IIT Working Paper ref IIT-16-155-A (Preprint)

Working Paper Enel Foundation XXX/2016

Research Project

Low-cost energy technologies for Universal Access

Evaluation of universal access to modern energy services in Peru

Case study of scenarios for Electricity Access in Cajamarca

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Acknowledgements

We are very grateful to all the students and researchers at MIT and IIT Comillas who significantly helped us in carrying the discussion along for the project, and help build the tools that would be eventually used for this research project. Special thanks are given to Douglas Ellman, Claudio Vergara, Lily Mwalenga, Yael Borofsky, Patricia Levi and Vivian Li.

Research Project Low-cost energy technologies for Universal Access

The UN Secretary General's Advisory Group on Energy and Climate Change defines Universal Access as "access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses". The International Energy Agency (IEA) establishes that achieving a minimum basic Universal Access to electricity and providing clean cooking facilities for 2030 would require around $1 trillion cumulative investment. IEA also highlights electricity as the most critical energy carrier for development while the use of biomass in inefficient stoves remains one of the main causes of premature deaths.

It is clear that a problem of this magnitude cannot be seriously approached without private capital and, most likely, with the serious involvement of major energy companies, although decentralized approaches –either transitory or not– cannot be ruled out and they are already taking place. Obviously this will happen only if an attractive business model can be defined with the participation of the concerned communities. This model must include: the definition of the appropriate (low cost) technologies to be used; a regulatory framework that clearly defines the rights and obligations of all parties involved and, specifically, the rules of remuneration for the provision of the service; and the sources of finance for this activity. Such considerations are central to this research project and represent a considerable challenge for rural areas.

The purpose of this project is to contribute to the development of Universal Access strategies and tools for policymakers, global businesses and practitioners. This Working Paper 4 refers to the case study in Peru developed in the Phase II of the Low cost energy technologies for Universal Access project by the Massachusetts Institute of Technology (MIT) acting through MIT's Energy Initiative (MITei) and in collaboration with Fondazione Centro Studi Enel (Enel Foundation).

Phase I of the project comprises the analysis of the State of the Art technologies, strategies and business models for electrification (Working Paper 1) and modern heat (Working Paper 2) as well as the proposal of a methodology to develop country studies for the establishment of roadmaps to universal access (Working Paper 3).

Phase II includes the application of this methodology to different countries, starting with a report for two case studies, Kenya and Peru.

The project is developed in collaboration with Comillas Pontifical University – Institute for Research in Technology (COMILLAS – IIT) under the scope of the Comillas University Massachusetts Institute of Technology Electricity Systems (COMITES) Program.

This Working Paper 4 applies the proposed framework to the analysis of Energy Access in Peru, showing the scenarios and outcomes of the electrification model and methodology to the case of the Michiquillay planning of rural electrification, in the region of Cajamarca. The methodology covers the collection of data, the logic processes and the potential use of software tools that make possible the development of a proposal including the different choices of technologies, business models, financial, regulatory and policy strategies that could lead to the provision of universal access to electricity in that area.

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Abstract

Achieving Universal Access to modern energy services, as discussed in depth in the previous Working Papers of this series, poses an enormous challenge not only for countries with a large share of potential beneficiaries of modern technologies for lighting, cooking and heating, but also for those countries as Peru where the population without access lives in very isolated or inaccessible areas, or also in new informal settlements in the suburbs, characterized by their very low income and marginality.

This Working Paper focuses on the alternatives, planning approaches and computer tools needed to reach this "last mile", with the necessary involvement of government, private capital and the beneficiaries. The electrification process that accompanies the transition from traditional lighting technologies (candles, kerosene, disposable or rechargeable batteries) to modern electricity supply modes (extension of the grid, microgrids or stand alone systems) must include: the definition of the appropriate (low cost) technologies to be used; a regulatory framework that clearly defines the rights and obligations of all parties involved and, specifically, the rules of remuneration for the provision of the service; and the sources of finance for this activity. The innovation on computer tools for Universal Access, as the Reference Electrification Model (REM) described and applied in this Working Paper, aim at being a valuable support for decision makers in the definition of successful and complex strategies.

This Working Paper is the fourth report of the *Low cost energy technologies for Universal Access* project by the Massachusetts Institute of Technology (MIT) acting through MIT's Energy Initiative (MITEI) and in collaboration with Fondazione Centro Studi Enel (Enel Foundation). The project is developed in collaboration with Comillas Pontifical University – Institute for Research in Technology (COMILLAS – IIT) under the scope of the Comillas University Massachusetts Institute of Technology Electricity Systems (COMITES) Program.

The purpose of this project is to contribute to the development of Universal Access strategies and tools for policymakers and practitioners. Building over an initial analysis of the State of the Art technologies, strategies and business models for electrification (Working Paper 1) and modern heat (Working Paper 2) the project proposes a methodology to develop country studies for the establishment of roadmaps to universal access (Working Paper 3). In the second phase the models and methodologies are applied to the study cases of Peru (Working Paper 4) and Kenya (Working Paper 5) to detail the potential of the application of these tools to the challenges of universal access planning and policy-making.

Keywords: *Universal Access, off-grid electrification, grid extension, modern heat, business models, regulation, energy policy, enabling environment, decision support models.*

Jel Codes: *Q4, Q41, Q42, Q43, Q47, Q48, N70, O13, O18, O19, O33, O38, O44, Q56*

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1 Introduction and situation analysis

1.1 Universal Access to modern energy services

Achieving Universal Access to modern energy services, as discussed in depth in the previous Working Papers of this series, poses an enormous challenge not only for countries with a large share of potential beneficiaries of modern technologies for lighting, cooking and heating, but also for those countries as Peru where the population without access lives in very isolated or inaccessible areas, like the highlands and mountains of the Andes or the depths of the Amazonian rainforest, or also in new informal settlements in the suburbs, characterized by their very low income and marginality.

This Working Paper focuses on the alternatives, planning approaches and strategies needed to reach this "last mile", the necessary involvement of private capital and, most likely, the serious involvement of major energy companies together with decentralized approaches – transitory or not – through the definition of attractive business models with the participation of the concerned communities who integrate the social embroidery and market at the "bottom of the pyramid".

The electrification process that accompanies the transition from traditional lighting technologies (candles, kerosene, disposable or rechargeable batteries) to modern electricity supply modes (extension of the grid, microgrids or stand alone systems) must include: the definition of the appropriate (low cost) technologies to be used; a regulatory framework that clearly defines the rights and obligations of all parties involved and, specifically, the rules of remuneration for the provision of the service; and the sources of finance for this activity. Such considerations are central to this research project and represent a considerable challenge for rural areas.

For the purpose of this document, we abide by the definition of "Universal Access" by the UN Secretary General's Advisory Group on Energy and Climate Change[1] extensively discussed and analyzed in previous Working Papers of this series.

Modern energy services are a key element for human development[2], as explicitly acknowledged by including Universal Access as the first of the targets defined in Goal 7 of the 2030 Agenda for Sustainable Development[3] adopted by the United Nations General Assembly in September 25th 2015:

> ***"Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all***
>
> *7.1 By 2030, ensure universal access to affordable, reliable and modern energy services*
>
> *7.2 By 2030, increase substantially the share of renewable energy in the global energy mix*
>
> *7.3 By 2030, double the global rate of improvement in energy efficiency*
>
> *7.a By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology*

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[1] (SG AGECC, 2010) defines Universal Access as "*access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses*" to a level "*needed to improve livelihoods in the poorest countries and drive local economic development*".

[2] (ESMAP, World Bank, & IEA, 2013; IEA, 2010; UN Energy, 2005; World Bank, 2013)

[3] (UN General Assembly, 2015a, 2015b; UNDP, 2015)

7.b By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programmes of support."

Universal Access is therefore a target that has to be considered conjointly, not only with other energy policies as share of renewable energy sources or energy efficiency, but also as a necessary infrastructure required for to achieve other development goals, as ending poverty (Goal 1), ending hunger, food security, improve nutrition and promote sustainable agriculture (Goal 2), ensure healthy lives and well being (Goal 3), inclusive and equitable quality education and learning opportunities for all (Goal 4), gender equality and empowerment of women (Goal 5), water and sanitation for all (Goal 6), economic growth and decent work for all (Goal 8), build resilient infrastructure, industrialization and innovation (Goal 9), reduce inequality within and among countries (Goal 10), make cities and settlements inclusive, safe, resilient and sustainable (Goal 11), ensure sustainable consumption and production patterns (Goal 12), combat climate change and its impacts (Goal 13), sustainability of oceans (Goal 14) and terrestrial ecosystems (Goal 15), promote peaceful and inclusive societies, justice and institutions (Goal 16) and finally strengthen the means of implementation and revitalize a global partnership for sustainable development (Goal 17).

From the specifications of each goal, the need of a number of energy services can be inferred to support, for instance, income generation, agricultural technologies, better education, women activities, water pumping, productive uses, better housing, safer streets, innovative activities, better information and communications, more sustainable environmental practices, or better patterns of consumption and production. The appropriate targets for access to electricity and modern heat should therefore be set in relation with the energy services that need to be provided for domestic, productive and community uses in order to achieve the policy goals established by each country or by international programs.

A more in depth discussion on establishing the targets for electrification planning can be found in Section 3 of this document

In this Working Paper we focus on the electrification process planning and policy-making to support decision-making by the government, companies, social enterprises, NGOs, practitioners and other electrification agents, according to their changing, diverse and interrelated goals, providing detailed techno-economic, regulatory and policy responses to "what if" questions in a flexible and rigorous manner.

1.2 Framing human development and sustainability in Peru

The Republic of Peru is extended over the west coast of South America, north of Chile, south of Ecuador and Colombia, and east of Brazil and Bolivia. With over 30 million people in 2014[4], 75% living in urban areas, and a population growth of around 1.6% per annum, Peru has seen the number of rural inhabitants decline, as can be noticed in Figure 1, because of an increasing internal migration to urban areas, especially to the city of Lima.

[4] Instituto Nacional de Estadística e Informática del Perú, INEI 2015.

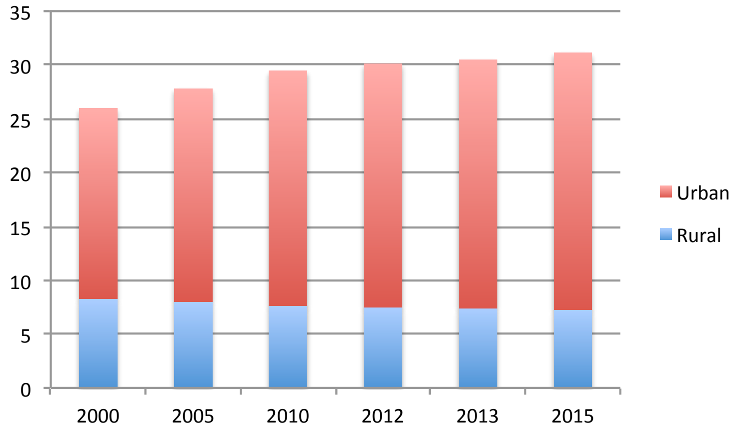

Figure 1. Evolution of the rural and urban population in Peru 2000-2015 (INEI 2015)

The pyramid of population is shown in Figure 2, depicting a country in demographic transition. The population is still expected to continue growing, though more slowly, to reach 40 million inhabitants by 2050.

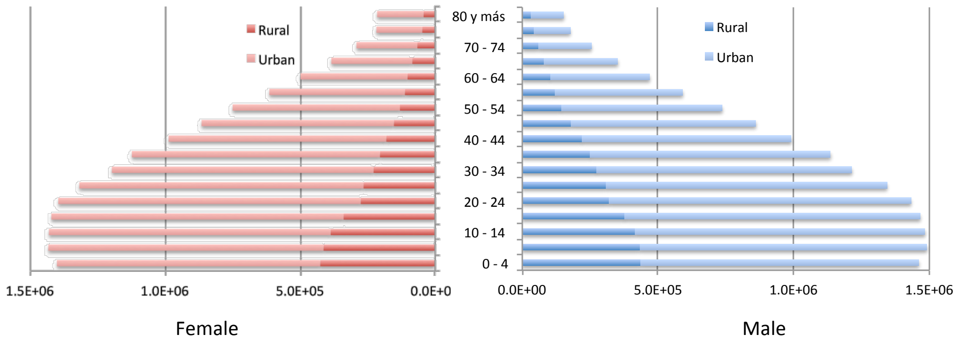

Figure 2. Population pyramid by gender in 2015 (INEI 2015)

The gross income received a renewed impulse in Peru with the beginning of this century, as can be seen in Figure 3. Growth in the mining and extractive sector was accompanied by the good behavior of industry, commerce and other services sectors. This has led to an enormous investment and expansion of the electricity and water sector, which almost tripled its size in 20 years.

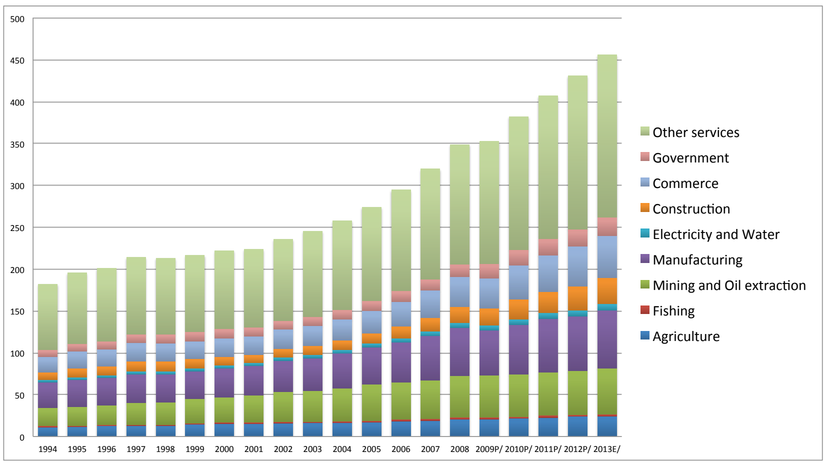

Figure 3. Evolution of the sources of income in Peru 2004-2012 (INEI 2015)

The improvement in the economic situation in Peru encompassed a very positive impact in national poverty. The share of population under the *absolute poverty line* (with income that provide for less than a *essential basket of goods and services*, that varies per region and rural/urban areas, with an average of 161 PEN/month, around 1.60 $/day in 2014) has fallen from 16.4% (2004) to 6% of the population (2012) and the amount of people *in poverty* (with income that provides for less than a *minimum basket of goods and services*, worth in average 303 PEN/month, roughly more than 3 $/day in 2014) has also been reduced from 58.7% to 25.8% between 2004 and 2012 (see Figure 4). Nevertheless, the inequality of income levels is still very high, resulting in a Gini coefficient of 0.35[5], with a higher divide between urban and rural areas than the one within any of them alone.

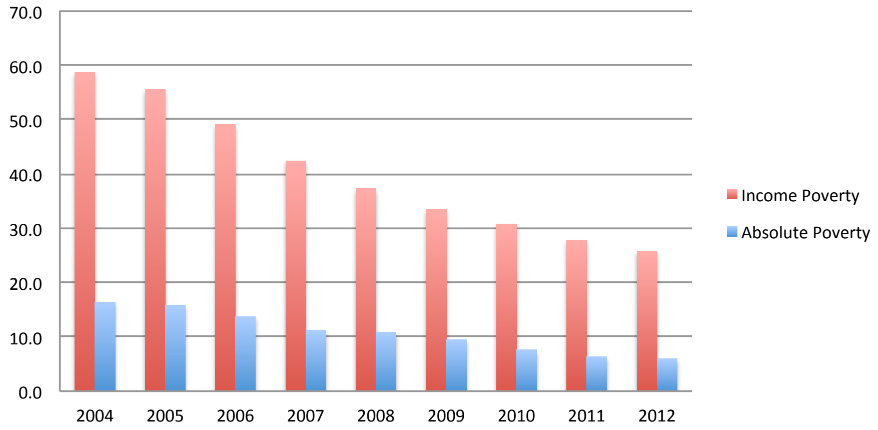

Figure 4. Population below the poverty and extreme poverty line in Peru 2004-2012 (INEI 2015)

Not only economic poverty has experience a notable increase, but also multi-dimensional development measured by the Human Development Index has improved even more in terms of life expectancy or education in the past 35 years, as can be seen in Figure 5

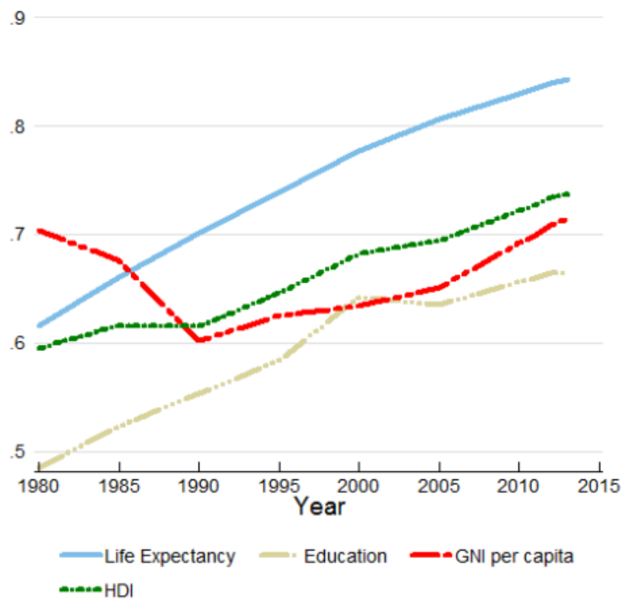

Figure 5. Evolution of the Human Development Index (HDI) and breakdown by components 1980-2014[6]

[5] (INEI, 2015)
[6] (PNUD, 2015)

The HDI of Peru (0.737) places the whole country among those with High Development Index (0.735). Still, it is slightly below the average in Latin America and the Caribean (0.740). The closest countries in his region according to human development would be Venezuela and Chile (see Table 1).

	HDI value	HDI rank	Life expectancy at birth	Expected years of schooling	Mean years of schooling	GNI per capita (PPP US$)
Peru	0.737	82	74.8	13.1	9.0	11,280
Venezuela (Bolivarian Republic of)	0.764	67	74.6	14.2	8.6	17,067
Chile	0.822	41	80.0	15.1	9.8	20,804
Latin America and the Caribbean	0.740	—	74.9	13.7	7.9	13,767
High HDI	0.735	—	74.5	13.4	8.1	13,231

Table 1. Peru HDI indicators for 2013 relative to selected countries and groups (PNUD 2015)

Still the challenges in rural areas are not small, as there is a sizeable inequality of HDI between departments and provinces. Cajamarca, with an HDI of 0.3773 is the 20th department of the country, out of 25, placed in the range of *Low Human Development* according to this index. But within Cajamarca the provinces of San Marcos and Celendín, where our test case is developed within the Michiquillay SER, show HDIs of 0.2565 and 0.2529, ranked 165 and 167, out of 193 in the whole country, all falling well below the line for Low Human Development.

1.3 Present and trends towards Universal Access to modern energy services in Peru

1.3.1 Peruvian energy and power system overview

The main drivers for the comprehensive Peruvian vision for the energy sector in the coming years are mainly defined by the National Energy Policy 2010-2040[7], which defines the general vision of "an energy system that satisfies the national demand of energy in a reliable, continuous, secure and efficient way, that promotes sustainable development and is supported by planning, constant research and technological innovation". The specific objectives of this policy are:

1. Diversifying the national energy mix, with emphasis in renewable sources and energy efficiency.
2. Competitive energy supply.
3. Universal Access to energy services.
4. Increase the efficiency in the energy production and in the uses of energy.
5. Achieve self-sufficiency in energy production.
6. Develop an energy sector with minimum environmental impact and low carbon emissions in a sustainable development framework.
7. Develop the industry of natural gas and its uses for domiciliary, transport, commerce and industrial uses, as well as for an efficient electrical generation.
8. Strengthen the institutional framework of the energy sector.
9. Integration with the regional markets, enabling the long term vision.

The National Energy Plan 2014-2025[8] aims at maintaining a high level of competitiveness of the sector in a environment of accelerated economic growth, relying on national resources with

[7] (República del Perú, 2010)
[8] (Ministerio de Energía y Minas - República de Perú, 2014)

special focus on natural gas and oil, the construction of pipelines, modernization of refineries, reducing the use of diesel fuel in transport, increasing the share of renewable energies in the national energy mix and promoting energy efficiency in order to contribute to the mitigation of Climate Change. Finally, access to modern energy services will focus on achieving universal access to electricity, universalizing the use of natural gas for heating and cooking.

Between 2003 and 2013 the GDP experienced a 86% growth, electricity consumption raised 92%, but the production of oil and gas was increased a 260%, of which 60% was sold in international markets and 40% consumed in Peru.

The main event behind this very fast advancement lays in the contribution of the gas from Camisea, which nearly multiplied by 3 its weight in the national share in one decade, followed by an also very positive evolution of national crude oil. This factor had a major impact in the redesign of the Peruvian energy sector both in terms of export and internal consumption, as can be easily appreciated in the Sankey diagram of energy flows in 2012, shown in Figure 6.

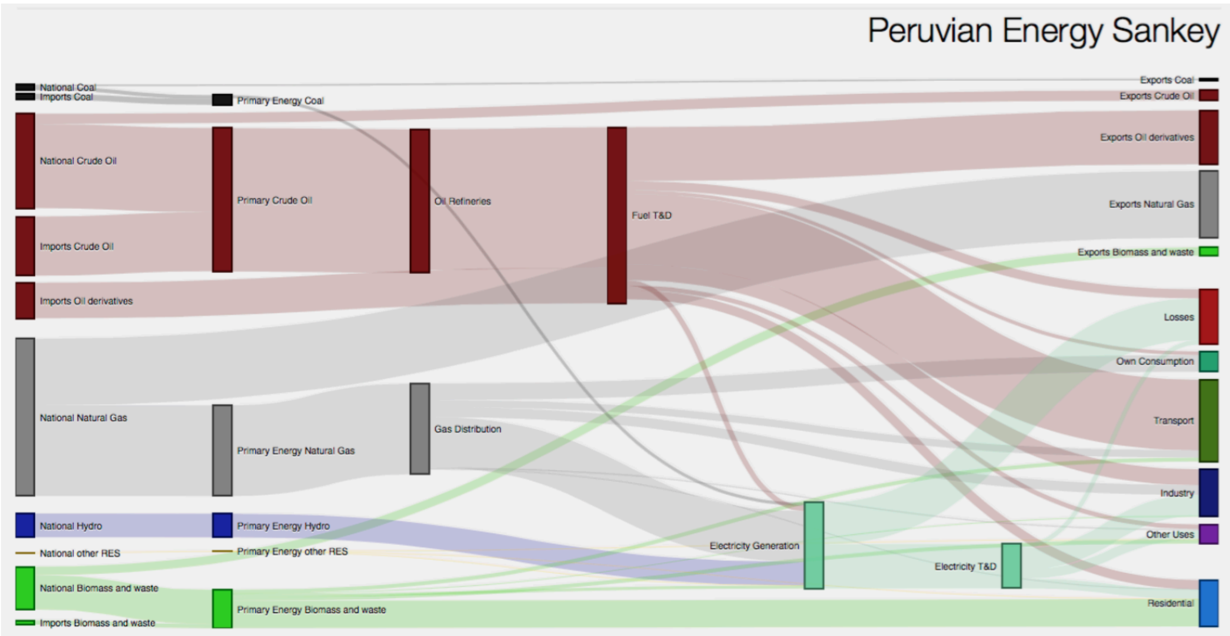

Figure 6. Sankey diagram of the energy balance in Peru 2012 [9]

Nearly 45% of the gas production is exported, while most of the national consumption is devoted to the production of electricity, completing the generation mix mostly with hydroelectric resources and very small shares of biomass and other renewable energy sources (solar and wind).

The Sankey diagram also shows that the modern energy sources are mostly devoted to transport, industry and other uses, while the residential sector (our focal point in this Working Paper) is dominated by the use of biomass and waste (mainly traditional wood and other raw fuels for cooking and heating). This inequity in the uses of energy for human development is one of the main challenges identified by the Peruvian energy policy, as will be seen later.

[9] Own elaboration based on data from the International Energy Agency (www.iea.org/statistics/statisticssearch/report/?country=PERU&product=balances&year=2012)

The relationship between the human development and economic growth and the energy sector is complex and multifaceted, as already discussed in previous working papers of this series[10]. In Peru, the increase in competitiveness and wellbeing has been encompassed by the growth of the energy sector in multiple dimensions. Peru is ranked 31 worldwide in the Energy Architecture Performance Index (EAPI), which benchmarks the energy systems of nations according to the dimensions depicted in Figure 7.

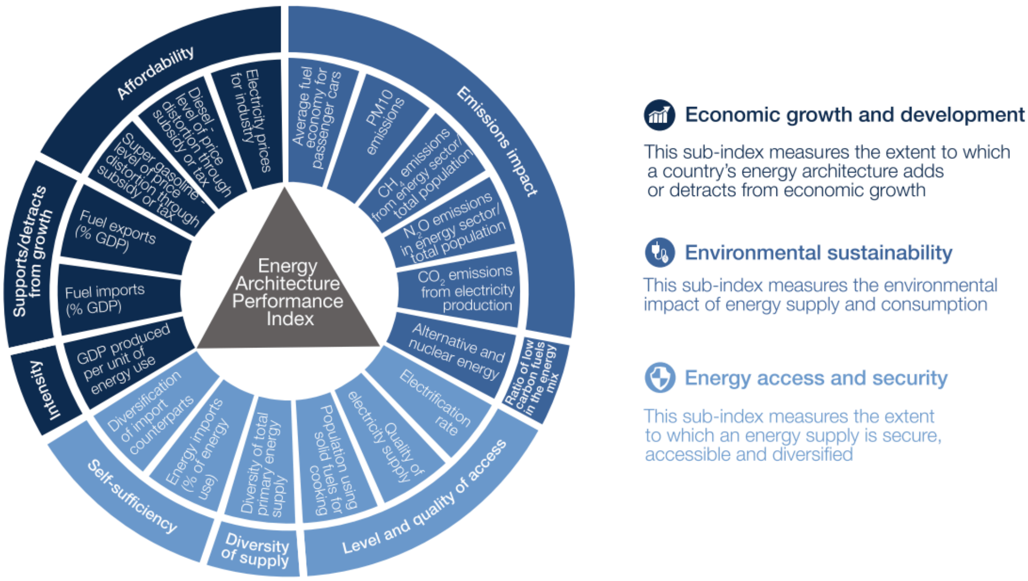

Figure 7. The Energy Architecture Performance Index[11]

This index shows that the energy system has a very high contribution to the economic growth and development of the country (79/100), raking the Peru as the 1st country in the world in this axis of the EAPI. The axis that evaluates energy access and security reaches 71/100 (please see sections 1.3.2 and 1.3.2.1 for further details regarding access to modern energy services in Peru) in terms not only of electrification rate or use of advanced technologies and fuels for heating and cooking, but also in terms of quality of electricity supply. Nonetheless, the country scores lower (55/100) in terms of environmental impact of the energy supply and consumption and faces important challenges regarding inequality of access to energy, especially in rural areas, as will be detailed in Section Universal Access to electricity.

In regards to the power sector, generation has grown at an accelerated pace, accommodating the growth in demand mainly due to the exponential growth of combined cycle power plants, as shown in Figure 8.

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[10] (Amatya, Gonzalez-Garcia, Stoner, & Perez-Arriaga, 2014; Gonzalez-Garcia et al., 2014; González-García, Amatya, Stoner, & Pérez-Arriaga, n.d.)
[11] (World Economic Forum, 2014)

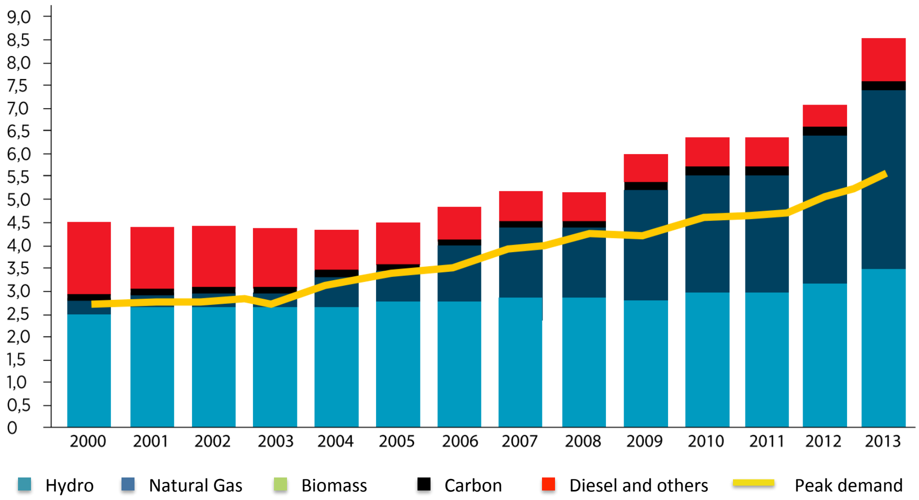

Figure 8. Evolution of the generation capacity and peak demand for the Power Sector in Perú[12]

Hydro is the main renewable energy source in Peru, and due to its high potential, it is still expected to more than double the installed capacity, to address the high demand growth that is expected for the coming 15 years[13] as shown in Figure 9.

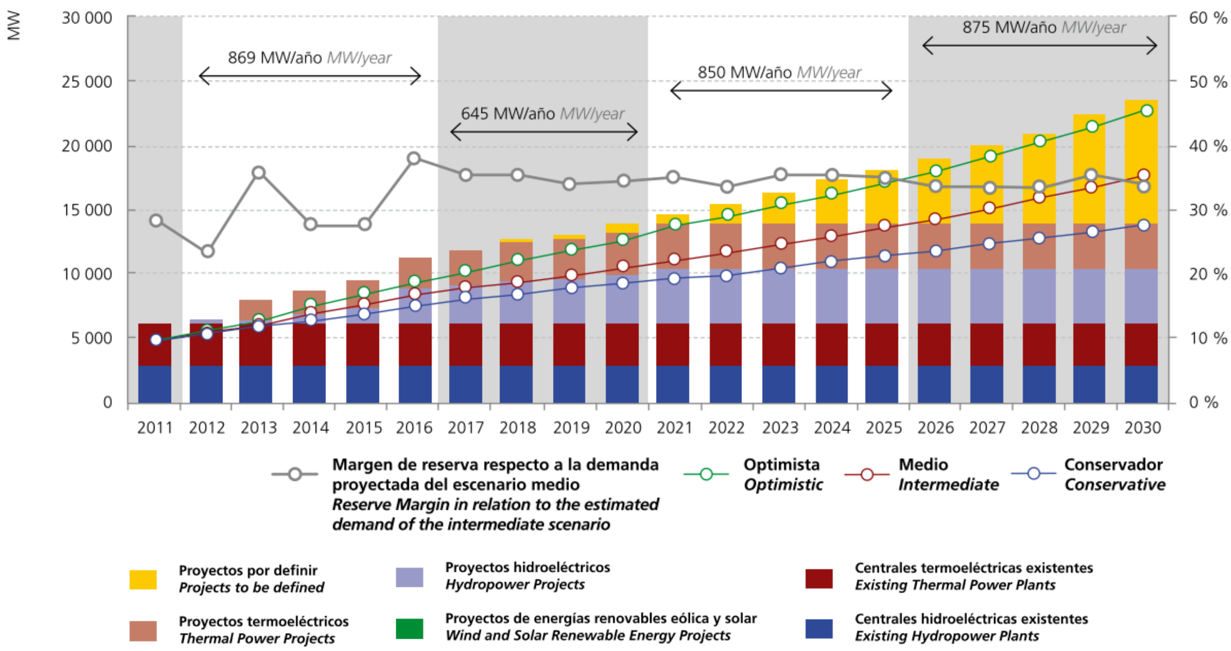

Figure 9. Three demand scenarios for 2030 and expected growth in installed capacity[13]

Despite the preeminence of hydro and CCGT for grid supply, off-grid power is also expected to experience a significant growth mainly based on solar power. Wind also shows a considerable potential, and hybrid wind-solar systems are expected in 167 communities across the country for a total investment of around 38 million USD[14].

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[12] (Singh, Tapia, & Chavez, 2014)
[13] (Ministerio de Energía y Minas (Perú), 2012)
[14] (Ministerio de Energía y Minas (Perú), 2013b; Singh et al., 2014)

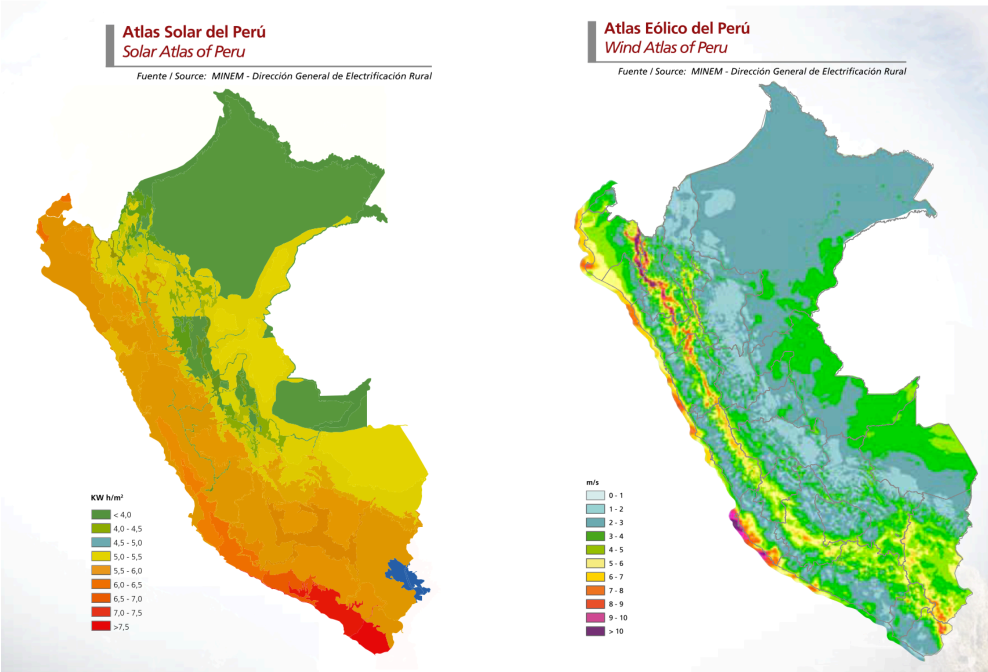

Figure 10. Solar Atlas and Wind Atlas of Peru [13]

1.3.2 Universal Access policy in Peru

Peru assumes the framework established by Sustainable Energy for All (SE4all)[15] and the Sustainable Development Goal 7 of affordable and clean energy for all approved by the Sustainable Development Agenda for 2030[16] with the three following specific targets:

- By 2030, ensure universal access to affordable, reliable and modern energy services
- By 2030, increase substantially the share of renewable energy in the global energy mix
- By 2030, double the global rate of improvement in energy efficiency
- By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology
- By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programs of support.

Peru has substantiated this commitment in its Plan for Universal Access to Energy 2013-2022[17] that establishes the general goal of *"promoting, from the energy field, an economically efficient, environmentally sustainable and equitable development, implementing projects that allow the expansion of access to modern energy, prioritizing the use of available energy resources, establishing the technical, social and geographical viability of the aforementioned projects, with the goal of achieving a higher and better quality of living for the population with less resources in the country, within the period 2013-2022"*.

The goals defined by the Universal Access Plan are:

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[15] (ESMAP et al., 2013; SE4all, 2013a; SG High-Level Group on Sustainable Energy for All, 2012)
[16] (UN General Assembly, 2015b; UNDP, 2015)
[17] Plan de Acceso Universal a la Energía 2013-2022 (Ministerio de Energía y Minas (Perú), 2013a)

- Access to electricity: lighting, communications and community services.
- Access to cooking and heating new technologies and fuels: improved cookstoves, natural gas, LPG, biogas (bio-digesters).
- Enable productive uses of energy, such as improvements in productivity (water pumping, mechanization or others), processing agricultural products for commerce and fuel for transport. Projects oriented to the use of Natural Gas must be prioritized in less-favored communities, to promote their wellbeing and economic development in the framework of the "social inclusion" policy.
- The projects implemented for Universal Access must be oriented towards energy efficiency.

This plan falls under the following policy and legal framework:

- National Energy Policy of Peru 2010-2040[18].
- General Law 28749 for Rural Electrification and all the subsequent norms and bylaws[19].
- Law 29852 for the creation of an Energy Security System for Hydrocarbon and the Social Inclusion Energy Fund (FISE) and all the subsequent norms and bylaws[20].
- Law 29969 for the massive distribution of Natural Gas and all the subsequent norms and bylaws[21].

This plan for Universal Access acknowledges the need to devote additional fenced resources for the achievement of it goals. Specifically, the plan defines the following funding sources:

- The Social Inclusion Energy Fund (FISE).
- Transfers from the Public Sector.
- Specific Funds created by the Government.
- External or international funding.
- Donations, contributions and other endowments.
- Resources funded by treaties or agreements.
- Resources defined by the Rural Electrification National Plan 2013-2022.
- Other resources.

The mechanisms and specific targets to achieve are the following:

- Massive access to natural gas for 50 thousand households in 2016.
- Subsidies for access to LPG for 550 thousand households in 2016.
- GLP cooking kits for 1 million households in 2016.
- Network Extension for more than 6 million inhabitants in 2022.
- 500 thousand off-grid PV stand-alone systems for 2016.
- 80 thousand improved cook-stoves in 2016.

[18] (República del Perú, 2010)
[19] (República del Perú, 2007)
[20] (República del Perú, 2012a)
[21] (República del Perú, 2012b)

1.3.2.1 *Universal Access to electricity*

The case of electricity access in Peru is very well documented[22], but for the purpose of this working paper we include here a brief description of the main issues to be taken into account for developing a decision-support strategy based on the Reference Electrification Model. Table 2 summarizes these pivotal topics concerning access to modern energy services in Peru.

Technology	Business models	Funding	Regulation	Governance
Small and Pico lighting systems				
DC Solar Lamps and Kits Light weight / portable, suitable for very remote and un-accessible areas in the Amazonian or Andean areas	Distributed by retail shops decentralized Standard commercial guarantees for replacement and repair	Absence of specific funding mechanisms	Absence of quality standards No subsidies nor incentives Open unregulated market	The introduction of these technologies would benefit from: awareness campaigns, creation of local capacities and businesses and technology hubs
Stand Alone Systems				
DC or AC for off-grid RES Mainly solar, wind and hybrids	Fee for service model. Mini-utilities approach (either companies, non-profit or social enterprises)	Off-grid tariff structure, funding gap provided by cross-subsidies	Limited quality of service standards Regulation of off-grid tariffs, incentives and subsidies Competition for the market (auctions)	Governance ecosystem includes government, companies and other agents Creation of local O&M capacities, back-office technology and business hubs
Isolated Microgrids				
DC or AC for off-grid RES Mainly solar, wind and hybrids	Fee for service model. Mini-utilities approach (either companies, non-profit or social enterprises) Higher capital needs and increased complexity	Off-grid tariff structure, funding gap provided by cross-subsidies	Limited quality of service standards Regulation of off-grid tariffs, incentives and subsidies Competition for the market (auctions)	Governance ecosystem includes government, companies and other agents Creation of local O&M capacities, back-office technology and business hubs
Grid Extension				
Standard grid extension technologies	Incumbent utilities with traditional approach	Social tariff for low-income users. Funding gap provided by cross-subsidies	Sound regulatory framework. Specific connection incentives for low-income population. Could benefit from grid-compatible microgrids approach	Conventional implementation by public companies, national and regional government

Table 2: Matrix of electricity supply modes summary issues for Peru.

[22] (FISE, 2015a, 2015b; Murillo Huaman, García Portugal, & Carcausto Rossel, 2015; NRECA International, 2001; SE4all, 2013b; van den Akker, 2008)

The General Law for Rural Electrification defines the main vehicle for access to electricity in Peru[23]. This law has the purpose of establishing the normative framework for the promotion and the efficient and sustainable development of electrification in rural areas, isolated villages and frontiers.

Its main mechanism is the concession of Rural Electrification Systems (SER) mainly to public utilities or to the National Company for Power Infrastructure Administration (ADINELSA) for operation and maintenance, but also allowing the participation of private companies mainly for off-grid electrification SER.

The priorities for the rural electrification policy (either grid and off-grid) are set by the National Rural Electrification Plan 2014-2023[24] that aims at supporting equal access rights to all citizens, specially regarding domiciliary service of electricity and addressing the divide between urban and rural areas, promoting the social inclusion and aiming at poverty reduction. This plan launched by the Ministry of Energy and Mines involves also regional government, distribution companies and other public and private organizations.

Technologies

The electrification mode mix is clearly dominated by the grid extension approach, which intends to achieve its full extension by 2022 providing new connections to more than 6 million people. Rural grid extension is subject to a national distribution grid code[25] that follows international standards for grid extension in rural areas. The possibility of using low-cost single wire earth return grid extension technologies would greatly reduce the cost of grid extension (as in the case of Brazil, where the use of mono-phase technology, initiated by Fabio Rosa, has brought down the connection cost per household from 7,000 to 400 USD[26]).

But the national plan also acknowledges the need to combine this strategy with off-grid electrification, including the deployment of isolated off-grid Stand Alone Systems and microgrids. Following the model of successful experiences as that from the social enterprise Peru Microenergía in Cajamarca[27] the government launched an auction in 2014 targeting to supply up to half a million households with stand-alone PV systems for 2016[28]. The auctions define the technical characteristics of the systems to be installed, also subject to the technical code for PV SAS[29].

The presence of solar lamps and kits[30] follows an unregulated scheme, but shows great potential at supplying at least an essential lighting and phone charging for the more isolated households located in areas with very low population density, either very far or very hard to access by boat or walking long distances, more than 12 hours away of any population center, located in the Amazonian region or in the Andean cordillera.

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[23] (República del Perú, 2007)
[24] (Ministerio de Energía y Minas (Perú), 2013b)
[25] (Ministerio de Energía y Minas (Perú). Dirección General de Electricidad, 2003)
[26] (Global Envision, 2006)
[27] (Eisman, 2011; Olivares Magill & Eisman Valdés, 2011)
[28] (OSINERGMIN, 2014a)
[29] (Ministerio de Energía y Minas (Perú). Dirección General de Electricidad, 2007)
[30] (Eisman, Olivares, Moreno, Verástegui, & Mataix, 2013)

Business models

Disregarding the still incipient market for solar lamps and kits, the Peruvian regulatory framework promotes the establishment of regional concessions for the supply of electricity services, either off-grid or with the extension of the grid, as shown in Figure 11.

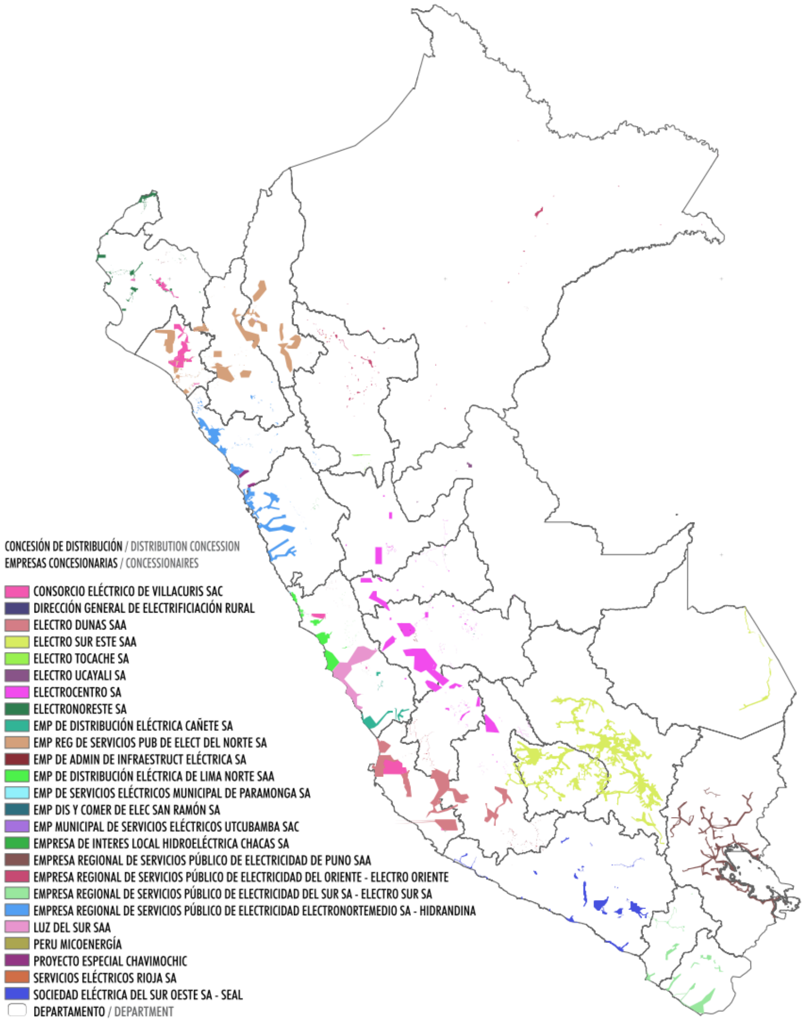

Figure 11. Concession zones granted for electricity distribution systems (network extension and off-grid) in 2012. MINEM Department of Power Concessions [31]

In absence of a pre-assigned incumbent utility, specially for off-grid Rural Electrification Systems (SER), as the Michiquillay SER analyzed in Section 2.3, the concession is regulated by an auction mechanism[32] that determines the best bid to satisfy the auction criteria and grants a concession over a certain area.

Grid extension is dominated by public utilities, whether national, regional or even metropolitan, but off-grid concessions can be allocated to other private companies, social enterprises (as Peru Microenergía) or NGO's supply projects (e.g. Practical Action[33]) establishing the conditions to attract private capital competing for the market.

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[31] (Ministerio de Energía y Minas (Perú), 2012)
[32] (Batlle, Barroso, & Echevarría, 2012; OSINERGMIN, 2014a; "Perú: subastas de Energía Renovable," 2013)
[33] (Dávila, Vilar, Villanueva, & Quiroz, 2010; Soluciones Prácticas (ITDG), 2009)

The users are charged in a fee-for-service base, according to the grid and off-grid tariffs defined by the government. The company will collect the tariff and then receive a subsidy from the government that covers the funding gap between the tariff and the total cost of service approved in the concession contract.

Social tariff and funding gap

For the National Interconnected System (SEIN) the regulation establishes a crossed subsidy to benefit low consumption customers[34] (defined as those below a consumption threshold of 100 kWh/month and over 30 kWh/month), or very low consumption customers (those below 30 kWh/month).

This first subsidy introduced in the electricity tariff in 2011 amounted 31 million USD in 2009, collected through an extra charge over the fixed and variable terms of the monthly fee on households consuming more than 100 kWh/month.

Users of	**Area**	**Tariff reduction for monthly consumption lower or equal to 30 kWh**	**Monthly consumption exceeding 30 kWh but less than 100 kWh**
Interconnected systems	Urban	25%	A reduction equivalent to 7.5 kWh/month
	Rural	50%	A reduction equivalent to 15 kWh/month
Isolated systems	Urban	50%	A reduction equivalent to 15 kWh/month
	Rural	62.5%	A reduction equivalent to 18.75 kWh/month

Table 3: FOSE Tariff Subsidy Scheme in 2009.

In October 2011 FOSE was applicable to about 3.1 million households in Peru (nearly 16 million people), 58% of the domiciliary customer base of the Peruvian power sector. The clients below 30 kWh/month represent 30.3% of the national customers, but only 2.6% of the total energy consumption.

Additionally, since 2012 the government established the Social Inclusion Fund[35] (FISE) intended to foster universal access to energy services, developing the social demand for natural gas and its use for household, transport, commerce and industrial applications. It is funded by the electricity, hydrocarbon and natural gas markets, and supports the least-cost technological alternative for vulnerable population in regards to cooking, lighting, productive uses and heating. The selection of population that can benefit from FISE combines low-income thresholds and the lack of satisfaction of basic needs by the beneficiaries. In electricity, FISE is only applicable to consumers with a consumption below 30 kWh/month and can benefit concessions that supply this vulnerable population with PV systems, 100W wind turbines, pico-hydro turbines between 100W and 2.5 kW, run of the river generators or even GLP/GN small generators.

[34] (SE4all, 2013b)
[35] (FISE, 2013; República del Perú, 2012a)

The regulation of Peru acknowledges, both for off-grid and grid extension concessionaries, the right to receive a fair compensation for the service provided to the users. Therefore, concessionaries receive a subsidy that compensates the different between their cost of service (established on individual basis depending on the area covered, electrification mode characteristics and costs) and the social tariff collected from the final customers. This "funding gap" is inescapable in rural electrification both in developed and developing countries (that we call "Iron Law of Rural Electrification") and reflects the fact that to maintain equitable conditions for rural and urban customers, the system has to provide for the higher cost of providing electricity to isolated and non densely populated rural areas.

This gap, as well as the necessary investments, is funded by the fenced funds allocated to rural electrification:

- Transfers from the national treasury approved on annual bases.
- External funding sources.
- 100% of the penalties decided by OSINERG for concessionaries.
- Up to 25% of the resources obtained by the privatization of energy or mining public enterprises.
- 4% of the revenue of generation, transmission and distribution companies.
- Any donation, or other voluntary assignation.
- Resources obtained for any work in progress with regional or municipal governments.
- Surpluses from funding of regulatory or normative agents.
- Others that might be assigned.

These funds are fenced against any other use apart from funding electrification projects, tariff subsidy or promotion of private investment.

2 The case of Cajamarca – Peru

2.1 Description of the department of Cajamarca

This large region in the North frontier of Peru with Ecuador has over 33.000 km^2 of mountain, coast and rainforest areas divided into 13 provinces and 127 districts. With an altitude between 400 and 3550 meters over the sea level, this mostly mountainous department is characterized by the inaccessibility and isolation of many communities.

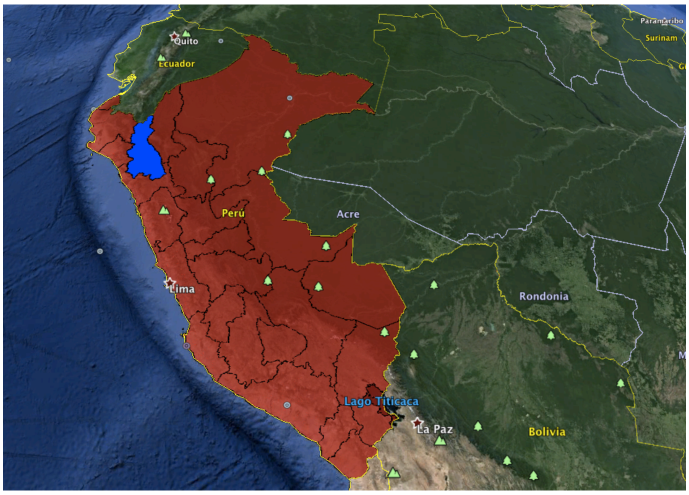

Figure 12 Location of the department of Cajamarca (blue area) in Peru (Map data: Google, DigitalGlobe, GADM 2015)

With more than 1,5 million people[36] in 2012, most of them living in rural areas (75%) it represents 5.1% of the Peruvian population but contributes to only 2,6% of the gross domestic product with an average annual income of USD 710. 52,5% of the population lives below the poverty line, 21,3% in extreme poverty and its Human Development Index is 0,3773 (almost half the average of Peru, 0,737) placing the department in the United Nations Development Program UNDP category of Low Human Development[37]. The main source of income for 55,9% of the population is agriculture (20,1% of the regional product) while mining reaches 20,2% of the regional economy and 8,9% of the national share.

2.2 Universal Access challenges in Cajamarca

In Peru, the study of the department of Cajamarca was selected for the following reasons:

- High level of poverty and extreme poverty, and very low human development.
- Lowest electrification rate in Peru (75,8% in 2013), though rapidly increasing, reaches up to nearly one quarter of the total electrification needs in Peru, most of them located in isolated Andean and Amazonian areas, very representative not only of Peru but of other South American regions.

[36] Sources: Instituto Nacional de Estadística e Informática (INEI), Censo de Población y Vivienda 2012, and Oficina de Gestión de la Información y Estadística of the Parliament of Peru.
[37] (PNUD, 2013)

- The climate is very cold in the Andean areas, where the main source of heating and cooking is the three stone fire. Thus the need of modern heating technologies in those areas is very high, while in the valley of Marañón river, an affluent of the Amazon, temperatures are warm and the main need for climate control is the use of fans, and therefore on access to electricity. Only 19.3% of the population in the region has access to modern cooking technologies.

Rural electrification in Peru is promoted by the National Plans for Rural Electrification developed by the Ministry of Energy and Mines. The most recent was approved in 2013 and covers the period 2014-2022, aiming to achieve 86% of electrification in the mid term, and universal access by 2021 (bicentennial celebration of the independence of the country).

The aim of the electrification process is to achieve equal rights for all the Peruvian citizens, in particular the access to electricity in their households, trying to solve the enormous divide between urban and rural or frontier areas in the country, integrating their population into the national market, productive activities and development, achieving their social inclusion and reducing poverty.

This strategy establishes clearly the funding sources both for the expansion of existing network and the implementation of off-grid electrification, combining public effort, external donors, 25% of the funds received from the privatization of energy companies and cross subsidies through a mechanism of compensation explicitly designed for isolated systems.

The program for rural electrification contemplates both connection to the national network (SEIN) and isolated systems (SSAA), implementing the definition of the Rural Electrical Systems (SER) regarding electrification with either of those modes. Figure 13 shows with green circles the location of the different SERs in the region of Cajamarca, the location of existing and planned MV network lines as well as a zoom over the SER Michiquillay Dist. Encañada, area selected to develop a case study with the REM model.

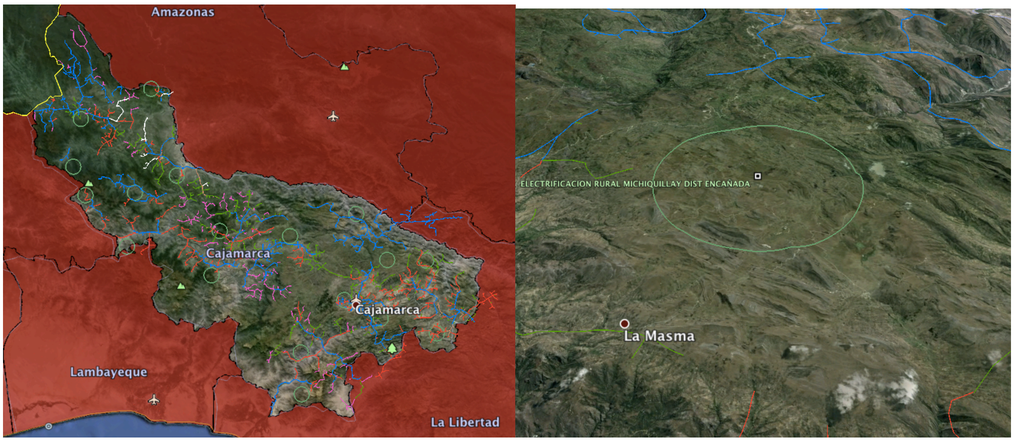

Figure 13 Electrification planning 2008-2017 in Cajamarca

Cajamarca has been receiving more than USD 86 million in rural electrification projects since 2011, benefiting more than 1,300 villages and 180,000 citizens, becoming the region with the highest investment in electrification in the country.

2.3 Techno-economical scenarios and alternatives

2.3.1 Base case scenario

The test case selected for Cajamarca is one of the SER defined by the National Plan for Rural Electrification, specifically the SER Michiquillay District Encañada that is shown in Figure 13.

To develop the Base Case Scenario, we assume that the entire network infrastructure defined by the Electrification Plan for Cajamarca 2008-2017 is already in place, that the energy supply of the network can serve 100% of the projected demand and that all the houses within the limits of the projected lines that surround the SER are not yet electrified[38].

2.3.1.1 Input data

Regional inputs and assumptions

The SER Michiquillay comprises nearly 6,700 households within the limits established by the nearest connection points to the 11kV projected network. It is a mountain area where population is very dispersed but also shows clustering patterns, as can be seen in Figure 14.

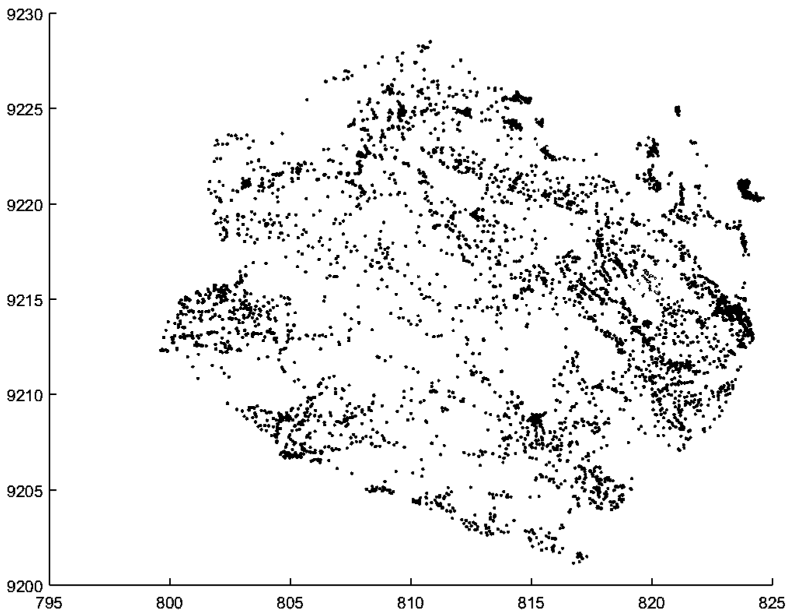

Figure 14 Location of the households in Michiquillay SER

The main resource in the area is solar, due to its location and altitude. Wind is also available at selected locations. The isolation and inaccessibility increases the local price of diesel as compared to cities and low lands. For our Base Case Scenario we assume an average price of US 2$/l.

[38] A field visit to the area in 2013 shows that some of the projected lines are in place but do not receive power supply yet, nor are connected to the households. Some of the houses had Stand Alone Systems, mainly solar but also hybrids solar-wind and diesel. In this study case we assume that all the houses are not electrified in order to determine the total cost of electrification for the area for the different scenarios studied.

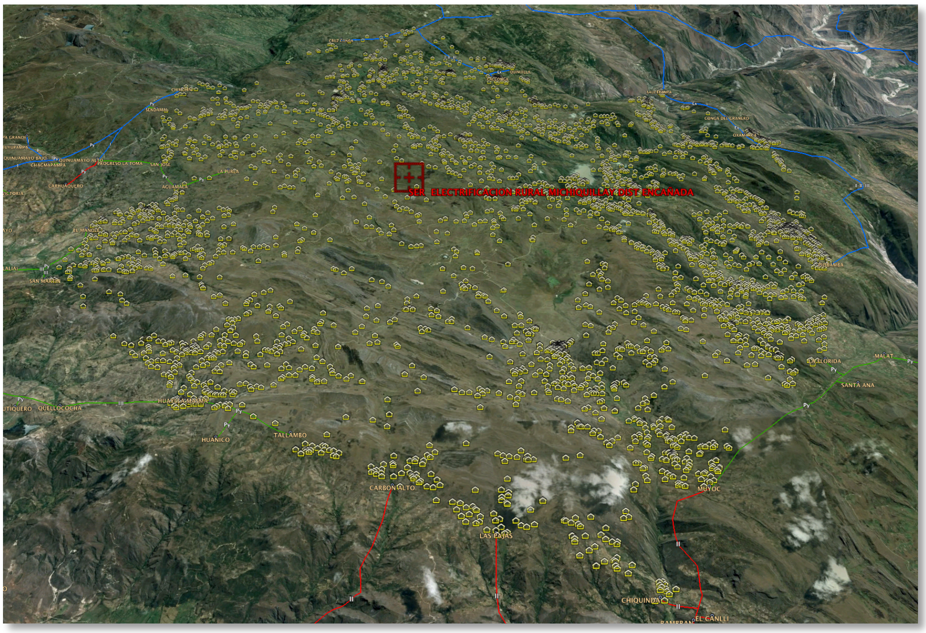

Figure 15 Satellite projection of the consumer location, in relation with the transmission and distribution lines either already in place or planned by the government

Michiquillay SER area in Cajamarca is located in the Andes Mountains, with heights between 2200 m and 4100m within an area of around 400 km^2. The network catalog used for our test case estimates the high cost of laying MV and LV lines and their increased length on these high and isolated slopes. The cost of MV and LV lines has been doubled, and the cost of HV lines increased in 50%, taking as an initial reference the standard and very detailed catalog derived from actual data gathered in Spain and flat regions of India[39]. Other costs are known also to be higher in isolated mountain areas, as the local cost of maintenance of equipment, but due to the lack of actual information from this region, this parameter has not been changed for our Base Case Scenario.

Grid supply is 100% reliable, considering that the additional demand added to the grid, even in the worst case scenario where all the population is connected with high consumption rates, will be negligible compared to the actual demand and generation capacity installed. Failure rates of all the supply systems and equipment have been set to standard values, the cost of energy purchased from the network at the connection points has been set to 0.045 \$/kWh[40] and discount rate is 10%.

To compare the value for the users of systems with different reliabilities, it is necessary to know the lost of utility associated to the energy that is not served. This allows REM to assess systems with different costs and different reliability levels, considering the cost of the lack of service for

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[39] For the purpose of actual planning REM would require the use of a more detailed local catalog, compliant with the national grid code and according to the availability, characteristics, prices of equipment, operation and maintenance costs in Cajamarca. Our estimation assumes the increase of 50% in cost of transmission lines specified by (Fürsch et al., 2012) whereas the increment in MV and LV distribution lines is known to be higher (even much higher in many cases) in isolated mountain areas (Ostojic et al., 2011; Ratnayake, 2015), supporting our assumption of increasing it 100%.

[40] This estimated value has been set considering the tariffs for Cajamarca 2015 ("Pliegos Tarifarios Aplicables a Usuarios Finales de Electricidad", retrieved from http://www2.osinerg.gob.pe/tarifas/electricidad/tarifasmapa.html), the impact of FOSE cross subsidies, and excluding the share of distribution costs for network customers (OSINERGMIN, 2008).

users under different assumptions. As explained by Borofsky[41] "this concept is actually quite subjective, but is intended to represent the cost (i.e., the loss of utility) incurred by consumers when there is no electricity at a time when they were planning to use it. REM requires two values for CNSE, one for essential load and another for nonessential load. The CNSE value for essential load should be higher than the CNSE value for nonessential load in order to represent the greater cost (equivalently, loss of utility) to the consumer for not meeting the most valuable demand. CNSE is also needed to size the generation source in a microgrid so that a theoretically optimal trade-off is reached between cost of supply and quality of service".

The CNSE in any case resembles the economic value of the non-supplied demand, not an actual cost for the supplier (unless the regulation establishes some penalties for lack of supply quality). Therefore hereafter the figures that describe the different solutions, unless explicitly said otherwise, only show the actual cost of investment plus operation and maintenance of the proposed systems, as the assumed cost of non-served energy is instrumental for the model.

Base case scenario regional inputs:

- Cost of diesel: 2 $/l (isolated)
- Cost of energy supplied from the grid: 0.045 $/kWh
- Critical CNSE: 10.00 $/kWh
- Normal CNSE: 1.5 $/kWh
- Network lifetime: 40yrs
- Distribution system losses: 5%
- Discount rate: 10%
- Demand growth rate: 1%
- Year for which generation is designed: 5 years from the present time, considering demand growth.
- Year of losses growth for which the network is designed: 10 years from the present time.
- Years of network useful life: 40.
- Solar PV data for the hourly DC output of a 1kW PV array for one year in Cajamarca[42]

Individual inputs and assumptions

REM calculates the demand profile of each individual household (within this document we will also use *customer*, *user* or *consumer* to refer to each household connection indistinctly) according to the pattern of use of different appliances taking into account temperature seasonal variations according to their individual location (e.g. for the patterns of use of fans). The further distinction between critical and non-critical loads enables REM to optimize the cost of off-grid generation, allowing the curtailment of non-critical uses of electricity in micro-grids and stand-alone systems.

The Base Case Scenario assumes a very basic demand where users will have:

- 2 lights and a phone charger for every household (critical demand)
- 1 additional light for 50% of the households (normal, non-critical, demand)
- 1 fan for 20% of the households (normal demand)
- 1 TV set for 30% of the households (normal demand)

The specific profile of each consumer is calculated according to variations in the ownership of appliances and their use, including the temperature ranges where fans are operated to allow both

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[41] (Borofsky, 2015)
[42] From http://pvwatts.nrel.gov/.

for seasonal variations of the demand, as shown in Figure 16. It also shows the different levels for critical demand (red line) and normal, non-critical, uses of energy (up to the black line) so to take into account the different energy services to be provided. This logic implies that the microgrid can somehow curtail non-critical uses of energy if the state of the generation and storage capacity requires it.

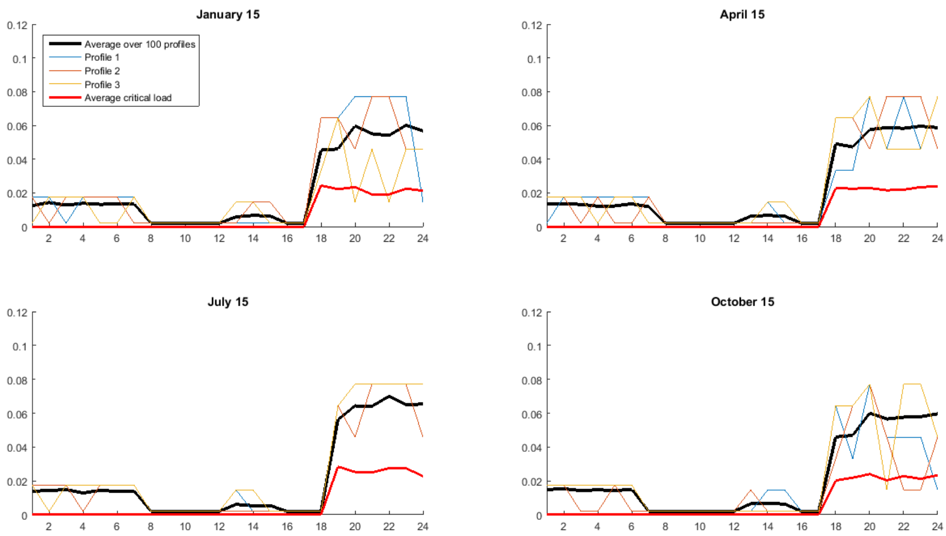

Figure 16 Sample and average demand profiles per hour of day in the Base Case Scenario

The peak demand per user in this scenario is 75.75 W and the average is 21.07 W. The energy consumption per year would be in average 185,5 kWh/household (100% of the demand satisfied) allocating the users in the BT7 tariff for grid connected consumers under 300kWh/year[43], and under the BT8-160 for off-grid rural electrification[44].

2.3.1.2 Techno-economic solution

For this Base Case Scenario the dominant electrification mode are microgrids, with a null presence of grid extension, as shown in Figure 17 and Figure 18.

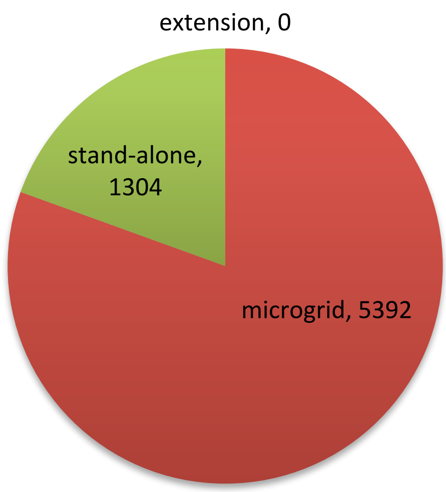

Figure 17 Mix of electrification modes in the Base Case Scenario for Michiquillay SER

[43] Pliegos Tarifarios Aplicables a Usuarios Finales de Electricidad: http://www2.osinerg.gob.pe/tarifas/electricidad/tarifasmapa.html
[44] (OSINERGMIN, 2014b)

The absence of grid extension in this initial scenario is due to the low level of demand by the customers, together to the high costs of extending the grid in this mountain area. We will see later that grid extension appears as a least cost solution for houses closer to the transformers as the demand increases (Section 2.3.6).

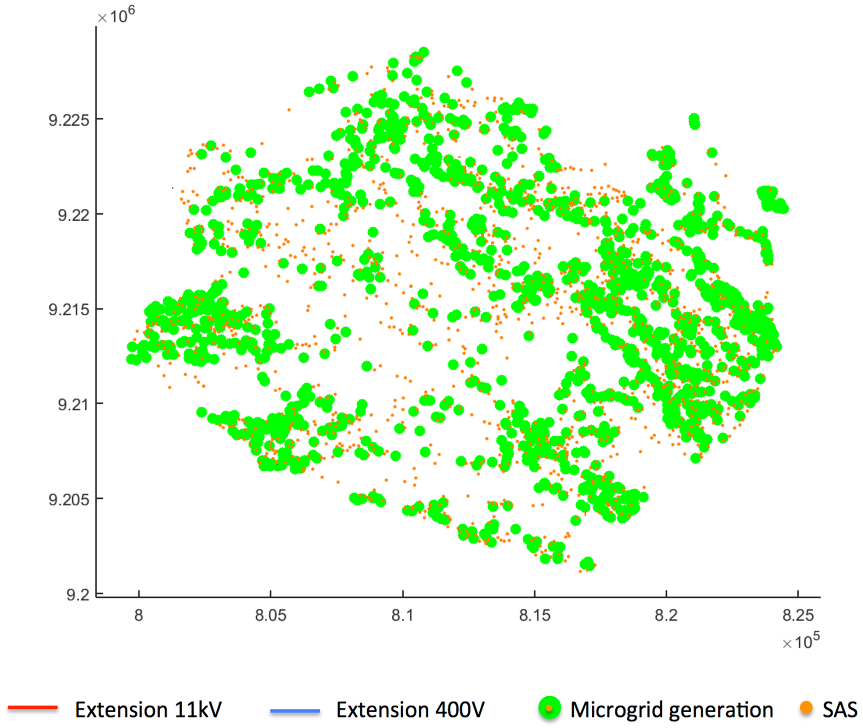

Figure 18 Electrification modes outcome in the Base Case Scenario for Michiquillay SER[45]

The average cost of investment plus operation and maintenance, detailed by the number of customers per system, is depicted in Figure 19 (annuity in USD/year) and Figure 20 (cost in USD per kWh), from single users (1 household) up to the largest microgrid in this Base Case Scenario (64 households).

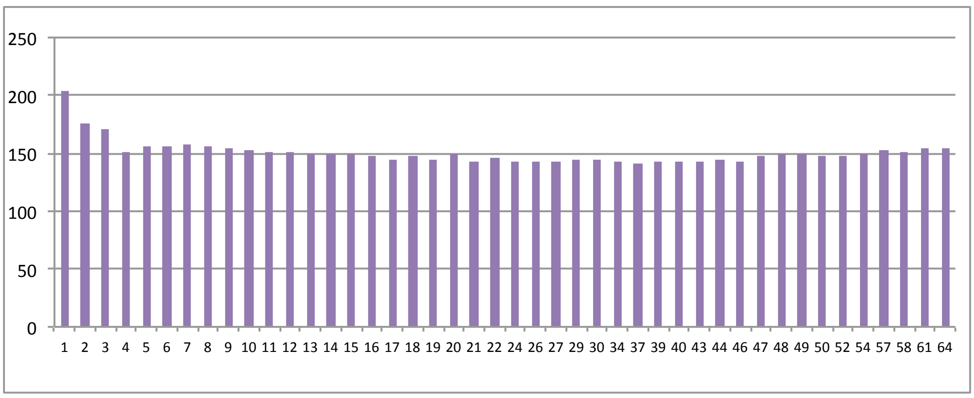

Figure 19 Annuity ($/year), including investment, operation and maintenance cost per off-grid system detailed by system size in the Base Case Scenario

[45] Please note that the microgrids resulting from this scenario are too small, so their network cannot be seen in this regional view.

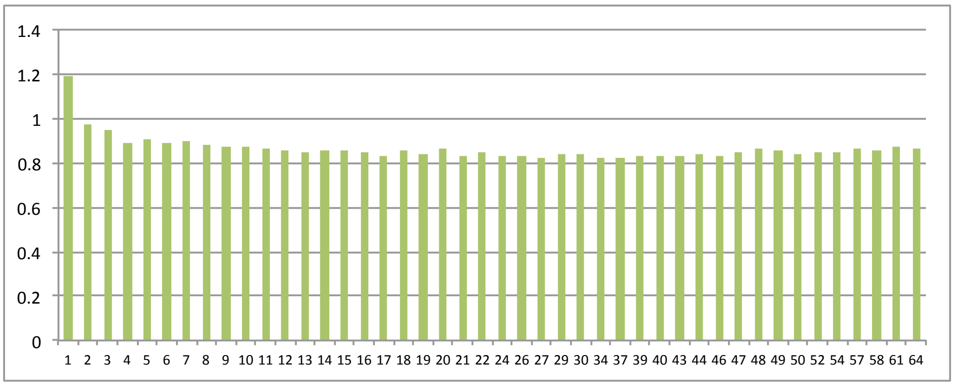

Figure 20 Cost of energy ($/kWh) by system size in the Base Case Scenario

The results show immediate economies of scale for microgrids with a small number of houses, with respect to stand-alone systems. Economies of scale are quickly used up. In the next Figure 21 we show both the actual annuity of the system provided to each customer type, together with the added cost of non-served energy (CNSE) that REM computes to take into account the impact of demand that is left non-supplied.

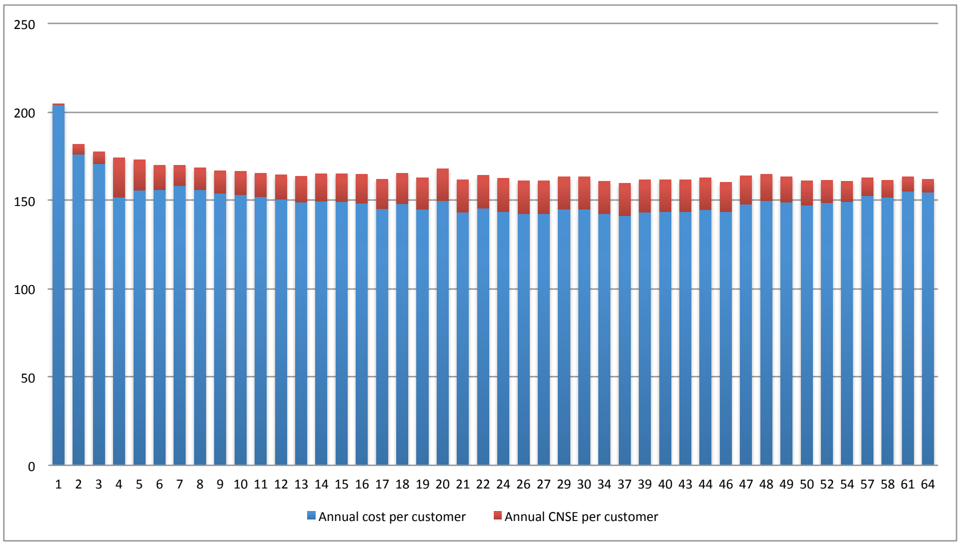

Figure 21 Cost of energy ($/kWh) by system size in the Base Case Scenario

This techno-economical minimum presents a low share of medium-size microgrids and a very high number of very small micro-grids, most of them with only 2 or 3 buildings (Figure 22).

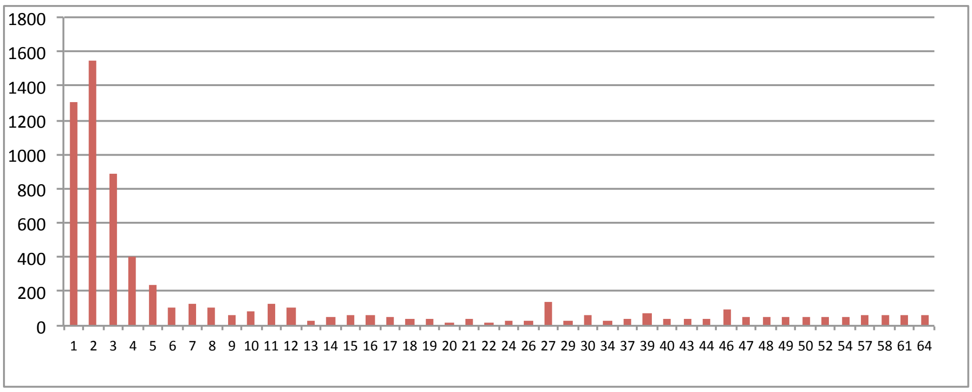

Figure 22 Number of off-grid customers detailed by system size in the Base Case Scenario

These very small groups of buildings may belong to a single customer (maybe for ancillary purposes, storage or cattle housing) so in these cases building a micro-grid for those 2 or 3 buildings would be a sensible solution. But it is also common in this area that sons and daughters build their family homes near their parents, but are in fact different customers. In these other cases the preferences of the users, the higher complexity for operation and maintenance and the logic of the business models may advise against building microgrids for less than about 10 buildings, providing these users with isolated Stand-Alone Systems (SAS) instead. The resulting mix of electrification modes replacing these smaller microgrids by SAS is shown in Figure 23.

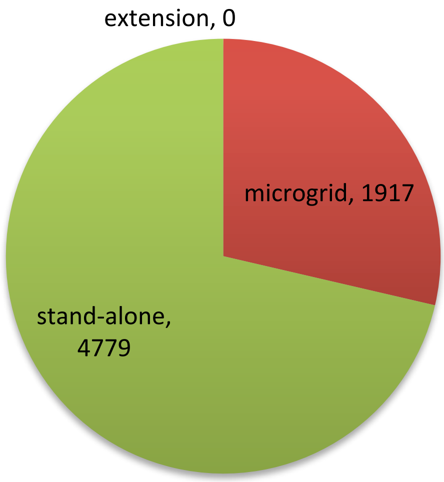

Figure 23 Mix of electrification modes with only microgrids over 10 buildings in the Base Case Scenario

This distribution is what we will take as our Base Case Scenario, as it is consistent with the actual business model found in the area, where mainly Peru Microenergía is distributing Solar House Systems under a pay-per-service model.

Figure 24 shows the average cost per customer of the Base Case Scenario.

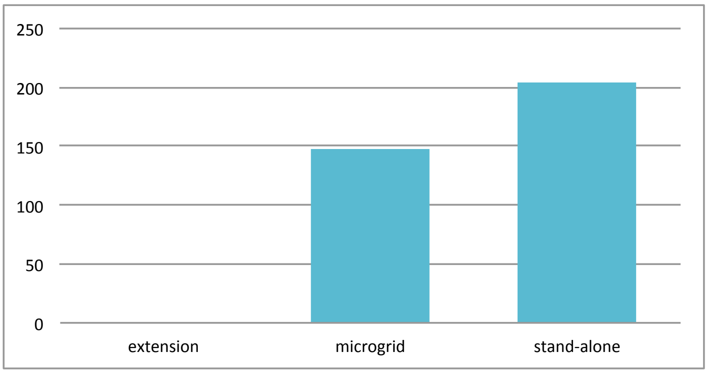

Figure 24 Annual cost ($/year) per customer in the Base Case Scenario

The average cost of energy supplied is shown in Figure 25 (in USD per kWh) and the total annuity of the investment cost plus operation and maintenance for each group of customers in the SER of Michiquillay can be seen in Figure 26 for the Base Case Scenario.

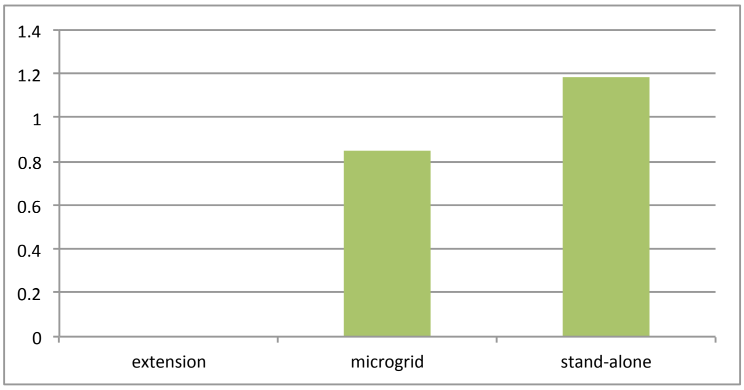

Figure 25 Cost of energy supplied ($/kWh) in the Base Case Scenario

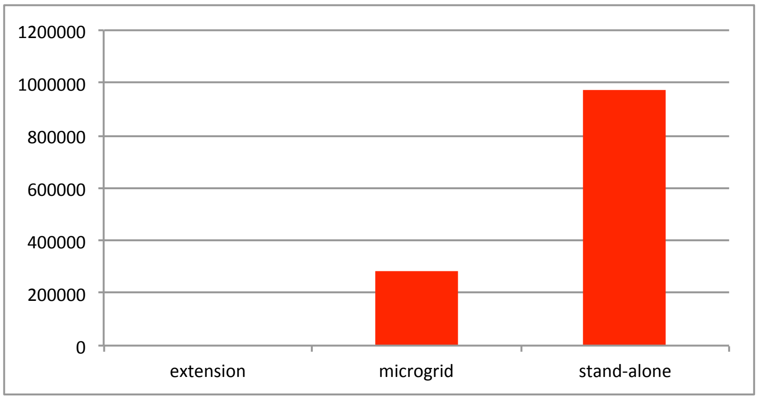

Figure 26 Total annuity ($/year) per electrification mode in the Base Case Scenario for the SER of Michiquillay

The total yearly cost of the electrification of the whole Michiquillay SER for BCS is 1.257 million USD, for a total investment cost in the next 20 years of 10.704 million USD.

It is very important to note that the Base Case Scenario, where microgrids smaller than 10 users have been replaced by isolated stand-alone systems because of business model and social considerations, as explained above, is actually more costly than the original techno-economic optimum, because microgrids from 2 to 9 users are significantly cheaper than the household systems. The different annuity of each solution is shown in Figure 27.

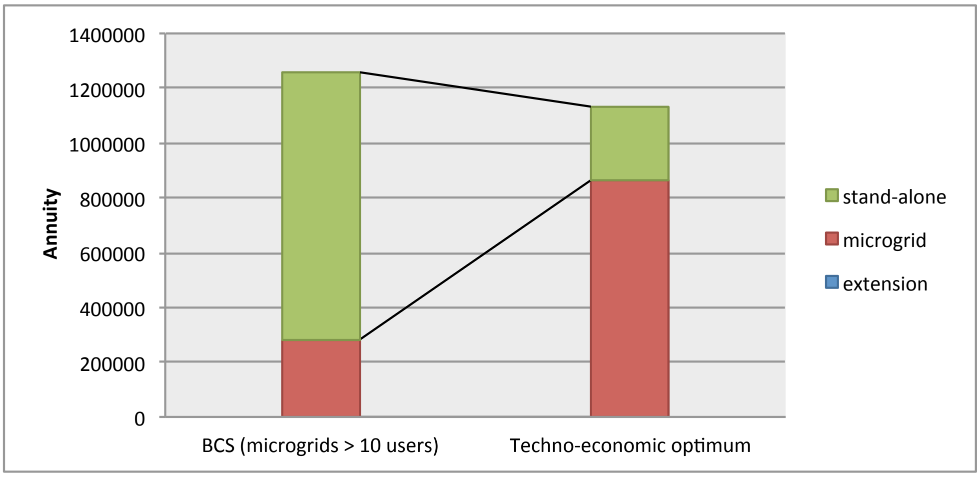

Figure 27 Total annuity ($/year) comparing optimum techno-economic solution vs. Base Case Scenario (BCS for microgrids with 10 or more customers)

It corresponds to the decision-maker to choose between the different options and outputs of the REM model, considering not only the techno-economic solution but other social, cultural, business model, regulatory or policy considerations, as explained in Section 3.

We are considering AC stand-alone systems, for an equivalent performance and comparability with the different electrification modes (AC microgrids and grid extension). If we would choose to install DC SAS instead, as the ones actually being supplied in the area by Peru Microenergía (AMP), the cost of the solution would decrease significantly for this very low demand set in the BCS[46].

The reliability of the supply systems is very high in this scenario, as can be seen in Figure 28. This is consistent with the high cost of non-served energy –critical and non-critical– that has been used as input to the REM model.

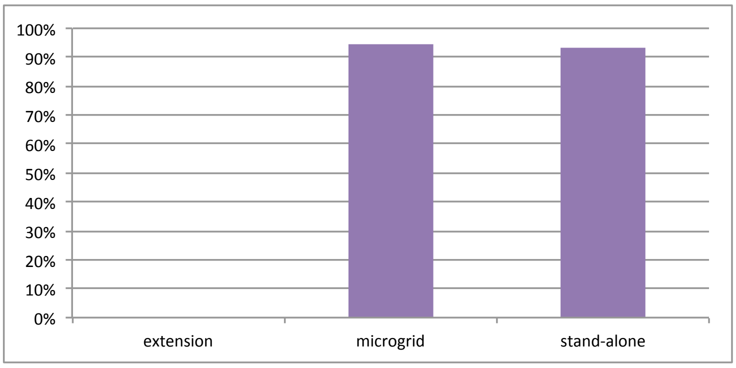

Figure 28 Reliability of supply modes in the Base Case Scenario

This outcome shows that microgrids and mainly stand-alone systems should be preferred for this region, and are able to satisfy more than 90% of this very low initial demand.

This Base Case Scenario penalizes heavily low reliability of services, which results in a very high reliability of off-grid solutions (94.45% for microgrids and 93.02% for SAS) with expensive microgrids (0.85 \$/kWh, 12.36 \$/household-month) and SAS (1.19 \$/kWh, 16.99 \$/household-month). In Section 2.3.2 we shall present two more scenarios with lower reliability levels (i.e. lower cost of critical and non-critical CNSE) to explore the impact of the amount of demand satisfied on the cost and design of the corresponding electrification modes.

2.3.1.3 Electrification modes

The mix of electrification modes for the Base Case Scenario includes only off-grid solutions (stand-alone systems and microgrids).

Stand Alone Systems

A total of 4779 households would receive a stand-alone system, all of them powered with a solar array of 180 Wp and a battery bank sized 960 Wh to supply 93.02% of the demand with an average yearly cost of 203.88 \$/customer, and an energy cost of 1.187 \$/kWh and a total present value of 8.29 million \$ in the coming 20 years.

Micro-grids

[46] According to AMP, a small PV household DC system of 80W, 100Ah for three lights and a phone charger) would have a total cost of 700 USD including duty, taxes, transport, and installation but not operation, maintenance and exploitation costs. Smaller portable 25W systems with ion-Li batteries would range from 250W to 300 W depending on the number of items purchased.

The disperse layout of the population in Michiquillay SER can also be noticed by the size and number of microgrids proposed by REM Base Case Scenario shown in Figure 29. There are 83 microgrids larger than a minimum set to 10 buildings serve a total of 1917 customers with an average consumption of 174.28 kWh/year. Most of them are located in the outer reaches of the area of study. Only 12 larger microgrids (from 46 to 64 customers) are supplied with a hybrid solar-battery-diesel generation. All the smaller ones from 44 to 10 users are designed with only solar PV and batteries. None of them include any MV lines for distribution.

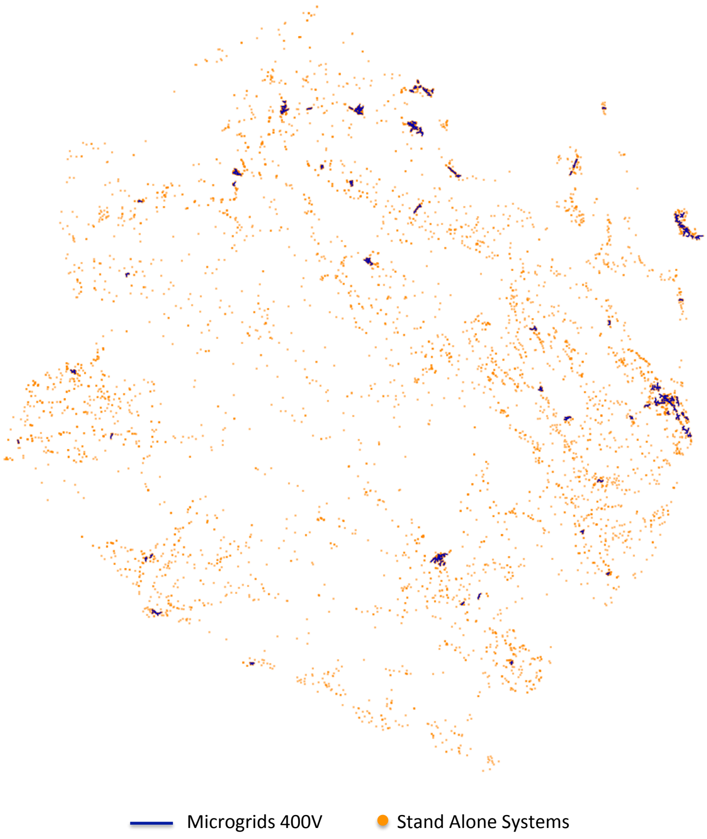

Figure 29 GIS map of microgrids (with more than 10 users) and isolated systems in the Base Case Scenario

The hybrid systems have, on average, a 7.76 kW panel array and a 39.42 kWh battery plus a 1kW backup diesel generator for 8 of the microgrids, and a 2kW one for the four largest (57, 58, 61 and 64 users). The average yearly cost is 149.28 $/customer, 0.8528 $/kWh serving 94.80% of the demand.

For the 100% solar microgrids, below 46 customers, the average PV array size is 3.62 kW and the battery bank stores 15.88 kWh. The average annuity is 148.17 $/customer, 0.8501 $/kWh serving 94.39% of the demand.

The total yearly cost for all the microgrid users is 282.96 thousand $ for a total present value of 2.41 million $ in the coming 20 years.

The resulting designs for the Base Case Scenario meet most of the demand, only leaving some non-critical energy non-served in the morning hours those days when the batteries could not be charged completely, as can be shown in

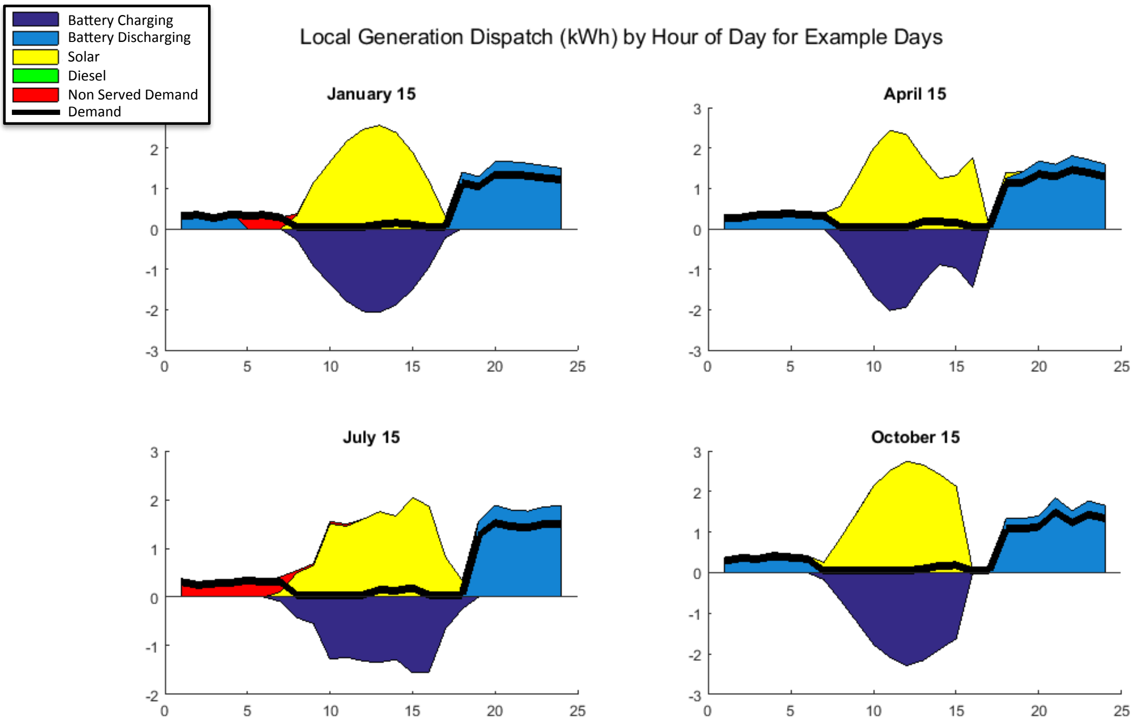

Figure 30.

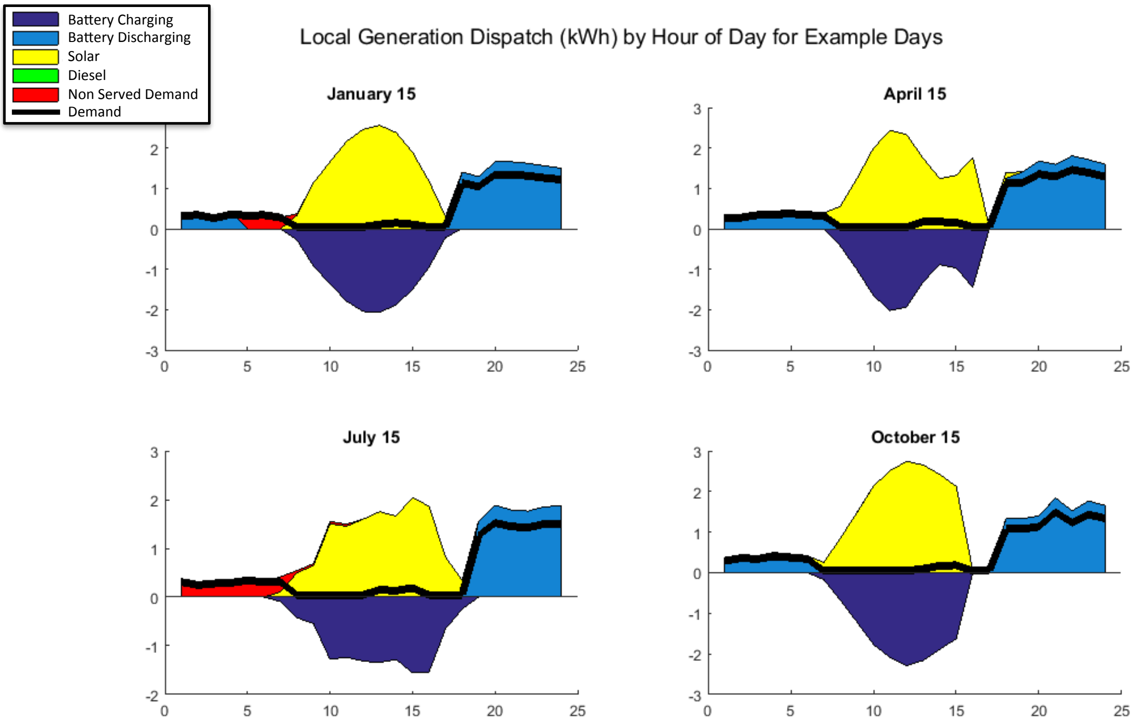

Figure 30 Off-grid generation dispatch by hour of day showing load met and non-served demand in the Base Case Senario

REM, for the Base Case Scenario, calculates the optimal design for the network and generation of the microgrids, minimizing cost of the system and non-served energy according to the costs defined for critical and non-critical load loss. This may result in a combination of several microgrids and SAS for a certain village site (Microgrid generation Microgrids 400V Stand Alone Systems

Figure 31 and Figure 32).

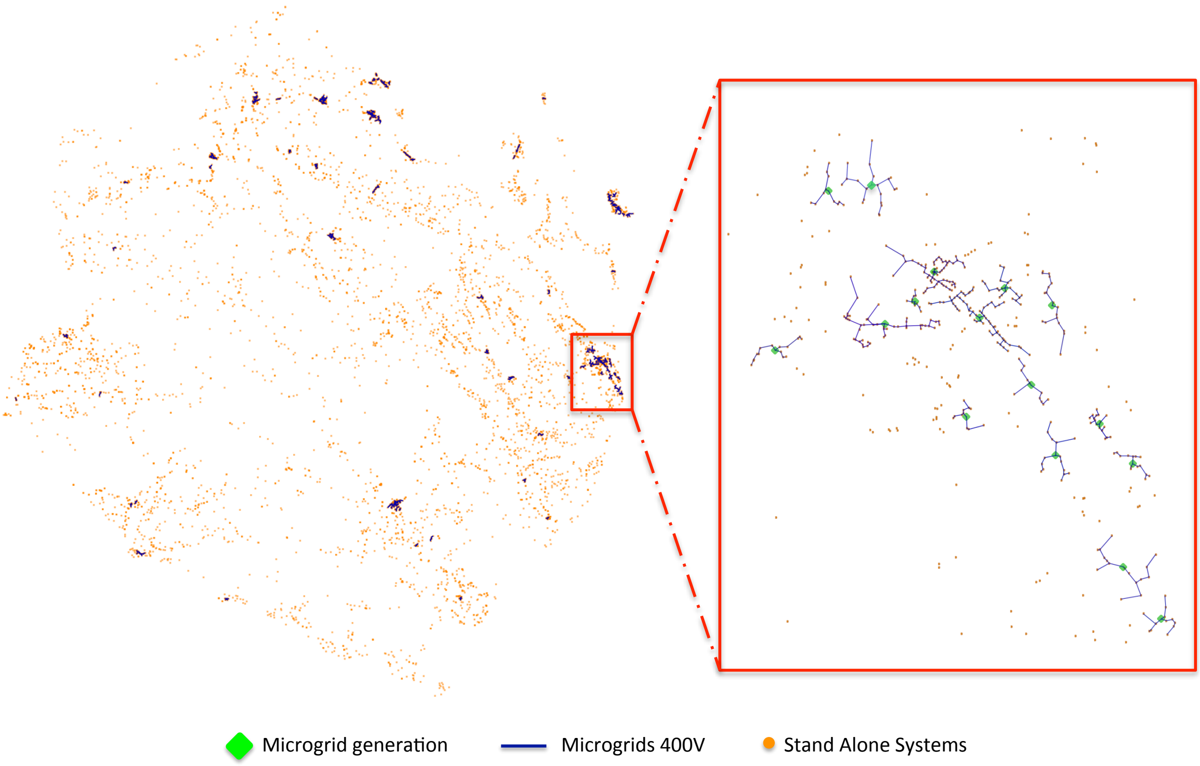

Figure 31 Zoom in cluster of microgrids in the Base Case Senario

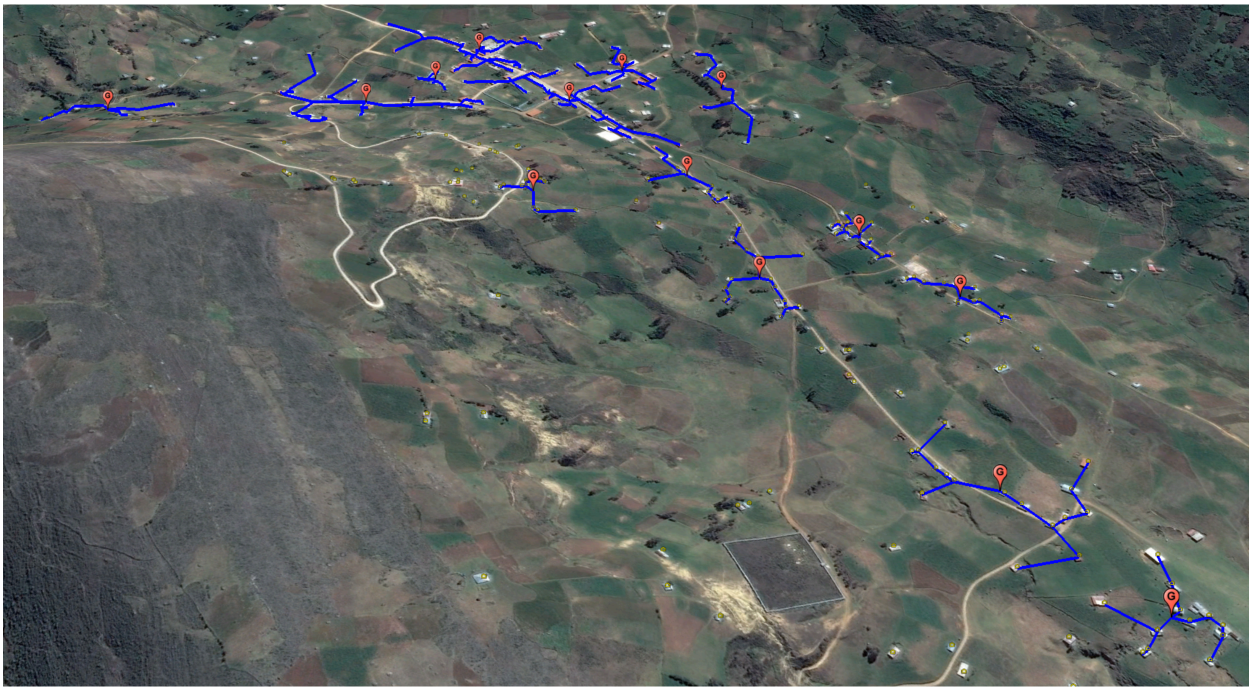

Figure 32 Zoom in land projection of a village electrified with 14 microgrids and several SAS for the Base Case Scenario

This figure shows the layout of the village overlaying the network design and generation sites of the different microgrids designed by REM as the minimum cost solution, as well as the location of isolated SAS that supply scattered buildings located around the village. For these cases, because of maintenance, logistics, management of the networks or stability, it might be preferable to integrate most of these customers under one single larger microgrid, either with centralized or distributed generation. The REM proposes techno-economic optimums, in which some of these concerns cannot be appropriately taken into account, therefore some post-processing and assessment of the results for the decision making process is always required. REM can be also used to help the decision maker during this post-process, by focusing on any plausible design alternatives proposed by the planner.

2.3.1.4 Funding gap

The resulting monthly cost reported by REM exceeds the social tariff that can be charged to these users which is:

- 0.1218 $/kWh for grid connected users in Cajamarca under 30 kWh/month (BT7)[47] (no users connected in this case)
- 4.42 $/month fixed charge for off-grid rural customers under BT8-160[48] for private capital business models[49] including the established subsidies.

Taking into account the expected income per customer defined by the applicable tariffs, Figure 33 shows the funding gap per year of the average microgrid and SAS customer for the Base Case Scenario.

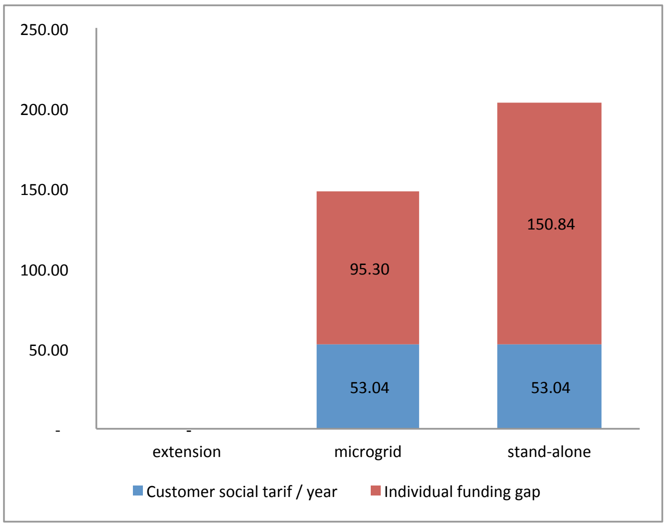

Figure 33 Annual social tariff and funding gap per customer ($/year)

[47] Pliegos Tarifarios Aplicables a Usuarios Finales de Electricidad, 2015
[48] (OSINERGMIN, 2014b)
[49] The methodology for the establishment of the off-grid PV tariff (OSINERGMIN, 2014b) defines two types of applicable tariffs, depending whether if the investment in the system has to be returned (private capital business model) or if the system has been deployed by the government (public business model). The private type includes the long-term reimbursement of the direct and indirect costs associated to the investment, plus the O&M and management costs, while the public type excludes the investment costs (considered as a donation by the government). For the purpose of our calculations, it is better to consider the tariff for private capital, because it better resembles the structure of cost of the systems, and because it is the one applied already to the SHS in exploitation in the area by Perú Microenergía (AMP), which after applying the FOSE subsidy is considered as affordable by the population living in Michiquillay.

Figure 34 shows the total amount of the annual funding gap per electrification mode for the whole Michiquillay SER under the Base Case Scenario. The total annuity of the funding gap reaches 902.2 thousand USD.

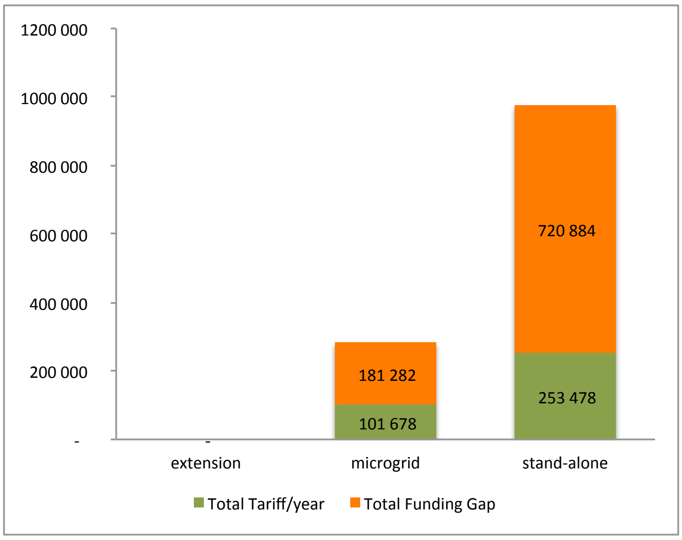

Figure 34 Total amount recovered from the social tariff and funding gap for the whole SER of Michiquillay in the Base Case Scenario

In practice the business models already established in this SER are designed to satisfy only the critical load proposed in our BCS (two lights and a phone charger, BT8-070 with 50 to 70 Wp PV panels and BT8-100 with 80 to 100 Wp PV panels) with DC systems.

These smaller systems do not fully cover the demand of electricity services by some of these customers, as can be learnt from the experience of Perú Microenergía (AMP) in the area. Despite the controls established by the social enterprise, a percentage of the users overload their SHS by connecting TV sets and other devices, exhausting very fast their batteries and accelerating the aging of their systems. In any case the government and the business model may choose to guarantee a smaller amount of energy per user according to the budget limitations for the financial gap and the actual capacity of payment of the consumers. The impact of the amount of load supplied is explored in the scenarios described in section 2.3.2.

In this document, considering AC systems for off-grid isolated systems, microgrids and grid extension facilitates the comparison between the three electrification modes. Nevertheless, we emphasize again that the catalog of REM can be adapted to include less costly DC solutions to accommodate other polices or targets to be analyzed, if needed.

2.3.2 Impact of the Cost of Non-Served Energy

One of the first policy choices the planner is presented with is the trade-off between cost and quality of the electrical service for the users. In our case we are maintaining the reliability of the grid constant, as the amount of new demand associated to Universal Access is very small compared to the total demand of the State. On the other hand, the off-grid systems designed in the Base Case Scenario (BCS) show a very high reliability all through the year, both in dry and rainy seasons. To see how the amount of demand met impacts in the design and cost of the electrification plan, two more cases have been run with the following specifications.

2.3.2.1 Low Reliability Scenario (LRS)

This scenario constraints the solution so all the critical load is still met, the essential demand that we need to supply at all times, but for normal (or non-critical) uses of energy it avoids expensive solutions that go beyond the substitutive cost of other energy solutions as kerosene or candles. Therefore REM will design cheaper systems that satisfy at least the critical demand, and as much of the normal demand as it is cost effective compared with these other alternatives in the market for non-essential uses.

The Cost of Critical Non Served Energy in LRS is still a very high value (10 $/kWh), the same as in the Base Case Scenario, to guarantee that the critical demand is met. On the other hand the cost of normal non-served energy is set to a value (0.75 $/kWh) that is equivalent to the approximate expenditure in alternative sources for house lighting and phone charging services, as purchasing kerosene or candles plus the price of charging phones in kiosks.

The resulting designs in LRS will have lower reliability than the ones in the BCS, but this design choice is actually consistent with the off-grid systems in place in Michiquillay, as the ones installed and managed by AMP[50].

2.3.2.2 Intermediate Reliability Scenario (IRS)

In this case the cost of critical non-served energy is again set to 10 $/kWh, but the normal value for CNSE is now set to 1 $/kWh.

The values used for the three scenarios are summarized in the table below.

	BCS	IRS	LRS
Critical CNSE	10 $/kWh	10 $/kWh	10 $/kWh
Normal CNSE	1.5 $/kWh	1.0 $/kWh	0.75 $/kWh

Table 4 Values of critical CNSE and normal CNSE for the Base Case Scenario, Intermediate Reliability Scenario and Low Reliability Scenario

2.3.2.3 Comparison of BCS, IRS and LRS

Figure 35 shows the average reliabilities of the different systems that correspond to the costs of non-served energy shown in Table 4. The first relevant finding is that micrograds are much less responsive to changes in the utility (cost) of non-supplied energy than stand-alone systems. The reason lays in the economies of scale, so that an equal decrease in CNSE has a lesser impact the final quality of the systems. Microgrids step down from 94.5% to 90.6% in IRS of demand met (there are no microgrids present in LRS), whereas SAS fall from 93% to 38.5%.

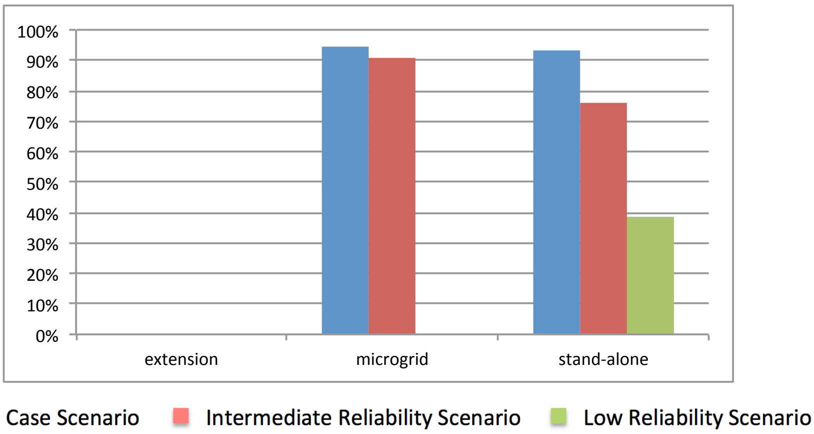

Figure 35 Share of demand met by the different electrification modes in BCS, IRS and LRS

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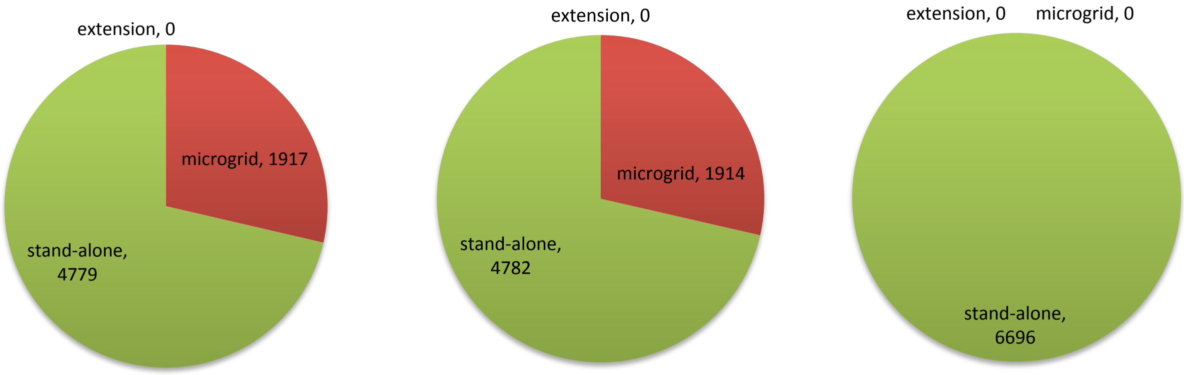
[50] (Eisman, 2011)

The second finding is that grid extension is not included in the solution of any of the three scenarios. This again confirms the actual strategy of the government, towards the deployment of isolated systems for the electrification of Michiquillay SER.

As in the BCS, only microgrids over 10 users have been accounted as such in IRS and LRS. Smaller networks have been replaced by isolated SAS. Particularly for LRS this criterion resulted in ruling out the construction of any low reliability very small microgrid (which in average had a size of 2.57 households). The final mix of electrification modes for the three scenarios is shown in Figure 36.



Base Case Scenario | Intermediate Reliability Scenario | Low Reliability Scenario

Figure 36 Comparison of electrification mode mix for Base Case Scenario, Intermediate Reliability Scenario and Low Reliability Scenario

BCS and IRS show no great differences, showing only a very small decrease in the number of customers connected to microgrids, but when we still lower the reliability requirement, microgrids completely desapear from the solution, in favor of stand-alone systems.

The comparison also shows that the total yearly cost of the solution proposed by REM decreases with the CNSE, as expected (Figure 37). Though IRS and BCS looked very similar, this first step is 15% less costly than our base case scenario. In LRS savings are over 40%.

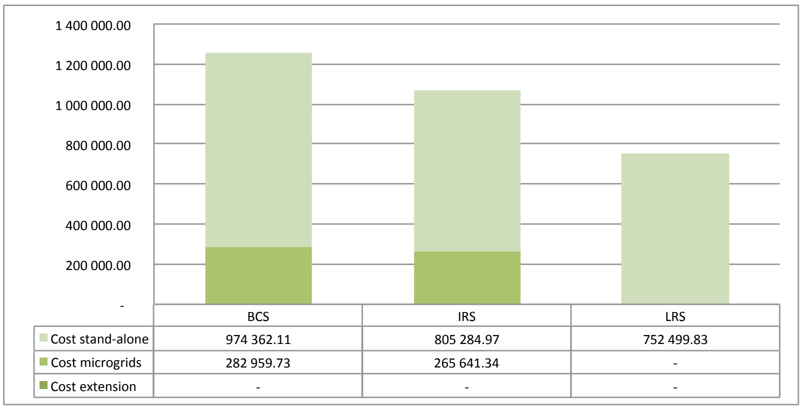


Figure 37 Annual cost of BCS, IRS and LRS detailed by electrification mode

Figure 38 and Figure 39 show the evolution of the annuity for each customer and the cost of the energy supply in the three scenarios and electrification modes. The cost of off-grid systems decreases as we allow the model to reduce the amount of demand met by each system as shown. The cost per kWh shows an ascending path for SAS, as the systems in LRS are far less efficient than the ones in the previous two. As for microgrids, the result is greatly affected by the size and shape of the resulting networks, and therefore the impact on the cost of energy is more complex to analyze. In our cases we could conclude that the cost of energy in microgrids is not affected by our changes in the CNSE parameter, as could also be expected because of its very small impact on the reliability of the networks.

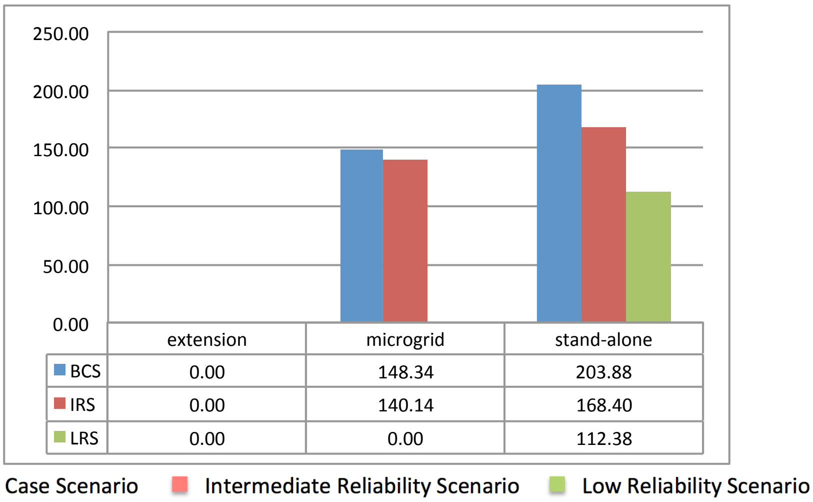


Figure 38 Annual cost per customers, electrification modes and reliability scenarios

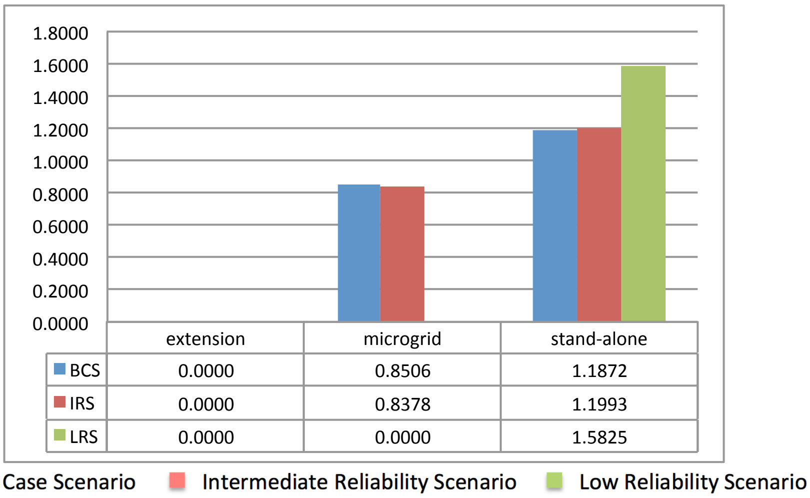


Figure 39 Cost per kWh per electrification mode and reliability scenarios

The total cost of the electrification plans will have to be paid both by the contributions of the customers and, when the capacity of payment of the population without access cannot cover the full cost of service, by non-refundable grants established by the government be established as cross subsidies with urban or wealthier customers (whether domiciliary, industries and services), donor funding by international agencies or development banks, industrial or international endowments that compensate for other social or environmental impacts (e.g. the case of mining companies in Cajamarca) or any hybrid for those.

In the case of Michiquillay SER we can establish the total amount of the contribution by each customer (under the assumption that they will be able to afford the social tariffs established both for off-grid and connected population with very low incomes). The average income level of the area as well as the experience with the very low default in the collection of fees reported by the established business models in the area supports this initial assumption. The amount of subsidies needed would have to cover at least the difference with the cost of service for each technological solution, plus a fair remuneration of the capital investment.

For our case we have assumed that the applicable tariffs for each level of energy service, according to the regulation for off-grid electrification of rural areas, are those designed for remuneration of private investors. Figure 40 and Figure 41 show the corresponding total and per household figures, detailed by scenario and electrification mode.

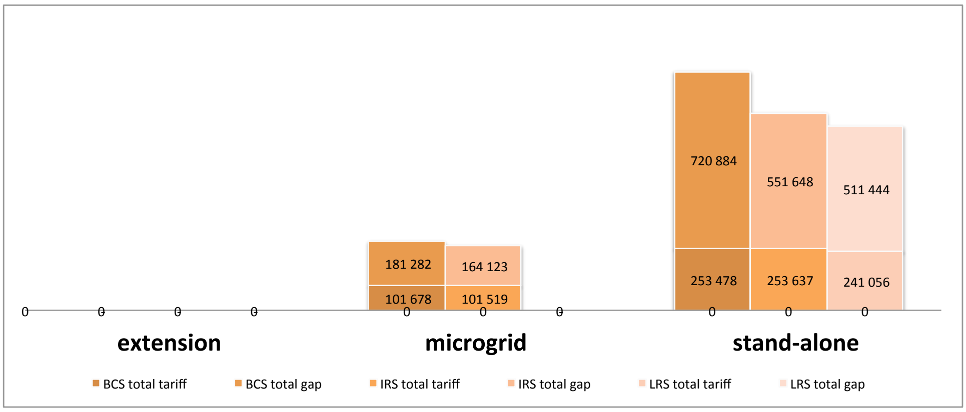


Figure 40 Total tariff collection and funding gap per electrification modes for BCS, IRS and LRS

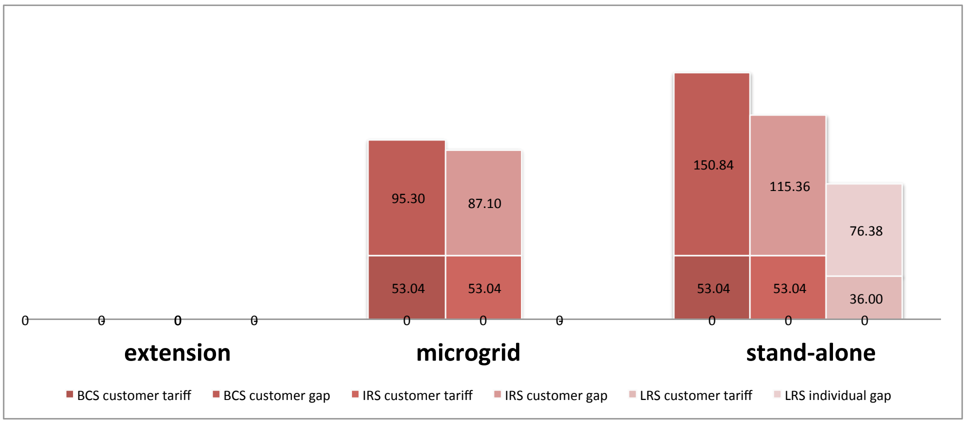


Figure 41 Applicable tariff and funding gap ($/year) per customer detailed by electrification mode and reliability scenarios

It is important to note that the tariff applicable to off-grid isolated solar systems changes in the LRS. As the level of consumption is reduced to 62 kWh per year, the systems are now within the limits of BT8-070 instead of BT8-100 applicable to the other scenarios.

2.3.3 Renewables vs. Diesel scenarios

All the previous cases have shown that for these isolated areas, the high cost of diesel always favors the selection of solar or other available renewables because of their lower cost. This is also in agreement with the off-grid solar policy of the government of Peru.

Nevertheless, the model is able to incorporate and study different scenarios. Here we will compare a scenario of low cost diesel with a full renewables scenario.

2.3.3.1 Renewable Energy Scenario (RES)

In this case, we are only considering solar power. By assuming a very high price of fuel, REM will choose a fully solar-battery generation for all the off-grid systems.

2.3.3.2 Low-cost Diesel Scenario (DIS)

This (unlikely) scenario may come to happen for instance if the isolation of the area were much reduced because of the construction of improved roads. In this case the cost of diesel, being the area only 60 km away from the nearest large population center, would drop instantly.

The low-cost diesel Scenario (DIS) assumes a price of 1$/l of fuel in Michiquillay, a price very similar to the one in the capital of Cajamarca.

Diesel is used in this scenario for microgrids over 14 customers, while in the BCS it was only used for microgrids over 45 households. The presence of much larger microgrids, as will be confirmed later, can be appreciated in this figure, as at least two can be identified very easily in the west of the region, because the 400V lines are now visible. Again, there are no HV lines nor for extension or microgrids.

2.3.3.3 Comparison of RES, DIS and BCS

The electrification mode layout, which at first sight looks very similar for RES and DIS, is shown in Figure 42.

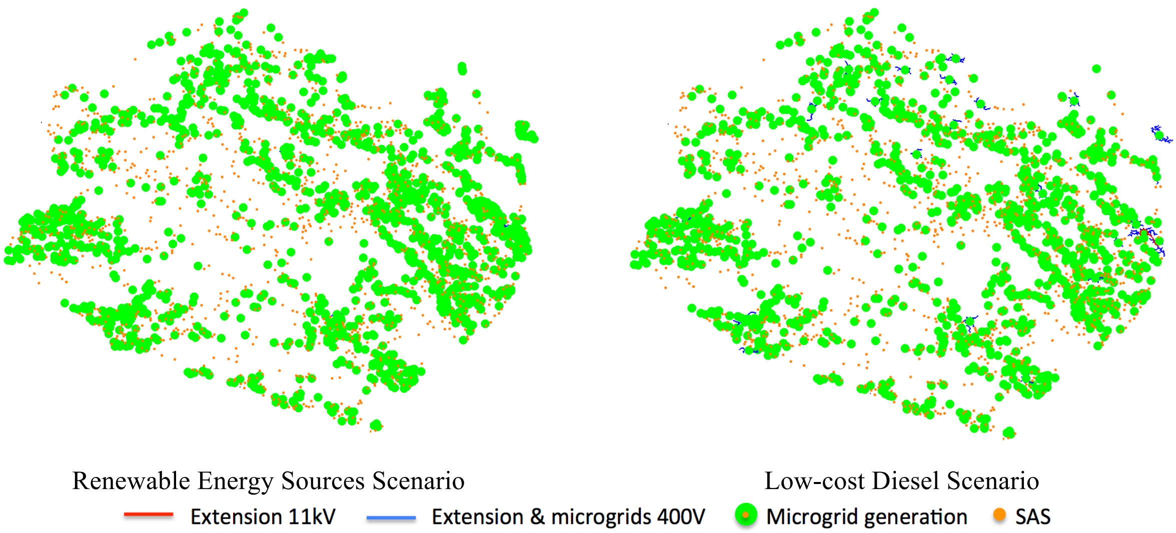
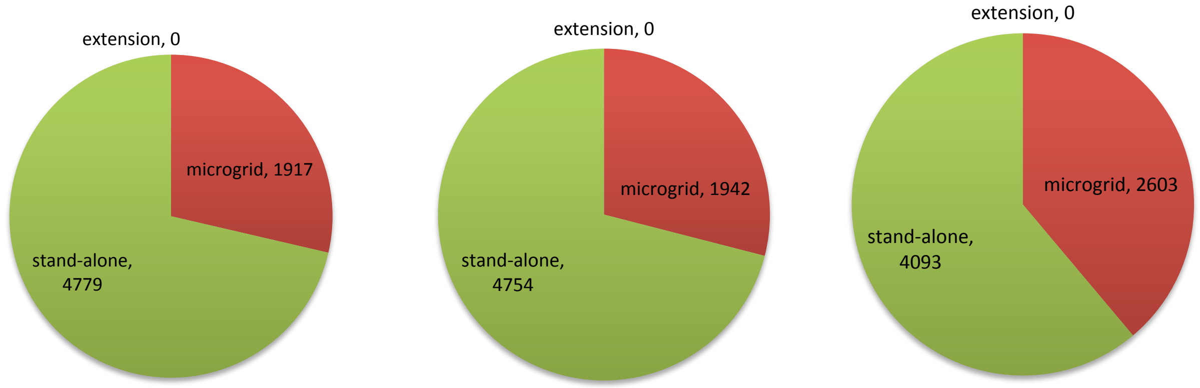


Figure 42 Electrification mode mix for the low-cost Diesel Scenario

The first noticeable feature of Figure 43 is that differences between RES and BCS look almost negligible, therefore also supporting in our case the decission of the government to support a 100% solar off-grid strategy. On the other hand, taking into account the high cost of extending the connected grid in mountain areas, a scenario with very low cost of diesel would completely bias the solution towards the use of micrograms. Again, only microgrids over 10 users have been accounted for.



Base Case Scenario (BCS) Renewable Energy Scenario (RES) Low-cost Diesel Scenario (DIS)

Figure 43 Comparison of electrification mode mix for BSC, RES and DIS

The second important difference lays in the size of the microgrids. The average size of a microgrid in DIS is 57.84 customers, as compared to 32.37 in RES and 23.09 in BCS. The economies of scale for large microgrids with a smaller running cost of the diesel generator are important.

Figure 44 shows the differences in the amount of demand served for the different scenarios, confirming clearly that the use of diesel in microgrids greatly enhances their reliability.

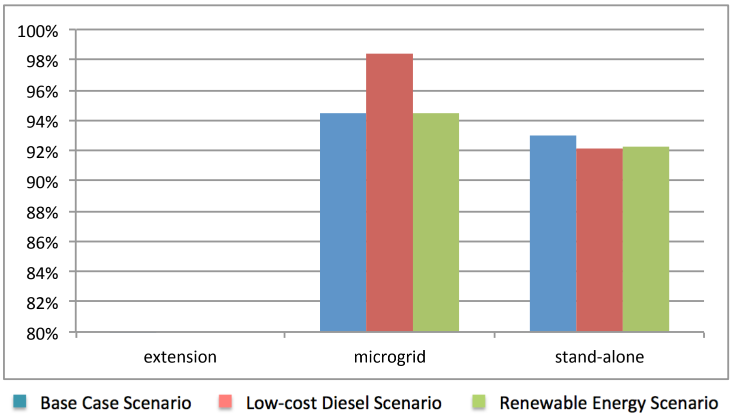


Figure 44 Comparison of the reliability for different electrification modes in the BCS, DIS and RES

Finally Figure 45 and Figure 46 show the changes in the total cost of the Michiquillay SER and the cost per customer, detailed by electrification mode and tariff / subsidy balance.

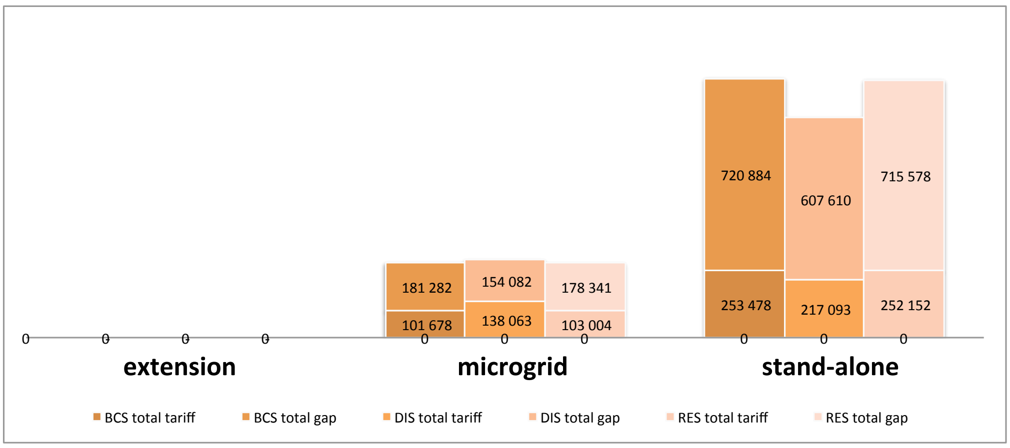


Figure 45 Total tariff collection and funding gap ($/year) per electrification mode for BCS, DIS and RES

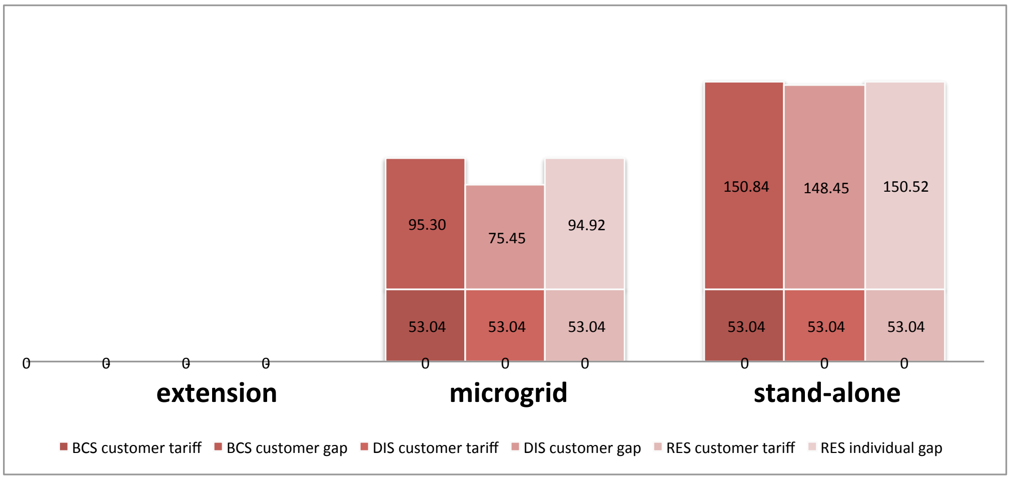
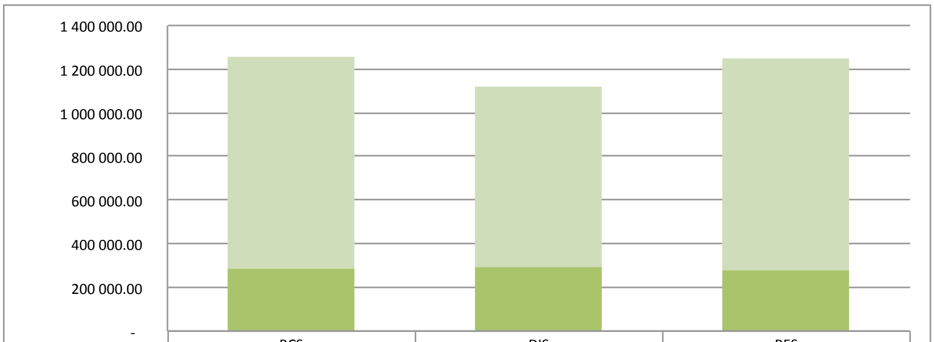


Figure 46 Applicable tariff and funding gap per customer detailed by electrification mode, and BCS, DIS and RES scenarios

The cost per customer for stand-alone systems is mostly the same for the three cases, serving a very similar demand (randomness in the generation of user profiles may generate slight changes on the solution) with 100% solar systems in the three scenarios. As for the microgrids, the presence of low-cost diesel has a direct impact in the cost of microgrids, but not as high as could be expected because of the larger number of microgrids and high dispersion of most of the households.

The total annuity for the three scenarios is shown in Figure 47.



	BCS	DIS	RES
Cost stand-alone	974 362.11	824 702.25	967 730.42
Cost microgrids	282 959.73	292 145.18	281 345.09
Cost extension	-	-	-

Figure 47 Annual cost of BCS, DIS and RES detailed by electrification mode

It is clear that DIS will be more favorable in terms of budget, but the assumption behind a low-cost diesel scenario for this area requires considerable investment in transportation that will no doubt exceed the savings here portrayed. This energy policy alone would not justify the need for better and faster roads, but if other development goals include their need, then diesel would be an option to consider (taking into account also other considerations as carbon emissions, reliability of the engines or business and logistic model of the fuel transport).

On the other hand, RES and BCS are very similar in terms of budget needs and financial gap to be covered. Therefore, assuming a 100% solar strategy proves to be comparable in comparison with BCS, and would bring associated benefits in terms of emissions, safety and contribution to the renewable targets of the country.

2.3.4 Impact of the grid cost

Another key factor in the techno-economical solution is the selection of the grid catalog. As stated before, the base case scenario assumes that the cost of extending networks in mountain areas is much higher than for standard zones. To analyze the impact of network cost, we will examine here two more scenarios:

- **Standard Grid Scenario (SGS)**: For comparability purposes we will assume here the same standard costs of flat areas, for which we are using a catalog equivalent to the one also used in WP5 for the studies developed in Kenya.
- **Low Cost Grid Scenario (LCGS)**: In (Gonzalez-Garcia, Amatya, Stoner, & Perez-Arriaga, 2014) we described different technological choices (as for instance the Single Wire Earth Return or SWER) for low-cost network extension, suitable for very scattered and low-demand rural areas. This strategy has been very successful in countries like Brazil or South Africa, it is easily scalable and provides considerable savings. In this LCGS we have studied the impact of a network catalog with half the cost as the standard catalog.

Figure 48 shows the layout of the different electrification modes for Michiquillay SER of these three scenarios:

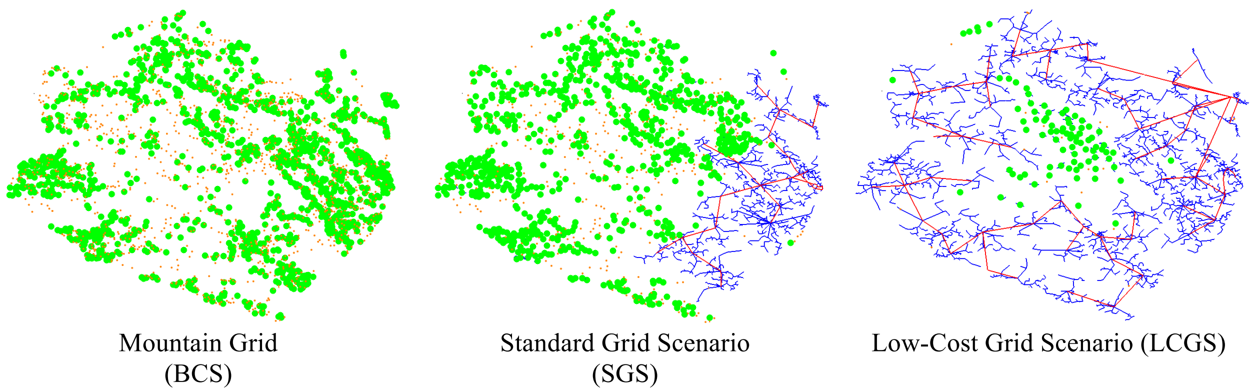


Figure 48 Electrification modes outcome in BCS, SGS and LCGS for Michiquillay SER

The impact of the grid cost is immediately visible in the previous Figure, that changes from a 100% off-grid solution (BCS) to a second one with significant share of grid extension (SGS) and a final scenario that shows a majority of households connected to the network (LCGS).

The different electrification mix is shown in Figure 49.

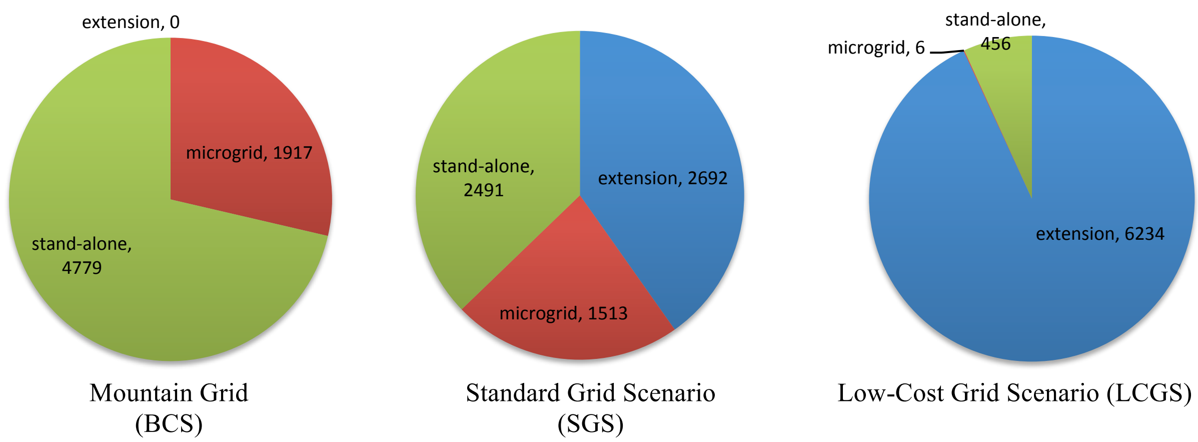
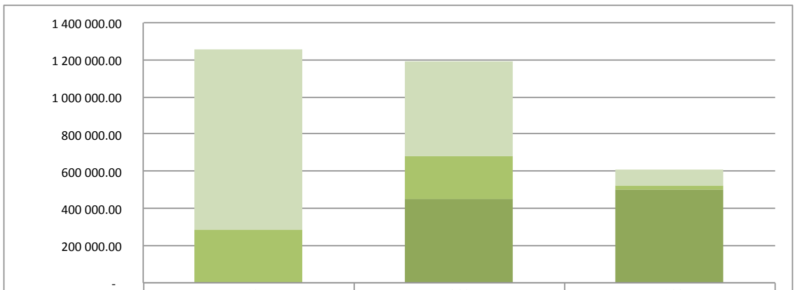


Figure 49 Comparison of electrification mode mix for BSC, SGS and LCGS

The comparative cost of the three scenarios is shown in Figure 50.



	BCS	SGS	LCGS
Cost stand-alone	974 362.11	508 918.52	91 684.45
Cost microgrids	282 959.73	229 744.63	20 196.76
Cost extension	-	455 003.80	500 288.66

Figure 50 Annual cost of BCS, SGS and LCGS detailed by electrification mode

From the figure above it is clear that an appropriate low-cost grid code for the electrification of very isolated areas has a great impact in the least-cost mix of electrification modes proposed for a region. LCGS is 51.3% cheaper than the BCS, whereas SGS is only a 5% cheaper, but completely reshapes the mix of involved electrification modes for the area.

Choosing one or another scenario is not only a question of establishing a different grid-code for rural electrification, as other considerations regarding social goals, attraction of private investment, remuneration of the utilities or upstream reinforcements required for generation, transmission and distribution networks must be taken into account. Nonetheless, the information provided by REM proves to be very useful for the comparison of the different scenarios.

2.3.5 Maximum Grid Extension Scenarios (MES)

The planner may decide that the best electrification mode for the population should be grid extension in almost all circumstances (for as many people as reasonable). In this section we intend to show the outcomes of the model for three 99.99% grid extension scenarios, also taking into account different grid technologies as in the previous section:

- **Grid Extension Scenario for mountain areas (Grid extension – mountain)**: We are modeling this scenario just by increasing the cost of all off-grid technologies, so REM will choose to extend the grid to everyone unless it is less costly to leave that demand un-served.
- **Grid Extension Scenario with standard catalog (Grid extension – standard)**: In this case we will use the same inputs as in the previous one, but using the same standard grid extension catalog as in SGS.
- **Grid Extension Scenario with low-cost catalog (Grid extension – low-cost)**: Again the settings will be the same, except for the low-cost grid extension catalog.

The corresponding layout of the three scenarios is very similar, though not identical, as can be seen Figure 53.

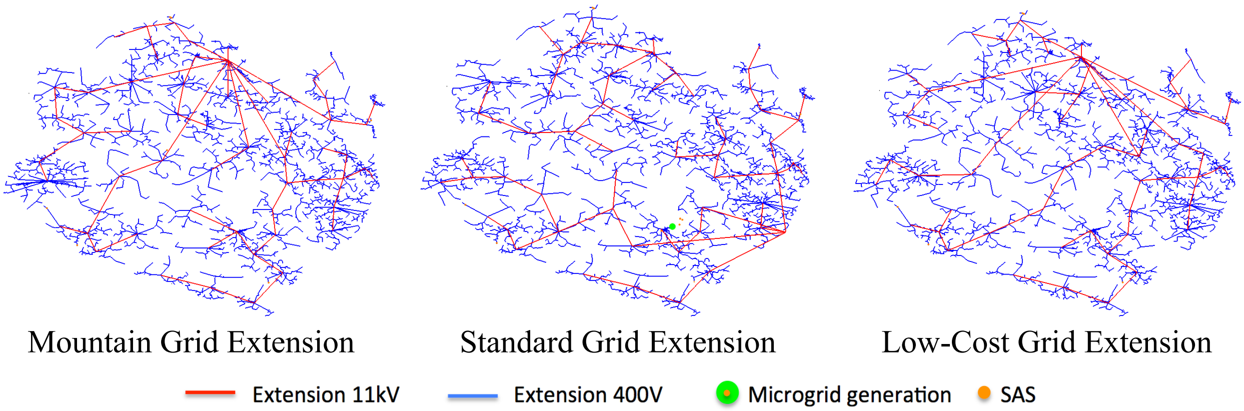


Figure 51 Grid extension layouts for mountain, standard and low-cost grid catalogs

The total annuity for Michiquillay SER of each different scenario can be seen in Figure 52 and detailed per electrification mode in Figure 52.

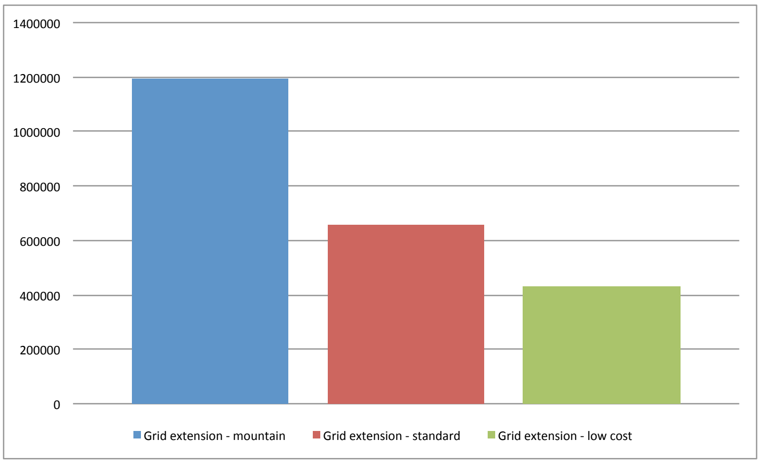


Figure 52 Total annuity for maximum grid extension scenarios with mountain, standard and low-cost grid catalogs

The differences in cost of the different scenarios are large, so strategies to follow would depend much more on the interest of the government on continuing extending the network using less demanding grid codes for these isolated areas, or else relay in stand-alone systems and microgrids for the access to electricity of this population.

Again, it has to be stressed that the selection of the appropriate catalog is an essential step of the planning methodology.

2.3.6 Demand ladder scenarios

REM software allows governments and companies to answer "what if" questions, modeling the impact of setting different policy targets.

One of the main electrification targets to be set is the amount of supply that will be provided to each customer. In our case we will use a blanket approach so all users share a basic demand profile for each scenario.

The demand profile for the Base Case Scenario is detailed in 2.3.1.1, adding to an average consumption of 185,5 kWh/user-year. This basic level of consumption does not even reach the minimum threshold established by the International Energy Agency for Access (though the definition of access as the supply of a certain amount of energy is under discussion as explained in Section 3).

In any case, the planner might need to know the impact of different supply levels (or tiers) on the design and characteristics of the solutions. In this section we will compare the outcome up to 5 demand steps shown in Figure 53.

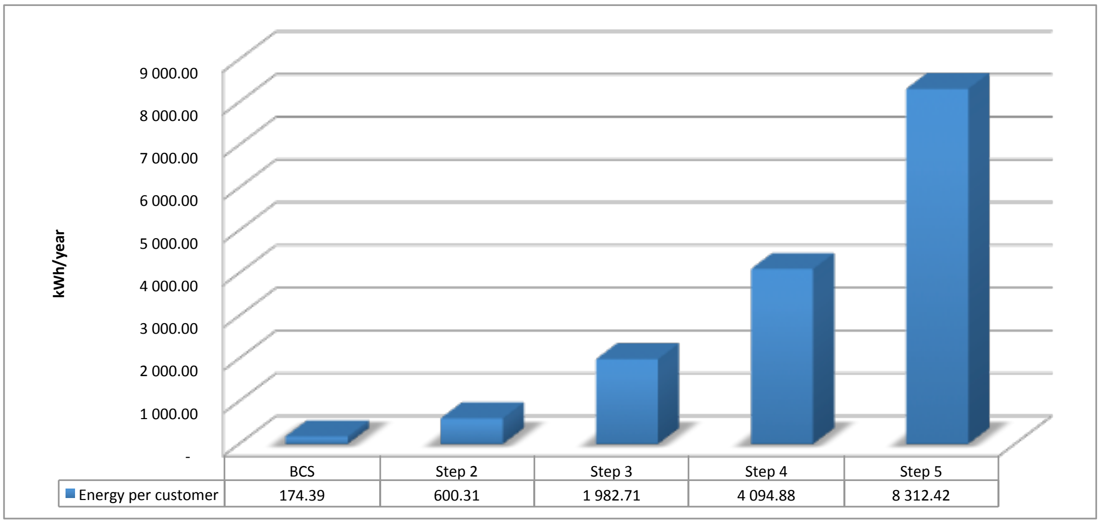


Figure 53 Annual consumption of energy (kWh/year) per household[51] of the selected demand ladder steps for Michiquillay SER

The steps of the model can be defined as convenient for the policy maker. The REM model calculates each consumer profile based on appliance ownership probability, level of consumption per appliance, average use at different times of the day and temperature ranges for house cooling devices. This definition is more detailed that general blanket approaches as the Tiers established by SE4all, but helps setting policy objectives in terms of energy services and supply technologies (considering their efficiencies) and not in terms of just kWh. Nevertheless, the different steps can be calculated so to match the consumption associated to the SE4all tiers, to the minimum levels defined by the IEA or to any other target-ladder set by the government.

Please note that the amount of energy is referred to the domestic consumption of each customer or household, not per capita (total share of electricity per inhabitant, including the consumption in every sector as industry and services per capita). But even if we account for the share of industrial and services consumption per customer in Peru, Step 5 is still 3 to 5 times lower than the average on an emerging economy like South Africa or Hungary in Europe.

In our case step 2 has been set as to comply with the IEA definition of minimum access for urban grid-connected customers (500 kWh/year). Step 5 reaches a slightly higher level of consumption than, in this case, the present per capita consumption in Peru (1,22 MWh/inhabitant or 7,32 MWh/household in 2012 including residential, community and productive uses[52]) set as a hypothetical objective step for the population dwelling at the SER Michiquillay in the coming years. Steps 3 and 4 are intended as intermediate targets.

[51] The per capita consumption can be estimated considering an average occupation of 6 dwellers per household in rural Cajamarca.
[52] www.iea.org

The share of electrification modes for the different steps can be seen in Figure 54.

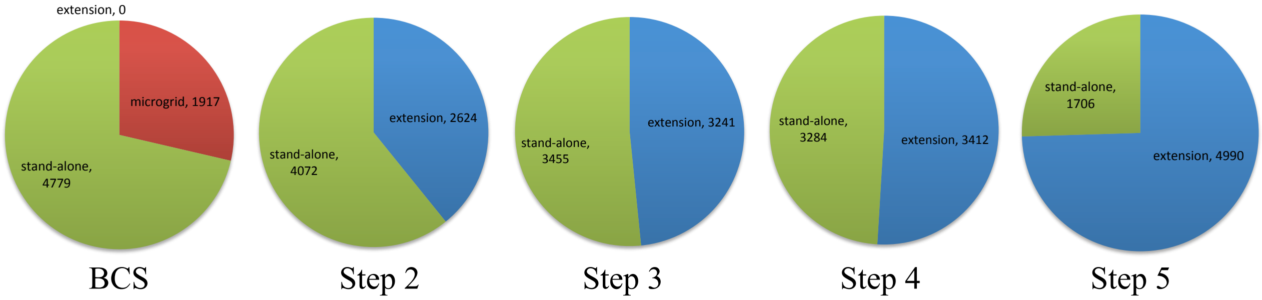


Figure 54 Comparison of electrification mode mix in the four steps of our electrification ladder

The first conclusion is that from the first step grid extension replaces all the existing microgrids, and keeps on growing until Step 5. The corresponding layouts for the different steps can be seen in Figure 55.

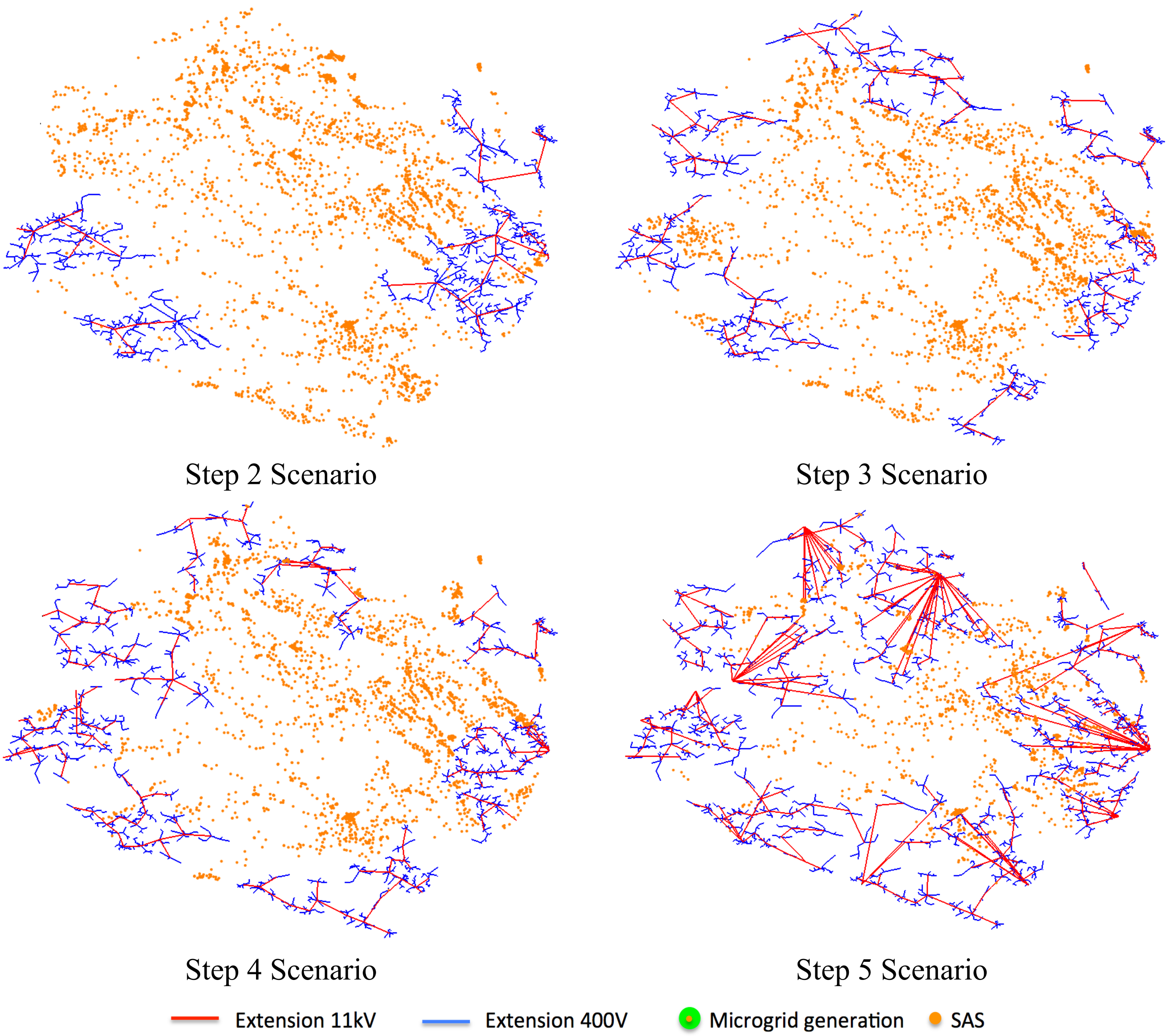
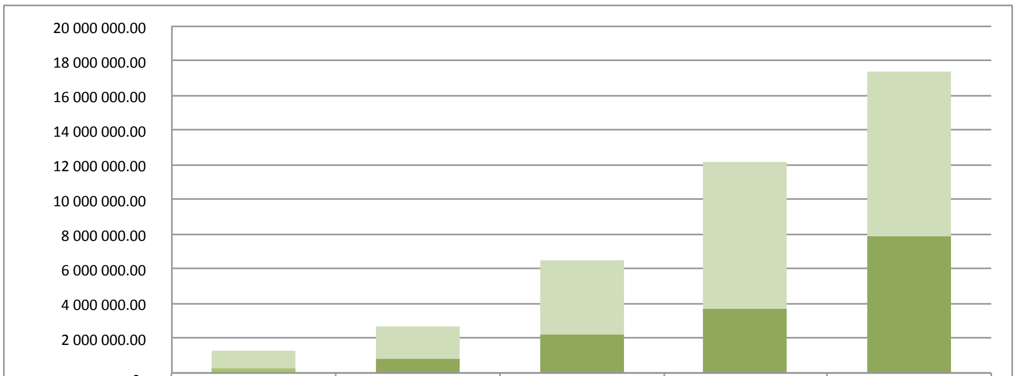


Figure 55 Electrification mode mix for BCS and demand Step 2, Step 3 and Step 4

Starting with Step 2, the increase in demand justifies the extension of the grid from several feeders, as compared to the BCS where all the customers where connected downstream one single transformer. Economies of scale in transformers (used much closer to their nominal capacity) justify this tendency. In Step 2 REM decides to design 6 different extensions, connected to 6 different feeders, and the number of connection transformers continues rising until Step 5.

The cost of the different steps can be compared looking into the total annuity for Michiquillay SER shown in Figure 56.



	BCS	Step 2	Step 3	Step 4	Step 5
Cost stand-alone	974 362.11	1 798 020.10	4 350 107.23	8 460 935.04	9 473 244.67
Cost microgrids	282 959.73	-	-	-	-
Cost extension	-	864 632.38	2 193 058.53	3 676 950.36	7 927 983.42

Figure 56 Annual cost ($/year) of BCS, Step 2, Step 3, Step 4 and Step 5 detailed by electrification mode

It can be easily seen that though the amount of energy served is nearly 50 times higher in Step 5 than in the BCS, the annuity is increased only by a factor of 15. These economies of scale can also be appreciated in the average cost of energy served, that falls by a ratio of nearly 3.5, from 1.09 $/kWh in the BCS to 0.44$/kWh in Step 5, as shown in Figure 57.

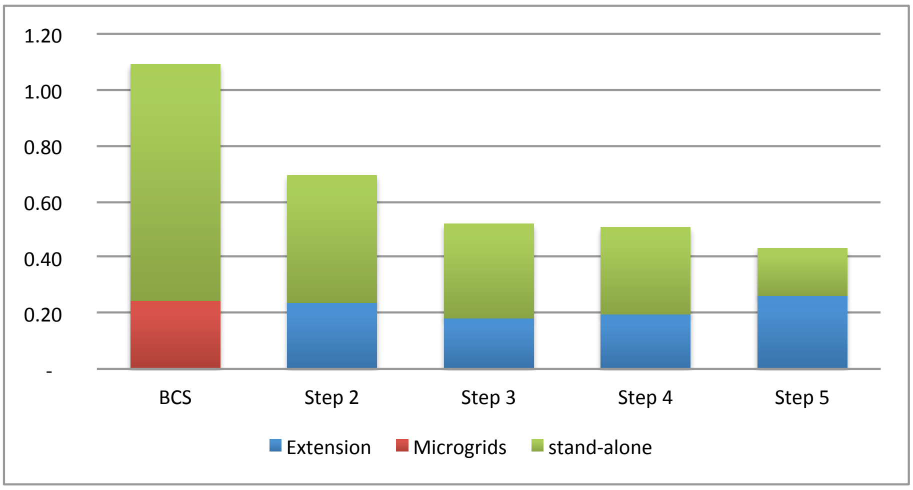


Figure 57 Average cost of Energy ($/kWh) for the four demand step scenarios and contribution per electrification mode

2.4 Conclusions

This section has shown a selection of the regulatory and planning questions that would benefit from the assessment of the Reference Electrification Model REM, which can be summarized in the following five key issues:

- **Choice between grid extension and off-grid electrification with microgrids or stand-alone systems**. The optimal choice of microgrids, SAS and grid extension to be established in any electrification planning by the government will receive an important support from the use of REM under different assumptions and scenarios. In Michiquillay it is clear that for most of the scenarios run, a mix is always advisable against any 100% grid, microgrid or SAS form the point of view of the techno-economic procedure. Nonetheless, other considerations as customer preferences or energy policy goals may argue against or for any one of these solutions, reshaping the final decision-making process outcome.
- **Grid compatible microgrids**. For essential demand defined in the base case scenario it is clear that the use of microgrids for high-density areas or villages is a viable solution for nearly 30% of the households, as a transitory solution until their demand growth reaches a level where the extension of the grid is more advisable. The establishment of grid-compatible standards for connectable microgrids, to be followed by mini-utilities or entrepreneurs that invest in those technologies, is very advisable according to our study of Michiquillay SER. Once the grid reaches those villages, it can be connected to the existing microgrid network, therefore avoiding the waste of investments (as in the case of incompatible microgrids) and allowing the purchase of the existing infrastructure by the incumbent utility, thus helping the original entrepreneur or mini-utility avoid the financial risk of not being able to recover their investment because of a premature arrival of the grid. The generation of the microgrid can also be connected now to the main grid, as an independent power provider, with clear remuneration rules.
- **Use of renewable energy sources vs. diesel generation**. Because of the high cost of diesel in this isolated area, the dispersion of the population and the high solar potential, the REM model shows that the potential of diesel generation for low-demand scenarios is very limited, therefore supporting also the choice of photovoltaic strategies in the SER Michiquillay.
- **Electrification ladder**. In the case of Michiquillay SER, it is clear that even in the case of very high domiciliary demand scenarios with high reliability, some households remain isolated and not connected to the grid in the least-cost solution. Hence any indicative planning that would take into account a very optimistic scenario for future demand growth should not rule out off-grid electrification for those customers, which account for at least 25% of the households in the region.
- **Funding gap**. It is also clear, from the different scenarios run, that non of them can happen without a commitment to support low income customers, either with grid extension cross-subsidized tariffs or off-grid electrification social funding programs. These schemes are already in place in Peru for basic electrification, but REM can also help determine the appropriate amount of budget necessary for a certain region or even down to system or village level, in order to help regulators, agencies and practitioners establish sound and comparable remuneration procedures that could benefit from an objective, flexible, customizable and fast procedure based on the reference electrification model.

3 ANNEX: Comprehensive electrification planning. The REM model

3.1 The electrification planning process

A more detailed description of the main components of a successful strategy towards Universal Access can be found in our previous Working Paper[53], but it is necessary to remark here the four main dimensions of the comprehensive approach we follow in our decision support methodology:

- Business models.
- Supply technologies.
- Community engagement and customer preferences.
- Electrification planning, regulation and governance.

It can be argued that "*the absence of a sound regulatory framework and of a comprehensive electrification planning approach are major impediments for the success of any serious attempt at providing electricity access that could dramatically improve the lives of so many people*"[54].

The scale of the challenge, the amount of information involved and the diversity of options compel the use of computer planning tools to help governments, companies, international agencies, donors and other stakeholders assess their choices between a large variety of technological and business model choices in vast regions, taking into account the detailed needs, location, socio-economic characteristics and preferences of each customer, using wisely their limited resources within an energy policy to support individual, productive and community development.

The problem of deciding which combination of grid extension and off-grid microgrids or stand-alone systems can greatly benefit from the use of a techno-economic procedure using the REM model, as could be seen in the previous section of this document. But any choice needs to be framed within a human-driven decision process that answers to many different contributions. In any case "*available tools, properly used, can inform policy interventions by governments and support the mobilization of resources (public, private and donor-funded) behind access initiatives. There are many potential impediments to successful implementation of such initiatives, including political and social barriers. But a case backed by scientific data, rigorously gathered, will always have a better chance of overcoming this barriers*"[55].

REM is an essential part of a comprehensive approach that includes a set of computer models and methodologies to support decision making and decisively contribute to the achievement of Universal Access, encompassed and coordinated with other energy policy or climate goals. The main phases of this comprehensive approach include:

a) **Data gathering and GIS processing**: Collection, processing and geo-enrichment of information to gather the attributes (e.g. location, demand profile, affordability, etc.) of each residential, community or productive customer in a given area (either individual

[53] (González-García et al., n.d.)
[54] (Pérez-Arriaga & Stoner, 2015)
[55] (Chattopadhyay, Kitchlu, & Jordan, 2014)

households or multiple and diverse connections within a given square in urban areas). It combines this information on demand with resources, economic and socio-demographic information from diverse sources, usually limited in developing countries.

b) **Reference Electrification Model (REM)**: Determines the electrification mode (grid extension, microgrids and stand-alone systems) as detailed in Section 3.2.

c) **Reference Cooking Model (RCM)**: Techno-economic model to determines the best strategy for access to modern cooking according to energy resources, available technologies, health impact, affordability and budget restrictions. For an in depth description, please see (Mwalenga, Amatya, Gonzalez-Garcia, Stoner, & Pérez-Arriaga, 2015).

d) **Model for Assessment of Sustainable Energy Roadmaps for All (MASTER4all)**: Optimizes between different investment choices in generation, transformation of energy, transport and energy services in the whole energy system, including different sectors and energy services, either centralized or de-centralized. It considers the detailed solutions provided by REM for each study area for the different scenarios and, according to the available budget, capacity of payment of the users, energy policy restrictions (use of fuel, emissions, energy dependency, share of renewables, etc.) and the different cost categories (actual cost, social and environmental costs, if applicable) and alternatives downstream and upstream the energy system, it calculates the minimum cost solution, being able to depict scenarios and answer "what if" questions at national or regional level[56].

e) **Others**: To asses the upstream impact of a certain scenario at regional or national level, specific professional-grade models developed by IIT and/or MIT can be needed (e.g. to calculate the necessary reinforcements of distribution and transmission networks, or upstream generation). These models have been thoroughly applied and tested in developed and developing countries, and help fulfill our goal of providing a comprehensive set of tools and approaches that cover the different perspectives required to achieve Universal Access in a given country, be it the size of India with hundreds of millions of users to electrify, down to the specific areas of Peru that still lack access.

3.2 Reference Electrification Model (REM) description

The Reference Electrification Model (REM) supports electrification planning of both grid extension and off-grid systems by producing near-optimal power system designs, including type, size, and locations of electricity generation, storage, and distribution assets, for a region. The REM model, a significant outgrowth of the Reference Network Model[57] (RNM) developed at the Instituto de Investigación Tecnológica (IIT) at Universidad Pontificia Comillas in Madrid, could be used by planners (including distribution companies, electrification agencies, policy makers and regulators) at a regional level, or by utilities, engineers and designers developing individual electrification projects:

A. **Electrification planning for large areas:** There is a lack of means to perform objective quantitative assessments about the most convenient way to provide electricity service,

[56] (González-García, Pérez-Arriaga, & Moreno-Romero, 2014)

[57] (Mateo Domingo, Gomez San Roman, Sanchez-Miralles, Peco Gonzalez, & Candela Martinez, 2011; Peco Gonzalez, 2004; Pieltain Fernandez, Gomez San Roman, Cossent, Mateo Domingo, & Frias, 2011). The RNM model is the outcome of more than a decade of research and successful implementation projects in distribution network planning at IIT. RNM has been used by the Spanish Energy Regulatory Commission to remunerate the distribution companies in Spain, with about 25 million customers, with the agreement and collaboration of these companies. RNM has been used for similar purposes in another countries and in several European research studies.

comparing together the three major electrification modes. This functionality of REM allows the evaluation of the merit of options such as: 1) extend the existing grid; 2) build isolated grids with local generation (micro grids); and 3) install isolated solar-battery systems on each target building.

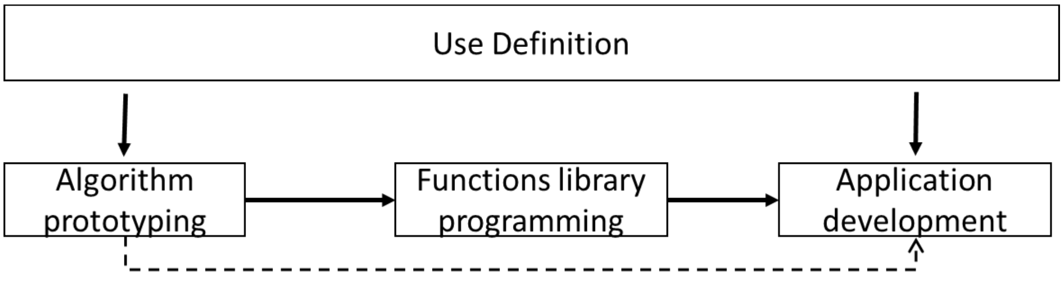
B. **Design of particular electrification projects:** Once a decision about the best way to electrify a group of buildings has been made, detailed local information needs to be incorporated in order to develop a reliable cost-effective design, which is particularly challenging in the case of microgrids. Existing tools[58] fall short in this, and also are very limited in their ability to represent different energy management strategies such as demand management and optimal battery utilization. This microgrid design software (MDS) version of REM is to be used by rural electrification practitioners developing microgrid projects. The MDS will have three main features: 1) simulate different operation strategies, from simple rules to forecast-based optimization; 2) determine best type and size of equipment for generation, energy storage and demand management (including deferrable loads such as pumps and heating/cooling loads); 3) design the lowest-cost distribution network respecting a user-prescribed grid code[59].

In addition to the ability to produce reliable results from a technical viewpoint, both proposed software products require that we understand the local landscape from the cultural, political, regulatory and environmental viewpoints. This includes different electric service requirements, and projections for both population growth and economic development. Moreover, future users of the tool will need to be able to incorporate these aspects for their particular case in order to get useful information out of it. For this reason, REM is embodied in a comprehensive methodological framework to facilitate the use of both tools, consider additional modeling needs and incorporate other relevant factors outside the scopes of the models.

3.2.1 Research approach

Both products are being based on ongoing developments at MIT and IIT. Besides final-user oriented tools, we intend to create and document a library of open-source libraries which can be used by developers around the world to create their own applications. We expect that this elicits the emergence of a community of developers around rural electrification which can greatly amplify the impact of our initiative.

Our proposed approach is illustrated in the figure below.



- On a first stage, the algorithms that we currently have will be used to produce a first version of the user-level applications. At the same time, existing algorithms will be

[58] For example, HOMER and ViPOR, developed by the U.S. National Renewable Energy Laboratory (NREL).
[59] The standards about type of conductors, voltage tolerance, protections and safety vary across countries and explain significant variations in the cost of distribution network. Also, it has been proposed that some modifications to existing standards could be made to be adequate for the particularities of rural locations.

improved and recoded into the first robust functions of the library, and the first potential users of the tools will be identified.

- The second version of the tools will make use of the robust functions, and be designed according to requirements derived from a utilization study done in conjunction with the identified initial users on selected case study cases.

- Our team will work together with a small group of initial users to assist them in the use of the tools in real-world studies and electrification projects. The learning derived from this process will inform modifications to the algorithms and to the user interface, which will be incorporated into the third and final version of the tools.

3.2.1.1 Reference Electrification Model (REM)

REM involves four main components, which can operate independently to do different types of analysis.

1. Data organization and inference. This stage involves extracting the location of currently non-electrified buildings, incorporating information about the existing grid, socio-economic characteristics in relation to the expected future electric load, local cost of equipment, etc. Primary information for this purpose is usually scarce, and a number of assumptions need to be made.
2. Electrification optimizer. Once the area to be electrified has been characterized at a building level, a battery of algorithms is used to group buildings into relevant units of analysis and to compare electrification options for them. The comparison involves a detailed design of both the supply and network (for microgrids and grid extension) parts, taking into account the expected hourly operation of the systems and the cost of imperfect reliability. The design of the network is done used a well established distribution network expansion software called Reference Network Model (RNM)[60].
3. Scenario formulation. The purpose of REM is to help planners make informed decisions, an in most cases they will be contingent on what happens in the short and mid-term, including policy decisions. For this reason, the tool will feature user-friendly and automated way to change hypothesis and perform sensitivity analysis.
4. Visualization and results processing. The results from REM accrue to a large number of files and details, which will likely need to be communicated to non-expert audiences in different (e.g., financial) terms. Also, the outcome from the *data organization and inference component* can be a valuable database for local analysts. Our team will work together with potential users to find out the most relevant data analysis features that need to be incorporated in the tool.

3.2.1.2 Microgrid Design Software (MDS)

The conceptual design of MDS is under development at MIT within the framework of the project for village electrification with anchor load in schools in Karambi, Rwanda. The first version of the tool will enable users to input detailed local information and test different microgrid designs. Local information will include equipment placement restrictions, the specific characteristics of each building and local weather patterns. Three basic features are contemplated:

1. Graphic design interface.

[60] The RNM was developed at IIT and has been being improved over the last 15 years working closely with Spanish distribution companies and regulators.

2. Automated design option. In the same way REM does, MDS will be able to find the optimal design.
3. Ability to manually impose any design aspect. For example, the designer may wish to enforce a zero CO2 microgrid, to distribute solar panels over several buildings or to wire an arbitrary group of buildings together.

Both the automatic and manual design modes will include a realistic representation of different operation strategies.

3.2.2 Input data[61]

Inputs to REM can be organized into two categories: regional inputs and individual inputs. Regional inputs are data about the region that apply to all or large clusters of buildings or demand points (e.g., houses, schools, etc.) in the region. Individual inputs are data that are specific to each building or demand point.

3.2.2.1 Regional Inputs

Location of Buildings

In order to develop a detailed system design, it is necessary to know the latitude and longitude of all buildings in the study area. This is the most basic input to the model and this level of specificity is critical for the realistic calculation of technical feasibility, as well as for cost estimation.

The location of the existing distribution feeders and transformers must be obtained for the study area. In the absence of this data, which can be challenging to obtain, it is possible to run the model assuming that no existing distribution grid exists (greenfield mode) or to use GIS to create a proxy distribution system that may approximate what actually exists. Another limitation of modeling the existing grid is that, in general, it changes frequently. A utility may have plans to expand the system or parts of the infrastructure may be destroyed by natural disasters, so it can be difficult to ensure that existing grid data is up to date (unless the distribution utility keeps a complete GIS record of its facilities, which is not the case in the areas of interest for this study).

Administrative or other context-relevant boundaries

Buildings should be grouped by the most relevant administrative or context-relevant boundary available. This information can be important both for processing a large dataset by analyzing it in smaller chunks and/or for ensuring that the results are produced subject to administrative or other organizing constraints. For example, breaking the analysis of a district into its sub-districts can ensure that a single system does not cross over jurisdictional boundaries where political interests, rules, and requirements, as well as citizen preferences may differ. More granular administrative boundaries can be also useful, like blocks, villages or wards (in India).

Un-electrified households

Amongst all the buildings in a region, it is necessary to determine which buildings are currently connected to the existing grid or are electrified already by other means, and which buildings require electrification. The model does not make determinations about whether existing grid infrastructure is cost effective. Buildings that are classified as electrified may not be considered in the model, which will be the case for the examples described in this document. Grid extension

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[61] This whole section reproduces the analysis developed in Yael Borofsky. 2015 "*Towards a Transdisciplinary Approach to Rural Electrification Planning for Universal Access in India*" Master Thesis, MIT, pp 50-53.

may require joint consideration of upstream network reinforcements (outside of REM) that are needed for the existing electrified and newly electrified customers.

Energy resources

The availability of different energy resources (e.g., solar irradiation, diesel availability, biomass resources, potential sites for mini-hydro plants) in a given area is necessary in order to determine the suitability of different types of generation. This data must be aggregated at the relevant unit of analysis, whether that is a value for each building, a value for a given area within the study region, or a single value for the entire study region.

Cost of Non-Served Energy (CNSE)

To compare costs between a grid extension and an off-grid system it is necessary to know the cost, to consumers, of energy that is not served in order to account for the reliability of each system (or unreliability, as the case may be). This concept is actually quite subjective, but is intended to represent the cost (i.e., the loss of utility) incurred by consumers when there is no electricity at a time when they were planning to use it. REM requires two values for CNSE, one for essential load and another for nonessential load. The CNSE value for essential load should be higher than the CNSE value for nonessential load in order to represent the greater cost (equivalently, loss of utility) to the consumer for not meeting the most valuable demand. CNSE is also needed to size the generation source in a microgrid so that a theoretically optimal trade-off is reached between cost of supply and quality of service. There could be multiple ways of arriving at a value for CNSE, but one way of calculating CNSE value is to determine the cost of an alternative energy solution (e.g., kerosene) that might be used when electricity is not available and adopt that value as a proxy, possibly adjusted by some arbitrary factor to account for the inconvenience of procuring the alternative energy source or to account for the type of demand not served (i.e., essential or non-essential).

Generation equipment catalog

A catalog of generating equipment to be considered, its specifications, and the cost of each piece of equipment is necessary in order to create a detailed system design and effectively compare costs between different systems and designs. Generation equipment includes components like solar panels, batteries, diesel generators, inverters, and other power electronics. Although it is probably impossible to collect an exhaustive list of all possible generation components in use throughout a region (e.g., there could be several models of solar PV panels), that is not a problem as long as there is a representative specification for each type of equipment that should be considered.[62]

Network technical requirements and catalog

This data set includes typical load voltage, generator voltage, network lifetime, reliability targets, and cost of network losses experienced in the region being studied or used in the Reference Network Model catalog. The catalog also contains equipment specifications, such as the technical parameters, costs, and failure rates of conductors, transformers, and substations.[63]

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[62] REM can be used to design optimally just one microgrid for a specific village, for instance. In that case the level of accuracy in the catalog of equipment has to reflect a satisfactory level of reality.

[63] For more information see Ellman, Douglas. 2015. "The Reference Electrification Model: a Computer Model for Planning Rural Electricity Access." Master's Thesis, MIT.

Reliability of the existing grid

In order to provide a more informed comparison between grid extension and off-grid systems it is necessary to know the reliability of the supply of electricity from the existing grid (i.e., the number of hours per year the grid is expected to be supplying electricity and when). This value can be expressed as one overall percentage or broken up into a percentage for off-peak reliability and peak reliability in order to reflect, for instance, the fact that in some areas the outages might be more likely to occur during peak demand hours. Reliability is also important to the concept of CNSE.

Price of diesel

Diesel generator sets may be used as a primary or supplementary source of electricity. Some microgrids also use a mix of solar and diesel generation in order to meet demand in areas where solar irradiation is more volatile. For this reason, it is necessary to model the price of diesel for generation. Estimating the cost of diesel is not so simple, since the official cost per liter does not take into account several associated costs, such as the cost of transporting the diesel to a rural marketplace, the cost of traveling to purchase diesel, as well as the cost of storing and protecting such a desirable product.

Discount rate

A discount rate is necessary to determine the net present value of a given project to the owner of the assets (e.g., the project developer). Depending on the planner running the model, the discount rate could be adjusted to reflect the assessed risk of power projects in a region, estimated time needed to recover the up-front investment, and several other factors.

3.2.2.2 Individual inputs

Classification of buildings

If data are available, buildings can be categorized by customer type (e.g., house, school, hospital, etc.), but this is not strictly necessary for the model to produce preliminary results. The added specification of customer types makes it possible to specify different electricity demand profiles, since households typically have different electricity demand profiles than public buildings, for example.

Characterization of demand

Following the classification of buildings, the demand for each building needs to be characterized. To design electrification solutions for un-electrified buildings it is necessary to estimate how much electricity each building might consume if it had access to electricity. Since the model will try to meet specified demand at the lowest techno-economic cost, more detail about demand at each individual load point is likely to have an influence on the results. Characterizing demand requires data about either

a) the hourly demand profile of similar buildings in a similar context (which includes affordability, geographical proximity, type of economic activity, type of house, etc.) that do have access to electricity,
b) constructing an hourly demand profile from a reasonable inference about what types of appliances the occupants of the building might use and how often, or
c) setting a demand target.

For the second method, characterizing demand may also require weather data and the timing of sunrise and sunset in the region in order to construct a more representative hourly demand profile. Once the demand profile is constructed, it must be classified into one of two tiers: 1) essential or critical load (e.g., lighting) or 2) non-critical load (e.g., television).

4 References

Amatya, R., Gonzalez-Garcia, A., Stoner, R., & Perez-Arriaga, I. (2014). *Preliminary candidate list of appropriate technologies , business models and enabling environment for universal access to modern heat*.

Batlle, C., Barroso, L., & Echevarría, C. (2012). *Evaluación del marco normativo e institucional del Perú para la promoción de energía eléctrica a partir de recursos renovables* (No. Nota técnica No. IDB TN - 480). doi:IDB TN - 480

Borofsky, Y. (2015). *Towards a Transdisciplinary Approach to Rural Electrification Planning for Universal Access in India*. Massachusetts Institute of Technology.

Chattopadhyay, D., Kitchlu, R., & Jordan, R. L. (2014, November 20). Planning for Electricity Access. Retrieved from https://openknowledge.worldbank.org/handle/10986/20596

Dávila, C., Vilar, D., Villanueva, G., & Quiroz, L. (2010). *Manual para la evaluación de la demanda, recursos hídricos, diseño e instalación de microcentrales hiroelélctricas*. Lima, Perú: Soluciones Prácticas (Práctical Action). Retrieved from http://www.solucionespracticas.org.pe/Descargar/183/1416

Eisman, J. (2011). PERU Microenergy : A sustainable model for rural electrification with renewable energy. In I. Pérez-Arriaga & A. Moreno (Eds.), *Tecnologías para el Desarrollo Humano de las Comunidades Rurales Aisladas* (pp. 128–132). Real Academia de Ingeniería de España.

Eisman, J., Olivares, J., Moreno, A., Verástegui, Á., & Mataix, C. (2013). La electrificación con pequeños sistemas fotovoltaicos domiciliarios (PSFD) ¿Un cambio de paradigma? Lima, Perú: Congreso Internacional sobre el Acceso Universal a los Servicios Públicos de Energía.

ESMAP, World Bank, & IEA. (2013). *SE4All Global Tracking Framework*. Washington D.C.

FISE. (2013). Fondo de Inclusión Social Energético ¿ QUÉ ES EL FISE ?

FISE. (2015a). *Gobernanza en la administración pública. Experiencia del administrador del Fondo de Inclusión Social Energético - FISE*. doi:10.1007/s13398-014-0173-7.2

FISE. (2015b). *Propuesta metodológica para el logro del acceso universal en el perú*.

Fürsch, M., Hagspiel, S., Jägemann, C., Nagl, S., Lindenberger, D., & EckehardTröster. (2012). *The role of grid extensions in a cost-efficient transformation of the European electricity system until 2050* (No. 12/04). Retrieved from http://www.ewi.uni-koeln.de/fileadmin/user_upload/Publikationen/Working_Paper/EWI_WP_12-04_Role_of_grid_Extensions.pdf

Global Envision. (2006). Fabio Rosa - Making the Sun Shine for All | Global Envision. Retrieved November 24, 2015, from https://www.globalenvision.org/library/10/954

Gonzalez-Garcia, A., Amatya, R., Stoner, R., & Perez-Arriaga, I. (2014). *Preliminary candidate list of appropriate technologies, business models and enabling environment for universal access to electricity.* (No. 16). Rome. Retrieved from www.enelfoundation.org

González-García, A., Amatya, R., Stoner, R., & Pérez-Arriaga, I. (n.d.). *Appropriate technologies , business models and enabling environment for Universal Access to modern energy services (in print)*. Rome.

González-García, A., Pérez-Arriaga, I., & Moreno-Romero, A. (2014). MASTER4all : A decision support model for roadmaps towards sustainable energy universal access for policymakers and utilities. In U. Berkeley (Ed.), *Innovating Access for Remote Areas. Discovering Untapped Resources* (p. 5). Berkeley. Retrieved from https://energypedia.info/wiki/A_Decision_Support_Model_for_Roadmaps_Towards_Sustainable_Energy_Universal_Access_for_Policymakers_and_Utilities

IEA. (2010). *World Energy Outlook: Energy Poverty - How to make modern energy access universal?* Paris.

INEI. (2015). *Evolución de la pobreza monetaria 2009-2014. Perú.* Lima, Perú.

Mateo Domingo, C., Gomez San Roman, T., Sanchez-Miralles, Á., Peco Gonzalez, J. P., & Candela Martinez, A. (2011). A Reference Network Model for Large-Scale Distribution Planning With Automatic Street Map Generation. *IEEE Transactions on Power Systems*, *26*(1), 190–197. doi:10.1109/TPWRS.2010.2052077

Ministerio de Energía y Minas - República de Perú. Plan Energético Nacional 2014- 2025 (2014). República del Perú. Retrieved from http://www.minem.gob.pe/_detalle.php?idSector=10&idTitular=6397

Ministerio de Energía y Minas (Perú). (2012). *Perú - Subsector eléctrico documento promotor 2012*. Lima, Perú.

Ministerio de Energía y Minas (Perú). Plan de Acceso Universal a la Energía 2013-2022 (2013). Peru: El Peruano.

Ministerio de Energía y Minas (Perú). Plan Nacional de Electrificación Rural. Periodo 2014-2023 (2013). Perú. Retrieved from http://dger.minem.gob.pe/ArchivosDger/PNER_2014-2023/C0-PNER-2014-2023.pdf

Ministerio de Energía y Minas (Perú). Dirección General de Electricidad. Norma DGE "Especificaciones técnicas de montaje de líneas y redes primarias para electrificación rural" (2003). Peru.

Ministerio de Energía y Minas (Perú). Dirección General de Electricidad. Reglamento técnico. Especificaciones técnicas y procedimientos de evaluación del sistema fotovoltaico y sus componentes para electrificacion rural (2007). Peru.

Murillo Huaman, V., García Portugal, E., & Carcausto Rossel, D. (2015). *Mapa Energético: Herramienta de gestión para el acceso universal a la energía* (No. Año 3, nº 1). Lima, Perú.

Mwalenga, L., Amatya, R., Gonzalez-Garcia, A., Stoner, R., & Pérez-Arriaga, I. (2015). *A Comprehensive Computer-Aided Planning Approach for Universal Energy Access. Case Study of Kilifi, Kenya* (No. (in press)). Rome.

NRECA International. (2001). *Electrificación Rural en el Perú. Diagnóstico y Propuesta de una Nueva Estrategia*.

Olivares Magill, J., & Eisman Valdés, J. (2011). Acceso Universal a la electricidad... ¿Y Perú? In *XVIII Simposio Peruano de energía solar y del ambiente (XVIII SPES)* (pp. 14–19). Lima, Perú.

OSINERGMIN. (2008). *Análisis Comparativo de las Tarifas de Electricidad a Nivel Internacional a Marzo 2008*.

OSINERGMIN. Bases Definitivas para la Subasta de Suministro de Electricidad con Recursos Energéticos Renovables en Áreas no Conectadas a la Red (2014). Peru.

OSINERGMIN. (2014b). *Fijación de la Tarifa Rural para Sistemas Fotovoltaicos 2014-2018* (No. 0248.2014-GART). Peru: Gerencia Adjunta de Regulación Tarifaria. División de Distribución Eléctrica. Retrieved from http://www2.osinerg.gob.pe/ProcReg/TarifaRuralSistemasFotovoltaicos/Fijacion_Tarifa_SisFotovoltaicos_2014_2018/0-Recursos/3.1 Proyecto Resolución/INF-0322-2014-GART_Publicación Proyecto Resolución SF 2014-2018.pdf

Ostojic, D., Jammi, R., Barnes, D., Sanghvi, A., Mathur, S., Zhang, Y., & Durix, L. (2011). *One Goal, Two Paths: Achieving Universal Access to modern energy in East Asia and the Pacific*. (The World Bank & Australian Government AusAID, Eds.). Washington D.C.: The World Bank. doi:10.1596/978-0-8213-8837-2

Peco Gonzalez, J. (2004). *A Reference Network Model: the PECO Model* (No. 029A). Madrid, Spain. Retrieved from https://www.iit.upcomillas.es/docs/IIT-04-029A.pdf

Pérez-Arriaga, I., & Stoner, R. (2015). Comprehensive planning and sound regulation: Two key enablers of universal access in Africa. *Oxygen Magazine (by ENEL)*.

Perú: subastas de Energía Renovable. (2013). In *Políticas y Mecanismos Reguladores en Apoyo de la Energía Renovable*.

Pieltain Fernandez, L., Gomez San Roman, T., Cossent, R., Mateo Domingo, C., & Frias, P. (2011). Assessment of the Impact of Plug-in Electric Vehicles on Distribution Networks. *IEEE Transactions on Power Systems*, *26*(1), 206–213. doi:10.1109/TPWRS.2010.2049133

PNUD. (2013). *Anexo: Índices para el Informe de Desarrollo Humano Perú 2013*. Lima, Perú.

PNUD. (2015). *Human Development Report 2014. Sustaining Human Progress. Peru*. Retrieved from http://hdr.undp.org/sites/all/themes/hdr_theme/country-notes/PER.pdf

Ratnayake, C. (2015). *Low Cost Grid Electrification Technologies. A handbook for* *electrification practitioners*. Eschborn, Germany.

República del Perú. Reglamento de la Ley General de Electrificación Rural (Perú) (2007). Peru: El Peruano.

República del Perú. Política Energética Nacional del Perú., Diario Oficial El Peruano 99 (2010). Peru. Retrieved from http://www2.osinerg.gob.pe/MarcoLegal/docrev/DS-064-2010-EM-CONCORDADO.pdf

República del Perú. Ley que crea el Sistema de Seguridad Energética en Hidrocarburos y el Fondo de Inclusión Social Energético (2012). Perú. doi:10.1073/pnas.0703993104

República del Perú. Ley que dicta disposiciones a fin de promover la masificación del gas natural (2012). Peru. Retrieved from http://www2.osinerg.gob.pe/MarcoLegal/docrev/LEY-29969-CONCORDADO.pdf

SE4all. (2013a). *Peru. Energía Sostenible para Todos. Evaluación rápida y análisis de Brechas*.

SE4all. (2013b). *Perú. Sustainable Energy for All. Rapid Assessment and Gap Analysis*. Retrieved from http://idbdocs.iadb.org/wsdocs/getdocument.aspx?docnum=39190914

SG AGECC. (2010). *Energy for a Sustainable Future*. *The Secretary-General's Advisory Group on Energy and Climate Change*. New York.

SG High-Level Group on Sustainable Energy for All. (2012). *Sustainable Energy for All. A Global Action Agenda*. Retrieved from http://www.se4all.org/wp-content/uploads/2013/09/SE4ALL-ActionAgenda.pdf

Singh, G., Tapia, A., & Chavez, S. (2014). *Perú. Evaluación del estado de preparación de las energías renovables 2014*.

Soluciones Prácticas (ITDG). (2009). *Electrificación rural con energías renovables. Proyecto Acceso a la energía en comunidades de la región Cajamarca a través de la planificación energética con energías renovables*. Lima, Perú.

UN Energy. (2005). *The Energy Challenge for Achieving the Millennium Development Goals*. *New York*. Retrieved from http://cn.unhabitat.org/downloads/docs/920_88725_The Energy challenge for achieving the millenium development goals.pdf

UN General Assembly. Resolution of the United Nations summit for the adoption of the post-w2015 development agenda (draft) (2015). United Nations.

UN General Assembly. Transforming our world: The 2030 Agenda for Sustainable Development (2015). United Nations.

UNDP. (2015). *Sustainable Development Goals*. New York. doi:10.1007/s13398-014-0173-7.2

van den Akker, J. H. A. (2008). *Electrificación Rural a base de energía fotovoltaica en el Perú. Evaluación final proyecto PER/98/G31* (Vol. 31).

World Bank. (2013). *Toward a Sustainable Energy Future for All. Directions for the World Bank*

Group's Energy Sector.

World Economic Forum. (2014). *The Global Energy Architecture Performance Index Report 2015*. Geneva. Retrieved from http://www3.weforum.org/docs/WEF_GlobalEnergyArchitecture_2015.pdf