever more competitive photovoltaics, efficient and reliable electronics, long lasting and compact lithium-ion batteries, smart pre-payment meters and real time microgrid performance information availability through telecommunications, all contribute substantially to enhance microgrid sustainability. Nevertheless, the human factor and its adequate inclusion in all stages of the project is of fundamental relevance for its long-term success and sustainability.

6. CONCLUSIONS AND FURTHER RESEARCH

Nowadays there is still a considerable fraction of the world population that does not have access to electricity and its remarkable positive effects on human and economic development. This is particularly acute in the African continent and other less developed areas. Rural microgrids can constitute an economically viable and environmentally sustainable solution to close this electrification gap. Relentless technological developments contribute with more efficient PV technology, ever more resilient electronics and accessible long-lasting batteries; thus, microgrids become each time more competitive and reliable.

The state of the art and literature review evidence that there is insufficient information about the performance of microgrids based on measured data under real field operative conditions. It is in this aspect that the present work has aimed to contribute, with the purpose of attaining better design capabilities. The Laguna Grande rural hybrid microgrid has been equipped with the necessary sensors and data loggers to measure and register electrical and meteorological parameters. Subsequent analysis allows for the microgrid´s technical performance to be assessed and the cost of energy be projected, having the battery as main determinant component. The measured solar and wind resources are converted to potential power capture and compared with measured data showing that a considerable fraction is left out due to limited battery size and concurrence between these two sources. Battery size can be increased for this purpose, contributing to lower LLP, but it is shown that this leads to an increase in investment and LCOE, thus, a compromise choice must be made. Parametric studies give insights to the effects produced on reliability and costs by adjusting design parameters as generating capacity and storage. The use of optimization software and models based on diverse algorithms can shed light on the behavior of microgrids, but it is important to validate these results with real measured data.

The cost analysis performed in a hypothetical rural electrification scenario shows that hybrid microgrids, especially when equipped with long lasting lithium-ion batteries, can supply energy at a lower cost, compared with conventional solutions as grid extensions or diesel electric generators. Micro-hydro systems are undoubtedly the most economical alternative for electric generation, but only a limited number of rural communities are fortunate to have access to this resource.

Successful rural microgrid design requires adequate measurement of available resources, a good estimate of projected loads and specifying high quality and long-lasting components, especially the main reliability and cost driver: the battery bank. But technical proficiency is not sufficient to ensure success and long-term sustainability of the rural electrification system: the human factor is of paramount importance. The social aspects of the microgrid project must be incorporated from the very start and all along its development. Working closely and in good terms with the community and paying adequate attention to the establishment of a management committee and corresponding written agreements is fundamental for the long-term success and sustainability of the rural microgrid.

The outlook for rural microgrids is very positive considering the enormous task of completing the electrification gap and the corresponding demand foreseen.

Technological developments keep producing better, more reliable and competitive key components as PV modules, power electronics and lithium-ion batteries. Furthermore, communication between devices and remote microgrid monitoring is now a reality. This feature now not only includes meteorological parameters, but most interestingly, detailed consumption profiles of each individual point of service by means of smart pre-payment meters.

New rural microgrid installations underway, with all the above-mentioned enhancements, will be the source of very valuable information for continuing this research towards better knowledge and design capabilities to be applied in future cases, including the upgrade of the now emblematic Laguna Grande system.

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